Assessing the Implementation of Ultrafiltration in a Brazilian Kraft Pulp Mill

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Abstract

The pulp and paper industry is one of the largest global consumers of freshwater resources. Reducing water usage is crucial, and innovation in the production process is challenging to implement due to high upfront costs. The industry is extremely sensitive to both market fluctuations and increasingly strict environmental regulations, as climate change issues demand a greater focus on sustainability. Furthermore, freshwater is becoming increasingly scarce and costly to obtain. Reusing water in the production process is one way to increase sustainability and remain competitive in the industry. Ultrafiltration (UF) membrane technology has the potential to reduce water usage by generating high quality permeates that permit their reuse in the production process. This thesis focuses on the implementation of UF membrane systems in a Brazilian bleached kraft pulp mill in the Doce River basin. The technology can be applied to various streams of water or effluents from the production process. However, pilot studies have identified three favorable scenarios. The first uses UF to treat ep-stage bleaching effluent. The second uses UF to treat whitewater from pulp drying. The third scenario uses UF to replace sand filters in the water treatment plant. Each scenario is assessed in this thesis based on technical, economic, and environmental benefits, risks and impacts. This assessment is under the umbrella of a wider governance context that is favorable towards the implementation of new technologies. The result is a realistic assessment of each scenario in the form of three empirical models. These models will contribute to the mill's final decision to implement the technology. The governance assessment may be applied to other mills or industries with similar challenges implementing novel, environmentally beneficial technology.

Keywords: Pulp and Paper Industry, Pulp Mills, Ultrafiltration, Water Reuse, Technology, Governance, Implementation

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List of Abbreviations

BATNEEC	Best Available Techniques Not Entailing Excessive Costs
BOD	Biochemical Oxygen Demand
BMT	Berghof Membranes Technology
CIT	Contextual Interaction Theory
COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
EC	Electrical Conductivity
FAPEMIG	State Funding Agency of Minas Gerais, Brazil
GAT	Governance Assessment Tool
NWO	Netherlands Organization for Scientific Research
SIA	Taskforce for Applied Research of the Netherlands Organization for Scientific Research
TDS	Total Dissolved Solids
TSS	Total Soluble Solids
UF	Ultrafiltration
WWTP	Waste Water Treatment Plant
WTP	Water Treatment Plant

1. Introduction

1.1 Background

The pulp and paper industry is one of the most water and energy intensive industries on the planet. The manufacturing process of pulp and paper requires a high quantity and quality of freshwater (Thompson et al., 2001). Pulp mills are often placed alongside major sources of freshwater, such as rivers, and have their own drinking water treatment plants and wastewater treatment plants. These mills generate significant volumes of effluent with high chemical-oxygen demand (COD) and biochemical oxygen demand (BOD), which could have a high impact on the environment if not properly treated. This occurs especially when the water is circulated from the freshwater source to the mill and back into the environment (Corcelli et al., 2018). Due to increasing water scarcity and stricter environmental regulations, it is preferable and increasingly necessary to reduce freshwater usage as much as possible to reduce both financial costs and environmental impacts (Soderholm et al., 2019). One solution to these challenges is to implement ultrafiltration (UF) membrane systems in the pulp production process, which has several benefits. First, UF is a low-energy-impact technology. Second, it can increase the quality of treated wastewater, enabling this water to be reused in the production process. This, in turn, reduces the amount of freshwater consumed by the mill and contributes to an increased quality of treated wastewater returned to the freshwater source (Chen et al., 2015; Mänttäri et al., 2010).

A kraft pulp mill operating in the Doce River Basin in Brazil is seeking to reduce freshwater consumption. The mill is jointly owned two international holding corporations with 7,600 employees in 54 countries. It has been in operation since 1973 (Dalvi, 2020). To achieve this, the mill is interested in purchasing and integrating UF membrane technology from the Dutch company Berghof Membranes Technology (BMT) in their production process. BMT manufactures tubular membranes and has been in operation for over 40 years, with 1500 system installations worldwide (Berghof Membranes Technology, 2019). The pulp mill and the Doce River are highlighted in Figure 1.

This kraft pulp mill is an example of how environmental, economic, and regulatory pressures are influencing technological changes that make pulp production less impactful on the environment. In 2015, the Doce River suffered an environmental disaster after a collapsed dam polluted the waters with large amounts of toxic mining mud. The quality of the water in the Doce River basin was drastically reduced, pressuring the government and many industries to find ways to reduce their water intake and ease the pressure on the river while remaining competitive both socially and economically (WatMin, 2017).

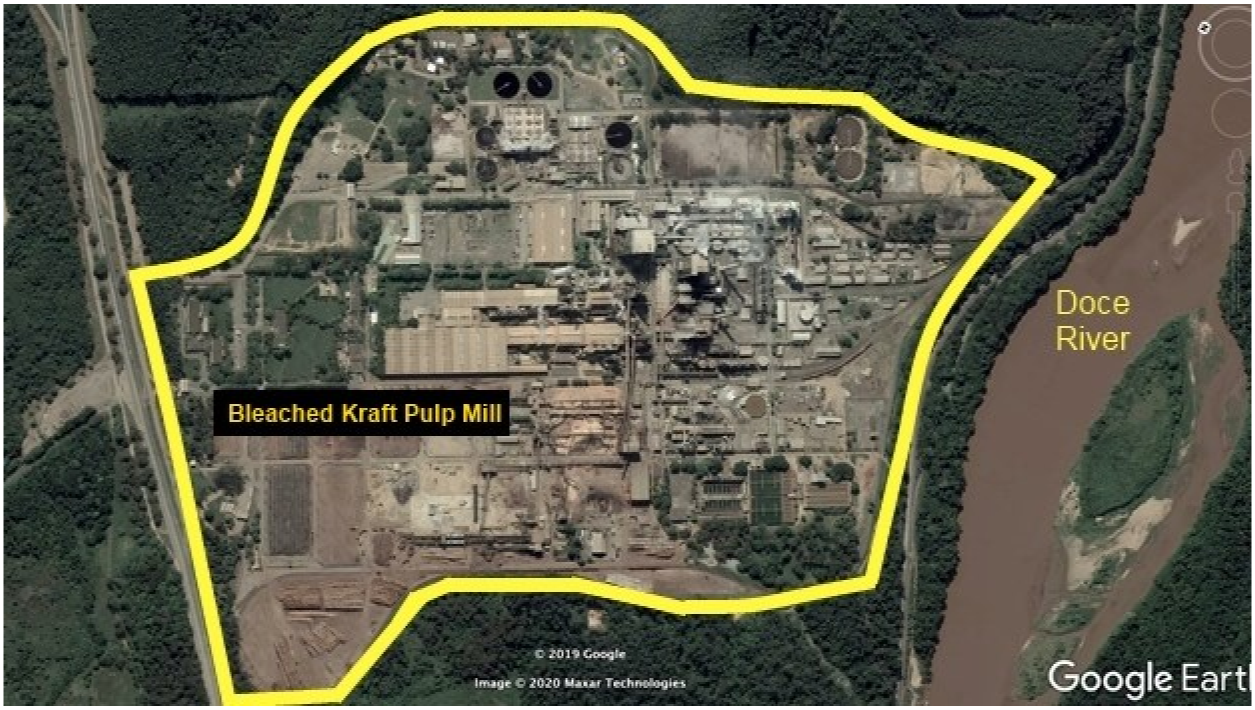

Figure 1: Map of the bleached kraft pulp mill (Google, 2020)

There are several possibilities in which the UF technology can be implemented in the pulp mill, however three main scenarios have been identified as the most favorable by previous pilot studies (Silva et al., 2019; van Leeuwen & Cappon, 2020). The first scenario involves applying the UF membrane on the bleaching EP-stage alkaline effluent. The second uses the UF membrane to treat whitewater from the pulp drying process. The third scenario replaces the current sand filters of the water treatment plant (WTP) with UF. This thesis analyzes each scenario to determine what the key economic, technical, and environmental benefits, risks and impacts are for implementing UF in the Brazilian pulp mill. It will also assess how the governance conditions of the pulp and paper industry affect the implementation of new technology. Of special consideration is the fact that financing and subsidy agencies from both the Netherlands and Brazil have been involved to facilitate the implementation of this technology, respectively the Taskforce for Applied Research of the Netherlands Organization for Scientific Research (SIA) and the State Funding Agency of Minas Gerais, Brazil (FAPEMIG). This thesis considers how this transnational cooperation may contribute to the implementation of technology that has a positive environmental impact. As such, several actors have key interests in the results of this research, which will contribute towards the decision process of purchasing and installing UF membrane technology in the pulp mill.

1.2 Problem Statement

By implementing UF membrane technology in the production process, the bleached kraft pulp mill aims to achieve several goals. These goals include reducing overall water usage, making the best use of permeate and concentrate, reducing costs, increasing efficiency, and complying with Brazilian environmental legislation. Achieving these goals will contribute towards the reduction of the environmental footprint on the Doce River, which has been severely impacted since a mining accident in 2015 discharged residues into its waters. The following three scenarios were identified by previous pilot studies to implement UF in the Brazilian pulp mill: 1) treating the EP-stage bleaching effluent, 2) treating the whitewater effluent from pulp drying, and 3) replacing the sand filters in the water treatment plant (WTP). Each of these lines produces effluent streams of varying quantity and quality, and the resulting permeate and retentate can be used or reused in different ways. The UF technology has different benefits, risks and impacts in each scenario. In order to make a correct decision, these aspects should be assessed. The assessment results in a decision based on a complex interaction of multiple actors with varying interests. The governance context of these interactions may support or hinder a result that leads to a lower overall environmental impact. In this case, several actors have key interests in the results. The mill is interested in the benefits, risks and impacts of this technology. BMT is interested in a realistic analysis of the capabilities of the UF system, including the quality of the generated effluent and any risks to the system. For academia, the scientific impacts, engineering novelties, and governance aspects are especially of interest. Finally, SIA and FAPEMIG wish to gain insight on technical solutions that decrease industrial impacts on freshwater bodies such as the Doce River. All these interests will be considered in this thesis alongside an in-depth assessment of the three scenarios. Ultrafiltration and similar technologies can contribute to an overall positive environmental impact. However, it remains to be seen to what extent the governance conditions in the pulp and paper industry facilitate the adoption of this technology.

1.3 Research Objective

This thesis has two objectives: 1) to analyze the technical, economic, and environmental benefits and risks of each of the three proposed scenarios, and 2) to assess the overarching governance conditions surrounding the implementation of new technology in the pulp and paper industry. These objectives reflect the integrative approach that this thesis adopts by combining the technical aspects of implementing UF in a specific case with the social aspects of implementing new technology by using elements of contextual interaction theory (CIT) (Bressers et al., 2016). This will highlight trends in the decision-making process and factors that facilitate or hinder implementation.

1.4 Research Questions

This thesis will answer two main research questions with several sub-questions:

1. What are the technical, economic, and environmental benefits, risks and impacts of implementing UF in the Brazilian pulp mill in each of the following three scenarios:

a) treating the EP-stage bleaching effluent

b) treating the whitewater from the pulp drying process

c) replacing the sand filters at the water treatment plant

2. How do the governance conditions of the pulp and paper industry affect the implementation of the UF systems? Is the governance context supportive or restrictive towards implementation?

1.4 Thesis Outline

The second chapter of this thesis provides an overview of the pulp and paper industry, ultrafiltration technology, and the governance challenges of adopting new technology. The third chapter presents the research design of the thesis, elaborating on the research framework and questions, the sources, data, and theories, and the analytical framework used. Chapter four consists of the analysis of the technical, economic, and environmental aspects of each scenario. Chapter five focuses on the governance assessment. Chapter six brings the results of chapters four and five together into a discussion comparing the three resulting empirical models of each scenario, answers the research questions, and offers a conclusion.

2. The Pulp and Paper Industry, Ultrafiltration, and Implementation Challenges

This chapter offers an overview of the pulp and paper industry, ultrafiltration technology, and the interplay of novel technology and governance. A summary of pulp and paper production processes is described here, along with common challenges, risks, and benefits involved in these processes. The application of ultrafiltration in the pulp and paper industry is also explored, along with the trends, challenges, and benefits of this technology. In the final section, different aspects of the relationship between governance and the adoption of new technology will be explored, including an assessment tool that can be applied to this specific case.

2.1 Pulp and Paper Mills

The pulp and paper industry is the third most water intensive in the world as well as the fifth most energy intensive. The industry consumes massive quantities of water and energy while simultaneously being capable of generating large volumes of pollution and waste (Deshwal et al., 2019). An average kraft pulp mill consumes almost 81,500 m^3 of water for every 1000 tons of oven dried pulp produced (Das & Houtman, 2004). Effluent discharges from pulp and paper mills often contain high BOD, COD, suspended solids, color, toxic compounds, and additive content (Adnan et al., 2010). The industry also contributes 2% of global industrial $C0_2$ emissions (Kong et al., 2016). Global economic development has increased the demand for pulp and paper, while simultaneously putting pressure on pulp and paper mills to reduce water consumption, costs, and environmental impacts due to stricter environmental regulations and increasing water scarcity (Boguniewicz-Zablocka & Klosok-Bazan, 2020).

2.1.1 History and Market Consideration

The pulp and paper industry is globally integrated. Since the 1980s, multiple international companies have been involved in the industry and rely on complex supply and distribution chains that extend through multiple countries. Due to the extremely wide use of paper and paper products, the industry is sensitive to market fluctuations and thus experiences slowdowns and decreased demand when markets are down as well as heavy demand when markets are up. According to Ghosal (2015), the core reason this sensitivity exists is that essentially the fundamentals of the papermaking process have not changed for a very long time. Pulp and paper mills produce a variety of paper products, and it is very difficult to differentiate these products simply because the knowledge of how to create them is widely available. Individual firms therefore tend to lack pricing power. This means that any advantage a company has usually comes from cost-saving measures implemented in the production process (Ghosal, 2015). Not only does market competitiveness put pressure on the pulp and paper industry to reduce costs, environmental pressures from more stringent regulations also pressure the industry to innovate as the industry generates tons of pollution and waste (Boguniewicz-Zablocka & Klosok-Bazan, 2020; Deshwal et al., 2019). Life-cycle assessment (LCA) studies have found that the majority of pulp and paper industry environmental impacts comes from the production process, contributing to 50% of the impact on water resource depletion and almost 90% of the impact on freshwater eutrophication (Corcelli et al., 2018; Das & Houtman, 2004). New technology can help reduce these impacts through more efficient water usage and less sludge generation. However, these technologies emerge at a slow pace in the industry due to the research required to ensure their technical feasibility and economic viability (Adnan et al., 2010). Thin profit margins along with high capital and operating costs also limit their implementation (Ghosal, 2015).

2.1.2 Pulp and Paper Mill Processes

The production processes in the pulp and paper industry are relatively simple and may vary in complexity depending on the final product, which can range from pulp to various paper products. Figure 2 shows an overview of the paper-making process as a whole, while Figure 3 illustrates the production process at the Brazilian kraft pulp mill (Deshwal et al., 2019; Silva et al., 2019).

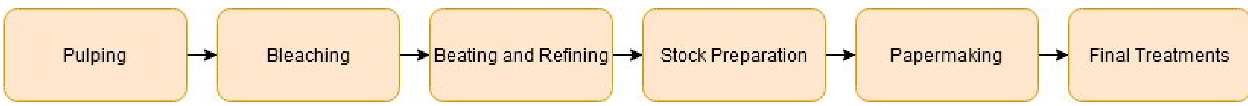

Figure 2: Papermaking process (Deshwal et al., 2019)

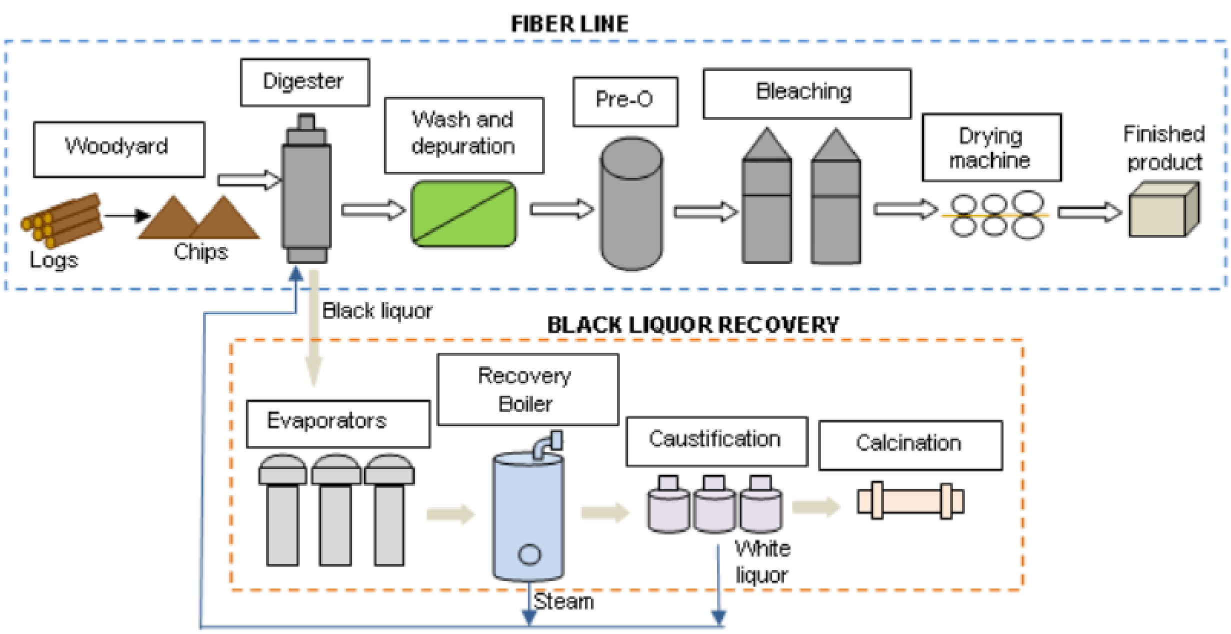

Figure 3: The bleached kraft pulp mill's pulp production process (Silva et al., 2019)

Most paper products are produced from wood pulp obtained from mechanically, chemically or thermally processing debarked and chipped timber or recycled paper (Deshwal et al., 2019; Ghosal, 2015). Next the pulp is bleached to improve its brightness. This is followed by refining processes that increase the surface area of the fibers, which increases both water holding capacity and bonding opportunities. Following this, the pulp fibers are chemically and mechanically treated and converted into paper by passing through rollers. Depending on the type of paper needed, finalizing treatments are applied to the paper, including calendering, laminating, and sizing, and the paper is packaged for transport (Deshwal et al., 2019). Water is used as a carrier among several other uses throughout the production process (Adnan et al., 2010). Figure 4 illustrates typical water usage in the industry along with the waste streams generated.

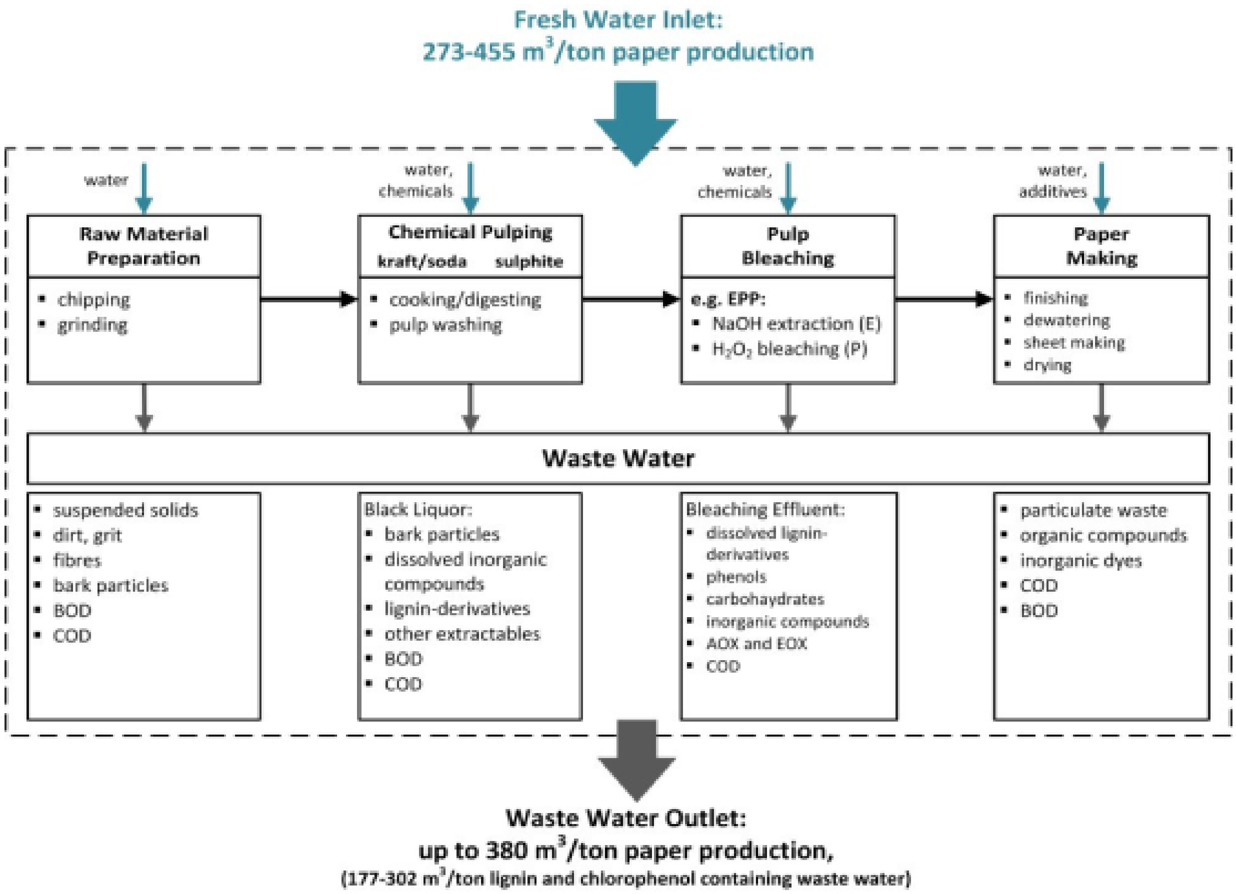

Figure 4: Water usage in the pulp and paper production process (Ebrahimi et al., 2016)

During the chemical pulping stage, the kraft chemical recovery process is especially important in the industry due the minimization of the impact of black liquor waste material, the ability to recycle pulping chemicals, and the ability to co-generate steam and energy. Figure 5 provides a general overview of this process, while Figure 6 outlines the kraft pulping process at the Brazilian mill.

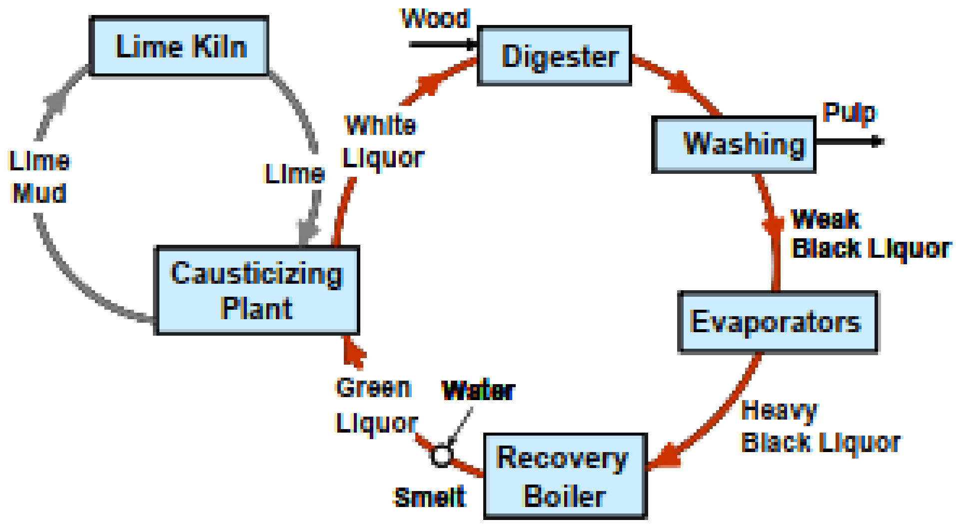

Figure 5: The Kraft recovery process (Tran & Vakkilainnen, 2016)

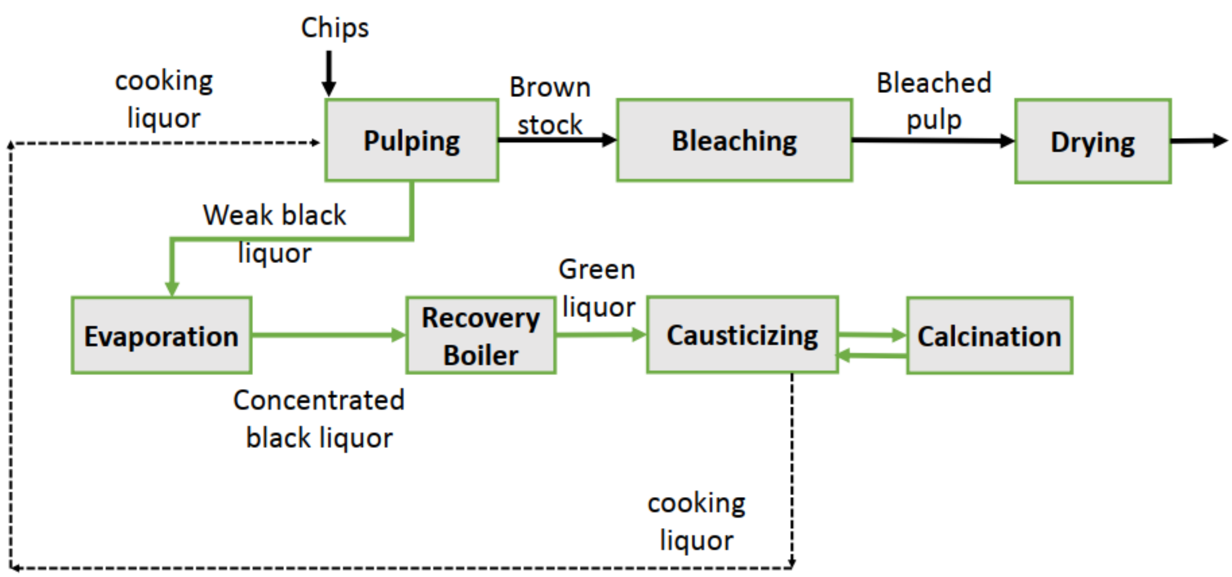

Figure 6: Scheme of the Brazilian pulp mill's bleached kraft recovery process (Silva et al., 2018)

Indeed, the processing of 1.3 billion tons per year of weak black liquor generates about 700 million tons of high-pressure steam in the industry, making this liquor the fifth most important fuel in the world. However, the efficiency of converting kraft black liquor into steam is lower than that of burning fossil fuels due to the heat needed to evaporate water entering with the waste. Additionally, the efficiency of this process may be affected by operational issues that affect evaporators and recovery boilers, including fouling, corrosion, foaming, damage, and poor water circulation, which must be avoided. Here as well, environmental regulations along with high energy and chemical costs have created a need for improved recovery of energy and chemicals from Kraft black liquor (Tran & Vakkilainnen, 2016).

2.1.3 Environmental Aspects and Challenges in the Pulp and Paper Industry

A life-cycle assessment of the pulp and paper industry conducted by Corcelli et al. (2018) found that the industrial production phase has the highest environmental impacts. The production of pulp and paper contributes 46% of the impact of the industry on global warming, as well as 39% of the impact on ozone depletion, 55% on freshwater eutrophication, and 46% on human toxicity. Waste and pollution in the pulp and paper industry can be separated into two broad categories: pulp waste and paper waste. Pulp waste includes residues from the pulping process such as lime, dregs, wood residues, wastewater, and chemicals. Paper waste includes rejects from the papermaking process such as fibers, metal, rubber bands, sizing agents, ink, coatings, and other additives (Deshwal et al., 2019). Figure 4 above details the typical waste products found in pulp and paper mill effluents. Wastewater and sludge are the two main resulting pollutants, and waste chemicals contribute to the highest environmental load (Corcelli et al., 2018). Studies have shown that in countries where pulp is produced, mill effluents have a high impact on the environment, impairing liver function in fish populations and increasing the amount of suspended solids in freshwater sources (Thompson et al., 2001). Sludge is an especially challenging waste product, with up to 60% of operating costs dedicated to managing sludge waste (Mahmood & Elliott, 2006). Landfilling and incineration have been the traditional means of managing this waste, however both have drawbacks. Landfilling, while the easiest option, is also the least favorable due to limited space, public perceptions, and legislation prohibiting potential groundwater leeching (Deshwal et al., 2019). Incineration is more favorable as it can be used for any type of sludge, however there are other considerations such as moisture content, fuel costs, upfront capital costs, and air pollution restrictions (Mahmood & Elliott, 2006). Energy recovery from incineration is also possible, as demonstrated in the Kraft recovery process described in the previous section above (Deshwal et al., 2019; Tran & Vakkilainnen, 2016). According to C. Silva (personal communication, August 2020), most Brazilian mills use sludge to make compost for use in land applications. The best available techniques not entailing excessive costs (BATNEEC) in the industry involve primary wastewater treatment followed by secondary biological treatments. However, concentrations of COD may still be present in mill effluents even after secondary biological treatments, sometimes necessitating tertiary treatment (Thompson et al., 2001). It is important to note that tertiary treatments usually only serve to prepare wastewater for reuse in production, as secondary treatments of wastewater are usually enough to comply with most wastewater discharge regulations (Mahmood & Elliott, 2006). For the Brazilian mill, tertiary treatment for all combined effluents would be an especially expensive option due to the high flow rate of the waste effluents released into the Doce River and the complex composition of the combined sectoral waste streams. Therefore, applying tertiary treatment to individual sectoral streams for reuse is a more viable option (Silva et al., 2018).

As water availability becomes scarcer, environmental regulations become more stringent, and input costs increase, pressure has been placed on the pulp and paper industry to find new ways to increase both sustainability and competitiveness (Johakimu et al., 2016; Yu et al., 2016). Companies generally measure their environmental performance utilizing eco-efficiency, which is defined as the ratio between environmental impacts and added economic value (Huppes & Ishikawa, 2005). According to ISO 14045, eco efficiency can be achieved by increasing product value, optimizing resource use, and reducing environmental impact. Because increasing the value of products is challenging in an industry where final products are difficult to differentiate, optimizing resource usage and reducing environmental impacts are essential to increasing eco-efficiency. In the pulp and paper industry, improving eco-efficiency is critically linked to reducing COD concentrations (Yu et al., 2016). Finding alternatives to managing sludge is one way to achieve this. Wastewater treatment produces large amounts of sludge, thus decreasing sludge production by improving fiber and raw material recovery can be of great economic and environmental benefit (Mahmood & Elliott, 2006). Recycling is another way to reduce costs. This reduces use of raw materials, and the discharges of wastewater from recycled paper production are less polluted than those from virgin paper production (Deshwal et al., 2019). Finally, increasing the efficiency of water usage also reduces impacts by reducing freshwater intake and decreasing the concentration of COD released in waste streams. This is known in the industry as "mill closure," or closing water circuits, and it is one of the greatest environmental challenges for pulp mills. Firstly, production processes in pulp and paper mills require a high quality of water. Recycled process water often contains chemicals and elements that interfere with operations over time, resulting in a lower quality final product. For example, non-process elements such as K^+ and Cl^- are often present in re-used process water, and if they are not controlled for, they can foul and corrode recovery boilers and evaporators. If non-process elements are left completely unchecked, mills may experience poor pulp quality, increased energy consumption, decreased energy capacity, and increased difficulty in complying with environmental regulations (Tran & Vakkilainnen, 2016). Therefore, a balance must be found between reusing process water to reduce freshwater intake and securing the efficient operation of the mill. It is recommended that stakeholders strive to close water circulation loops in an integrated manner to increase sustainability while maintaining productivity, efficiency, and competitiveness (Boguniewicz-Zablocka & Klosok-Bazan, 2020).

2.2 Ultrafiltration Membrane Technology in the Pulp and Paper Industry

As discussed, saving costs by improving the efficiency of the production process is the ideal way to comply with environmental regulations while remaining competitive in an industry with low profit margins and low product differentiation (Ghosal, 2015). Ultrafiltration (UF) shows great promise in reducing freshwater consumption by facilitating the reuse of process water, otherwise known as whitewater, however it comes with several limitations including the potential for membrane fouling and low flux rates (Chen et al., 2015).

2.2.1 The History of Ultrafiltration Technology

The pulp and paper industry has benefitted from the use of membrane filtration technologies since the 1970s. The first reported application of membrane technology was in 1972 in the form of reverse osmosis filtration, while the ultrafiltration membrane technology was first applied in the 1980s in Japan and Sweden with high success at removing color contamination and reducing COD and BOD. In Japan, for example, the Taio Paper company was able to use UF to remove 80% of COD from the E-stage bleach plant effluent (Mänttäri et al., 2010). Despite these early successes, membrane technology application in the pulp and paper industry represents less than 6% of the global membrane market (Adnan et al., 2010). This limited market penetration is mainly due to the high capital and operating costs associated with this technology, as well as its susceptibility to fouling and low permeate flux (Kong et al., 2016). However, membrane technology research and use is increasing in the pulp and paper industry due to changing local and municipal environmental regulations and increased water scarcity and costs (Adnan et al., 2010). Of all membrane types, UF membrane technology tends to be the most popular due to its high level of contaminant removal, relatively low energy consumption, small floor space requirements, and ease of integration into existing processes (Chen et al., 2015).

2.2.2 Technical Aspects and Limitations of Ultrafiltration

Ultrafiltration works by concentrating high molecular weight compounds from low molecular weight solids. A pressure gradient is used to separate the stream of liquid through a membrane that is semi-porous or semi-permeable, resulting in a high concentration of solids on one side that can be reused in a variety of ways while at the same time generating a high quality permeate stream (Kong et al., 2016). Figure 7 illustrates the basic principle of the UF technology, while Figure 8 highlights the porous working range of the UF membrane alongside other membranes (Adnan et al., 2010).

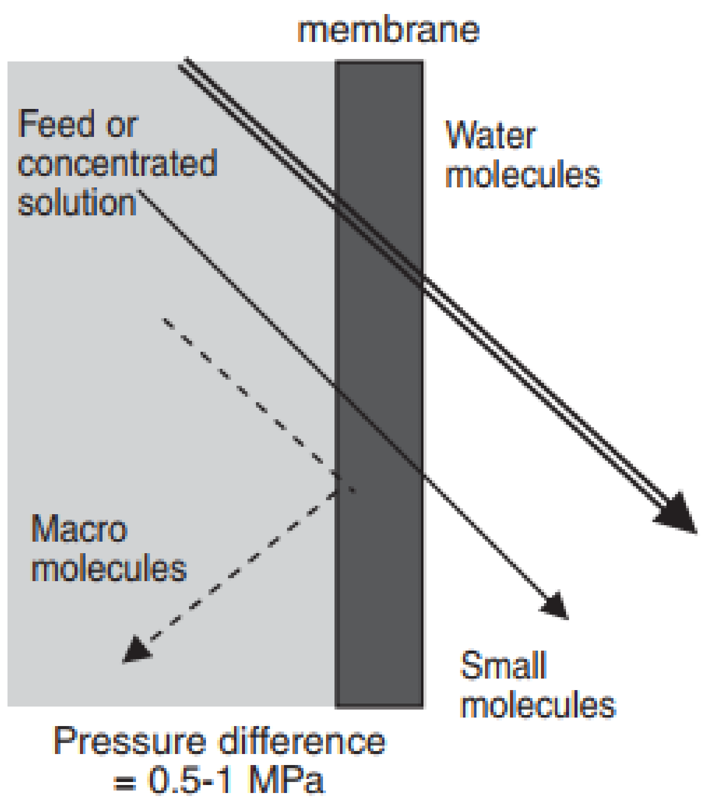

Figure 7: The basic principle of the UF membrane technology (Adnan et al., 2010)

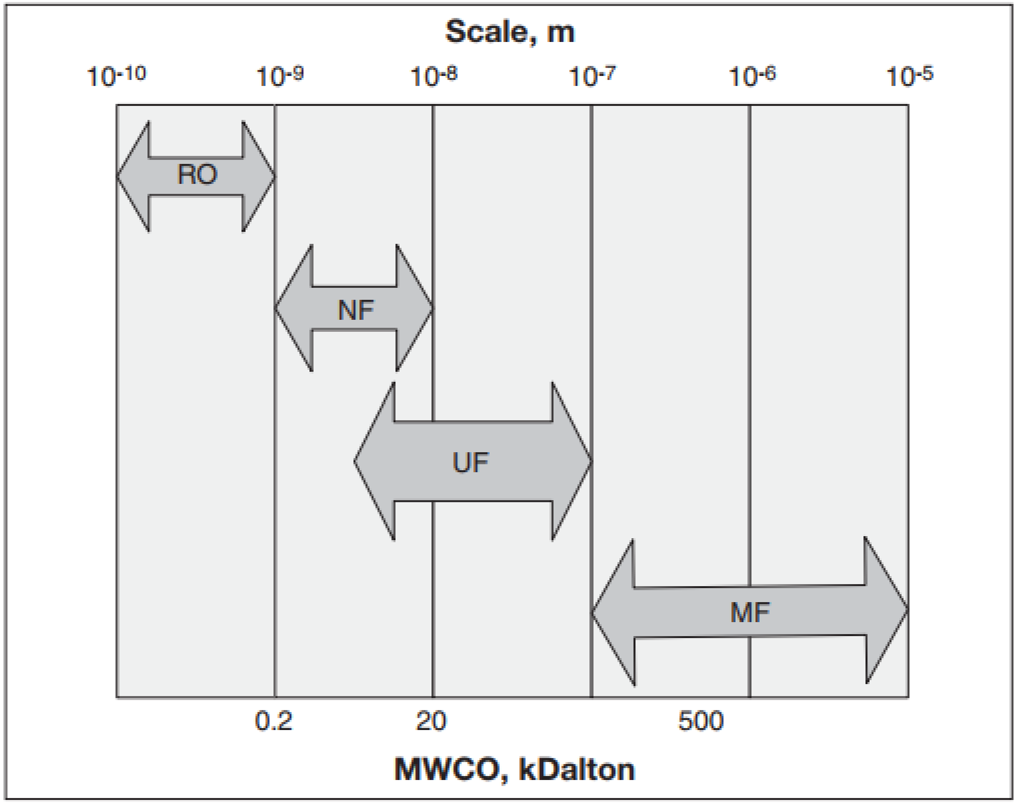

Figure 8: The porous working range for different membrane filtration types (Adnan et al., 2010)

Several studies have investigated the technical and economic feasibility of the use of ultrafiltration membrane technology in the pulp and paper industry. The most significant limitations of UF are low permeate flux rates, large membrane area requirements, and a susceptibility to irreversible membrane fouling, which reduces the performance of UF membranes by up to 80% and can only be corrected by chemical cleaning (Chen et al., 2015; Ebrahimi et al., 2016). Nuortila-Jokinen et al. (1998) found that the most feasible applications for UF are in membrane systems or modules with low pressure, high flow velocity, and a low tendency for membrane fouling. Optimizing the process by using chemical pretreatments such as Raifix 07525 increased flux rates and reduced fouling (Nuortila-Jokinen et al., 1998, 2004). Nuortila-Jokinen et al. (2004) found that the most cost-effective pre-treatment techniques to enhance fluxes and reduce membrane fouling are chemical flocculation, adjusting pH, and thermophilic aerobic biological treatment. However, some pretreatments were found to impact later stages in the papermaking process which are sensitive to pH changes and chemicals. Therefore, a balance must be found between cost effective and non-impactful pre-treatment, gains in flux rate, and reductions in membrane fouling. Payback times of 10 years were found to be feasible in a UF plant treating 2000m^3/day of a mill's circulation water at 0.42€/m^3 (Nuortila-Jokinen et al., 2004).

Chen et al. (2015) found that the best way to prevent membrane fouling is to reduce dissolved multivalent metal ion content, especially calcium ions, using natural substances. It is also beneficial to identify whitewater streams prone to fouling membranes and provide proper pretreatment. However, this is difficult due to the diversity of compounds in found in whitewater streams. To avoid fouling, Rudolph et al. (2018) found that a two-step cleaning process involving enzymes in the first step and an alkaline cleaning agent in the second step was the most effective at restoring the permeability of fouled membranes. Using enzymes or alkaline alone is not enough, as enzymes are prone to adsorption on the membrane surface, and harsh alkaline agents decrease the lifetime of the membrane.

Once flux rates are stabilized and membrane fouling is reduced, UF provides several benefits. Koyuncu et al. (1999) found that UF combined with reverse osmosis was highly efficient at reducing chemical oxygen demand (COD), color, conductivity, and ammonia. Sakurai et al. (2010) add that UF is highly efficient at removing COD and color and has 99% efficiency when treating turbidity When used to treat bleaching effluent, UF can be used to separate and recover valuable lignin compounds, separate COD and BOD, and remove fibrous materials (Adnan et al., 2010; Ebrahimi et al., 2016; Humpert et al., 2016). Rudolph et al. (2018) add that UF can be suitably used to separate profitable hemicelluloses from process water once membrane fouling challenges are overcome.

2.2.3 Reuse Potential for UF Permeate and Concentrate

Oliveira et al. (2007) studied the reuse of whitewater after UF and found that it was technically feasible and showed great reuse potential in processes such as water cleaning devices and low-pressure showers. However, pretreatment is essential to prevent contaminants in the filtrate that affect the production process. Previous pilot studies of UF implementation in the Brazilian pulp mill have identified high concentrations of potassium (K^+) and chloride (Cl^-) ions as a potential limitation of the UF membrane, as UF does not separate these ions from the process stream. This means that reusing UF filtrate in the process has the potential to increase the electrical conductivity of the process water, potentially affecting the operations of the pulp mill (van Leeuwen & Cappon, 2020). As discussed previously, high concentrations of K^+ and Cl^- in process water have the highest impact on the Kraft recovery process. For example, K^+ accumulation in the process water can lead to corrosion and leeching in the recovery boiler, especially when Cl^- is also present (Tran & Vakkilainnen, 2016). High K^+ concentrations may also form a gel in the causticizer that is difficult to clean. Temperature must also be accounted for concerning reuse of permeate streams, as the UF membranes in the pilot tests were able to handle streams of up to of 40°C, meaning that permeate streams would also be at this temperature. Additionally, conductivity, pH and total dissolved solids (TDS) and other components must also be accounted for in UF filtrate, as they may impact process equipment by forming new compounds in unknown chemical reactions (Chen et al., 2015; van Leeuwen & Cappon, 2020).

Chen et al. (2015) add that UF whitewater permeate is clean enough to be reused in most mill processes due to the effective separation of macromolecular solutes and colloids. Thus, UF permeate can greatly contribute to closing water circuits while significantly reducing the volume of untreated bleaching effluent discharge, easing pressure on the wastewater treatment plant and reducing sludge generation up to 20% (Mahmood & Elliott, 2006). UF concentrate may also be reused with several benefits. The solid content of concentrated black liquor may be increased to over 30%, which reduces the energy costs for black liquor evaporation due to reduced evaporation volume. Evaporators treating UF concentrate experience less fouling due to less inorganic content, while a lower boiling point means that recovery boilers require less energy to heat UF concentrate (Kong et al., 2016; Rudolph et al., 2018). As shown in Figure 9, there are several possibilities for treating membrane concentrate depending on the application of the UF membrane.

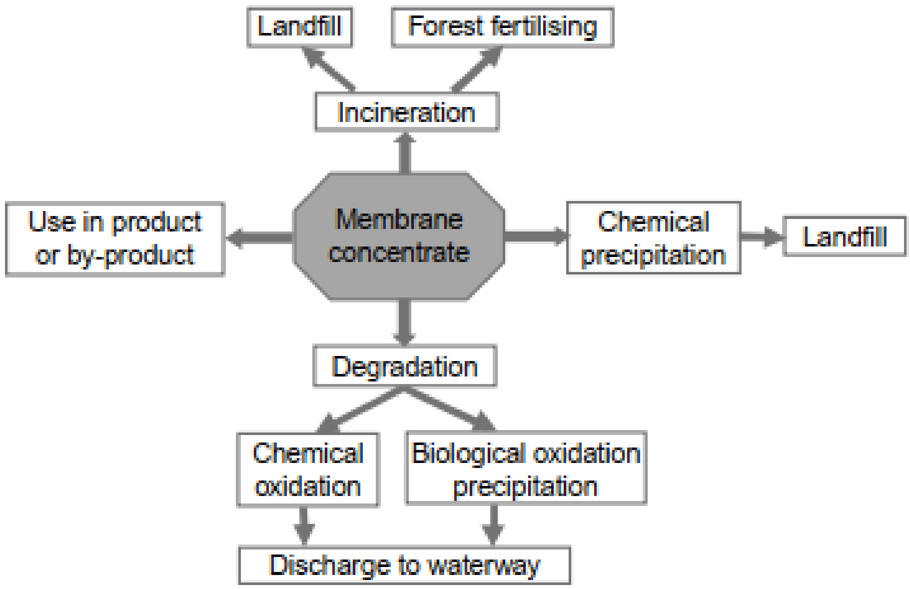

Figure 9: Various uses for membrane concentrate (Mänttäri et al., 2010)

The most economical option is to reuse concentrate in the production process as much as possible, especially when there is a possibility to recover fibers and lignin products for sale or reuse and organics for energy production. Waste concentrate that cannot be reused must be treated via chemical or biological processes before discharging into the waterway or sent to a landfill (Humpert et al., 2016; Kong et al., 2016; Mänttäri et al., 2010; Rudolph et al., 2018). Reusing effluents is an especially appealing option for the Brazilian pulp mill considered in this thesis due to the potential to reduce waste and re-use water (Silva et al., 2018).

2.3 Technology and Governance

The application of UF in the Brazilian pulp mill is subject to multiple considerations. As discussed, the pulp and paper industry is extremely sensitive to market fluctuations and to increasingly stringent environmental regulations. Papermaking is such an old and well-known process that paper mills must rely on more efficient innovations and new technologies on the production side in order to remain not only competitive, but sustainable as well (Ghosal, 2015). The costs of introducing new technology must be balanced against the need to increase the efficiency of the production process and the need to reduce environmental impacts to comply with future regulations (Adnan et al., 2010; Johakimu et al., 2016). As Ghosal (2015) points out, the decision-making process of pulp and paper mill managers and top executives is geared towards incremental gains in efficiency rather than great technological breakthroughs. In China, for example, many pulp and paper mills are reluctant to upgrade the production process and prefer conventional production processes due to the high cost of upgrades coupled with financial issues.

However, this attitude is likely to lead to a loss in competitive edge, as technological breakthroughs, though crucial, are few in the industry. Domestic financing mechanisms along with government funding help alleviate the financial burden of technological upgrades, and this in turn can be achieved by integrating environmental issues with economic policies while in the planning stage (Song et al., 2015). Studies have shown that higher environmental standards from governments and competitors push industries to improve management towards eco-efficiency. Often, the availability of funding is not enough. Indeed, strengthening companies' internal environmental management mechanisms by increasing environmental awareness among staff and top management is as essential to encourage eco-efficient technological innovation (Song et al., 2015; Yu et al., 2016). Assessing the favorability of the governance conditions towards implementing UF in the Brazilian mill is of interest to this research both academically and technically. These conditions may help the application of new technology in other mills or industries facing similar challenges.

2.3.1 The Governance Assessment Tool

The implementation of UF in the Brazilian mill is ultimately decided by more than technical specifications that prove the efficiency and capabilities of the technology. The decision is also the result of a complex network of multiple actors, each with their own knowledge, motivations and resources. The conditions within which these actors interact may be favorable or unfavorable towards implementation. The Governance Assessment Tool (GAT), based on Contextual Interaction Theory (CIT), is a way to assess implementation processes through the lens of multi-actor driver interaction processes (Bressers, 2007; Bressers et al., 2016). Climate change and sustainability challenges often require a holistic vision in terms of implementing innovations and shifting away from long-held standards (Tran & Vakkilainnen, 2016). This is especially true in the pulp and paper industry where innovation and technical novelties require significant upfront investments (Ghosal, 2015). CIT assesses decision-making from three main actor characteristics, namely: motivations, cognitions (or knowledge) and resources. These three characteristics are influenced by different contextual layers that are case-specific, including the technological development context, the environmental context, and the economic context of a given project. The GAT presents a series of descriptive and evaluative questions in order to assess five dimensions of governance with four main criteria, shown in a matrix in Figure 10.

Governance dimension	Quality of the governance regime			
	Extent	Coherence	Flexibility	Intensity
Levels and scales	How many levels are involved and dealing with an issue? Are there any important gaps or missing levels?	Do these levels work together and do they trust each other between levels? To what degree is the mutual dependence among levels recognised?	Is it possible to move up and down levels (upscaling and downscaling) given the issue at stake?	Is there a strong impact from a certain level towards behavioural change or management reform?
Actors and networks	Are all relevant stakeholders involved? Are there any stakeholders not involved or even excluded?	What is the strength of interactions between stakeholders? In what ways are these interactions institutionalised in stable structures? Do the stakeholders have experience in working together? Do they trust and respect each other?	Is it possible that new actors are included or even that the lead shifts from one actor to another when there are pragmatic reasons for this? Do the actors share in 'social capital' allowing them to support each other's tasks?	Is there a strong pressure from an actor or actor coalition towards behavioural change or management reform?
Problem perspectives and goal ambitions	To what extent are the various problem perspectives taken into account?	To what extent do the various perspectives and goals support each other, or are they in competition or conflict?	Are there opportunities to re-assess goals? Can multiple goals be optimized in package deals?	How different are the goal ambitions from the status quo or business as usual?
Strategies and instruments	What types of instruments are included in the policy strategy? Are there any excluded types? Are monitoring and enforcement instruments included?	To what extent is the incentive system based on synergy? Are trade-offs in cost benefits and distributional effects considered? Are there any overlaps or conflicts of incentives created by the included policy instruments?	Are there opportunities to combine or make use of different types of instruments? Is there a choice?	What is the implied behavioural deviation from current practice and how strongly do the instruments require and enforce this?
Responsi-bilities and resources	Are all responsibilities clearly assigned and facilitated with resources?	To what extent do the assigned responsibilities create competence struggles or cooperation within or across institutions? Are they considered legitimate by the main stakeholders?	To what extent is it possible to pool the assigned responsibilities and resources as long as accountability and transparency are not compromised?	Is the amount of allocated resources sufficient to implement the measures needed for the intended change?

Figure 10: The GAT matrix and its evaluative questions (Bressers et al., 2013)

These five dimensions are: levels and scales, actors and networks, problems and goals, strategies and instruments, and responsibilities and resources. The four criteria used to assess these dimensions are: extent, coherence, flexibility, and intensity. Extent refers to the level of completeness of a certain regime, or in other words how closely, the involved scales, actors, instruments, perceptions, and resources are relevant to the project. If a regime has an insufficient extent, it is considered weak. Coherence refers to the way different layers of an interaction process depend on and influence one another when centered around the same objective. It has to do with coordination of the various actors and organizations along with their responsibilities and resources involved in applying a project. The more dysfunctional this coordination is, the lower the coherence is. Flexibility refers to the freedom of action of the various actors involved based on formal or informal liberties. For example, a regime is more flexible if there is a high level of trust among the different actors and power is decentralized. A regime is less flexible if it is less open to uncertainty and relations among the actors are more controlling. Finally, intensity refers to the degree to which a regime urges changes in standard operating procedures and development. Intensity is usually greater if high level actors are committed to change and employ the use of adaptive strategies. The more conservative and traditional higher-level actors are, the less intense a regime is. Answering the questions in the matrix indicates whether the governance context of a situation, which in this case involves implementing new technology, is supportive or restrictive. A regime is more supportive if all four criteria for each governance dimension are assessed to be primarily moderate to high, and more restrictive if the criteria are found to be low.

This assessment can be applied to multiple implementation projects (Bressers et al., 2016). Previous studies have applied the GAT to various cases to assess policy implementation. Casiano Flores et al. (2019) applied the GAT to three case studies in central Mexico to assess the role of governance in the implementation of wastewater treatment policy. The study found governance context to be restrictive towards implementation due to limited stakeholder involvement and a lack of long-term perspectives. However, more state government involvement was identified as a way to increase supportiveness. Another case study conducted by Al-Khatib et al. (2017) in Jericho, Palestine used the GAT to identify several governance-related issues restricting the reuse of treated wastewater in irrigated agriculture. Weak actor coherence, low extent of legal instruments, and low resource extent were all factors restricting the implementation of wastewater reuse. As seen in the above examples, restricting governance factors have the potential to disrupt implementation despite clearly designed plans. Much as in cases of implementing policy, implementing new technology in the Brazilian mill also involves multiple actors and networks of actors. Therefore, the governance context of implementing UF in the mill may be assessed using the GAT to identify restrictive or supportive factors, highlighting the interplay of technology and governance in the industry.

3. Research Design

This chapter is dedicated to systematically establishing the methodological foundation of this research project. According to Verschuren & Doorewaard (2010), a research design sets the foundation for a research project by establishing both the research strategy as well as the data collection and analysis methods, planning, and activities needed to put together this content in order to achieve an objective. All necessary research content and the activities that were carried out in order to produce a realistic analysis of the technical, economic, and environmental impacts, benefits and risks of the three UF scenarios, along with an assessment of the governance aspects involved, are explained.

3.1 Research Strategy

This thesis employed a single-case study approach, utilizing an in-depth analysis of theoretical and actual parameters obtained through literature, pilot studies, and interviews. The case of UF implementation in a Brazilian pulp mill was selected as it presents an example of international governmental, environmental and financial pressures contributing towards the implementation of new, more sustainable technology in a resource-intensive industry. Each scenario was thoroughly analyzed based on the established criteria in order to produce a comparative evaluation of the resulting empirical models. Figure 11 provides a schematic illustration of the research framework used in this thesis.

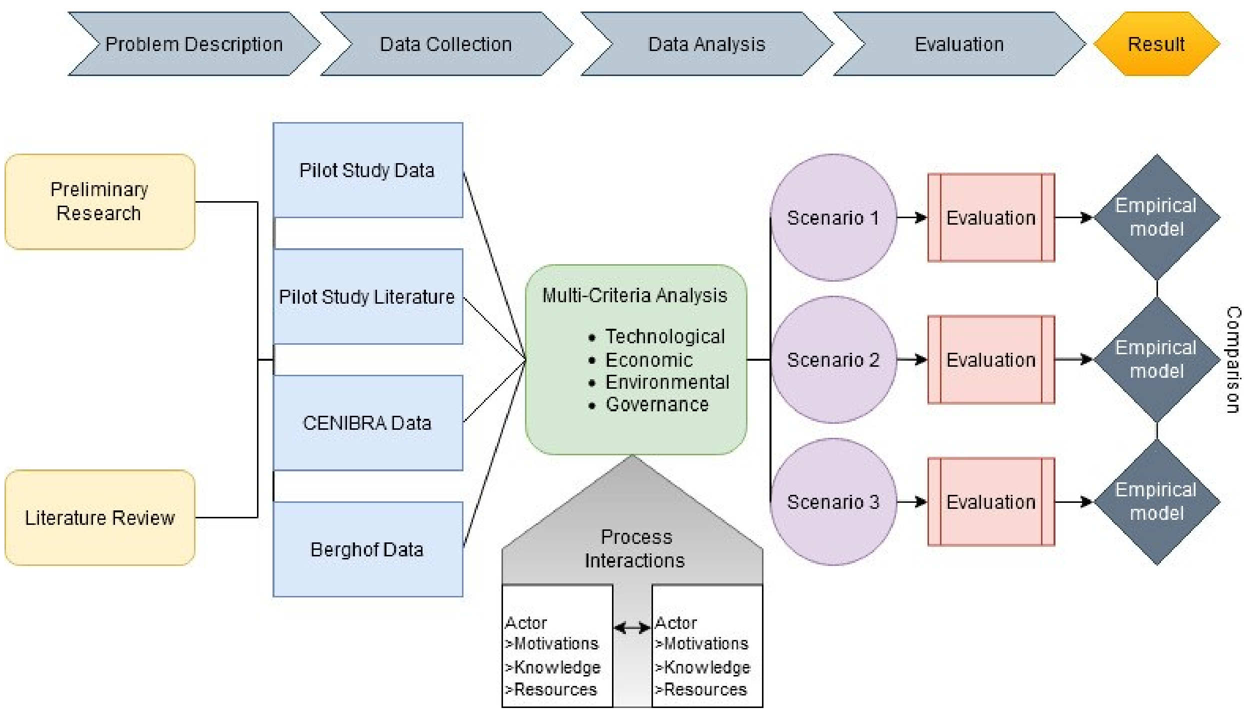

Figure 11: Research framework, own source

Preliminary research and a literature review were conducted in order to gain a clear insight into the problem description, namely what the potential technical, economic, and environmental aspects of each scenario are considering current literature on pulp and paper mills and ultrafiltration technology. Following this, data was collected from previous pilot studies as well as BMT and the Brazilian pulp mill and combined with the theoretical literature in a multi-criteria analysis that examined the technological, economic, and environmental aspects in the specific context of the Brazilian pulp mill. During this phase, process interactions among the actors involved were also assessed via interviews and incorporated into the multi-criteria analysis to complete the governance assessment using elements of the CIT (Bressers, 2007). This resulted in a complete evaluation of each scenario to create a realistic assessment in the form of three empirical models.

3.1.1 Research Units

The research units of this project were limited to three specific UF scenarios that were determined by past research as the most promising based on water quality parameters. These parameters included temperature and turbidity, flow rates, and recovery rates that are within the capabilities of the UF systems. These units formed the basis for a comparative evaluation to determine impacts, benefits, and risks based on technical, economic, environmental, and governance criteria.

3.1.2 Research Boundary

The research was limited to the three specific UF application scenarios in the Brazilian pulp mill. No other scenarios were considered in this research, and no other pulp mills were studied in the interest of time. This did not affect the quality of the results. The stakeholders and actors that were analyzed were limited to those invested in this specific project, including those working the companies, organizations, institutions, and agencies involved. The selected research units were subject to the criteria mentioned in Section 3.1.1.

3.2 Data Collection

This section will describe the data and information required to answer the research questions, along with the methods of accessing the research. This information is presented in Table 1 and Table 2.

Table 1: Data sources and collection methods

Research Question	Information Required	Sources	Accessing Method
What are the technical aspects and impacts of the three scenarios?	Water parameters, flow rates, recovery rates, risks, benefits	Scientific literature, pilot study data, past reports	Search method and content analysis
What are the economic aspects and impacts of the three scenarios?	Recovery rates, reuse options, risks, benefits, water parameters	Scientific literature, pilot study data, past reports	Search method and content analysis

What are the environmental aspects and impacts of the three scenarios?	Water parameters, concentrate and permeate quality and quantity, destination	Scientific literature, pilot study data, past reports	Search method and content analysis
How do the governance conditions of the pulp and paper industry affect the implementation of the UF systems, and are they supportive or restrictive towards implementation?	Motivations, attitudes, opinions, concerns, objectives, knowledge, levels, networks, strategies, responsibilities, resources	Online interviews conducted with actors working closely with technology implementation in the pulp and paper industry using questions derived from the GAT, online meetings, emails	Questioning and observation

A series of five interviews were conducted with eight key actors involved in the implementation of UF at the Brazilian mill. Representatives from the Brazilian pulp mill, BMT, the Government of the Brazilian State of Minas Gerais, and academia were interviewed. Interview questions were drafted according to the GAT matrix shown in Figure 10 (Bressers et al., 2013). These questions may be found in Appendix II. The anonymized interviewees are referenced in Chapter 5 as presented in Table 2.

Table 2: Summary of Interviewees

Interviewee	Association	Reference Name
A	Government of Minas Gerais	"MG"
B	Berghof Membranes	"BMT"
C, D, E	Members of academia working closely with the pulp and paper industry	"AD"
F	Pulp mill top management	"PTM"
G, H	Pulp mill engineers	"PME"

3.3 Data Analysis

The information required for this thesis has been analyzed using qualitative methods with quantitative elements. For example, some of the economic aspects were determined by the quantity of recovered material, however this data along with information obtained from questioning and observation formed the basis of an overall qualitative multi-criteria analysis. This questioning and observation was used in the governance analysis to determine whether the governance context of the actors is supportive or restrictive based on the GAT (Bressers et al., 2016).

3.3.1 Methods of Data Analysis

The methods of data analysis for the required information are presented in Table 3.

Table 3: Methods of data analysis

Data and Information Required	Method of Analysis
Water parameters, flow rates, recovery rates	Qualitative; embedded quantitative data and trends from scientific literature and pilot studies
Risks, benefits, reuse options, possible destinations	Qualitative; trends from scientific literature and past reports
Motivations, attitudes, opinions, concerns, objectives, knowledge	Qualitative; trends that work towards or against implementation

3.3.2 Validation of Data Analysis

Experts involved in the WatMin project working closely with both the Brazilian kraft pulp mill and Berghof membranes were consulted to ensure that the data analyzed was as recent and valid as possible. Various sources were used to gather data and information including scientific literature, past reports, pilot test, and the knowledge of experts involved, and the information was compared using triangulation of the results iterated from these sources. Any conflicts of opinion or information were resolved via cross checking with multiple experts to ensure validity.

3.3.3 Analytical Framework

A schematic representation of the analytical framework used in this thesis is shown in Figure 12.

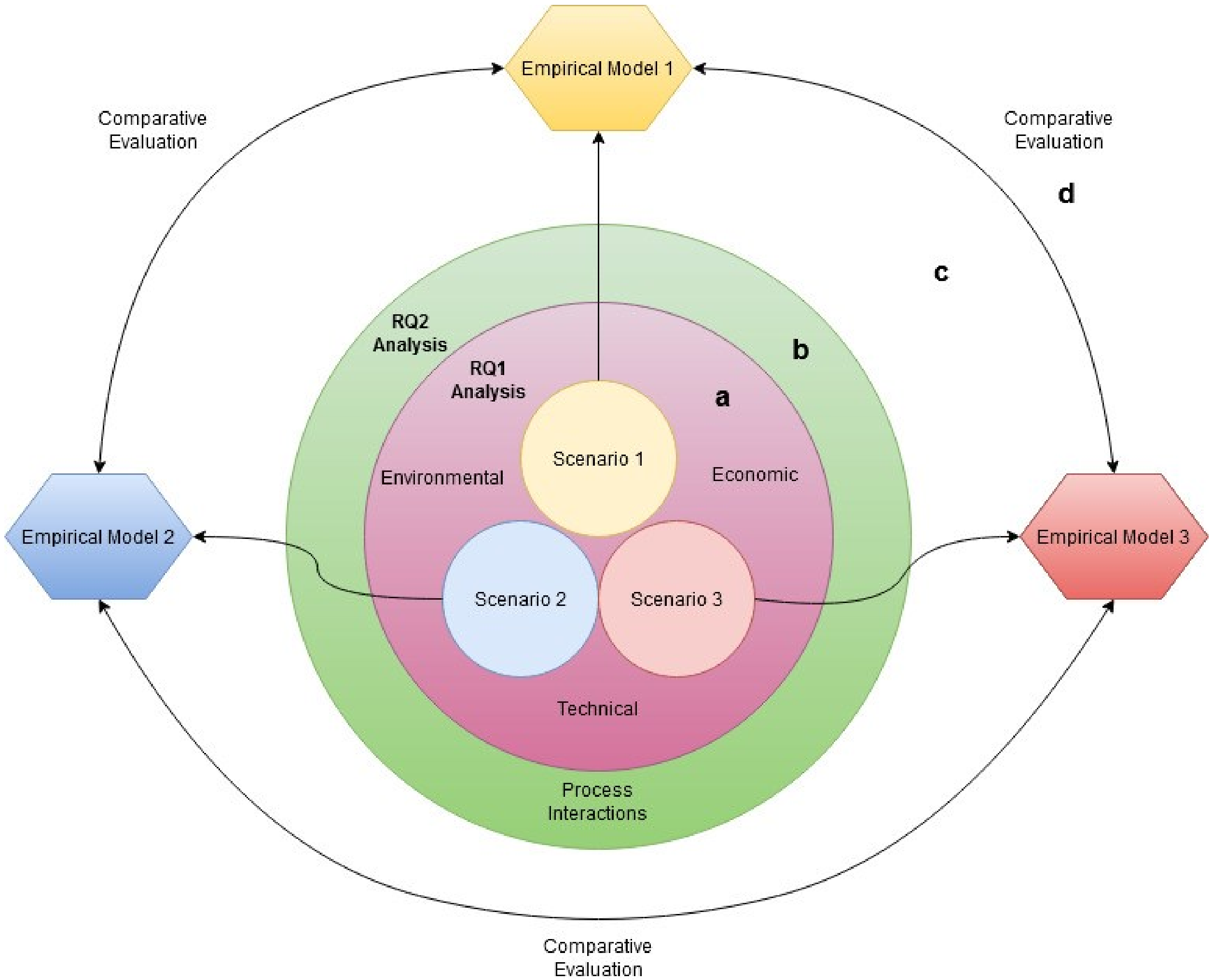

Figure 12: Schematic representation of analytical framework, own source

The analysis is composed of the following four phases, lettered from **a** to **d**.

- **a)** In the first phase, the three scenarios were analyzed based on technical, economic, and environmental criteria. Data were obtained from past pilot studies and reports and compared with theoretical scientific literature to create an accurate picture of the benefits, risks, and impacts of each scenario.
- **b)** The second phase analyzed the governance aspects of each scenario with respect to the previous layer of analysis. Process interactions resulting from the motivations, knowledge, and resources of the actors involved were understood within the context of the previous analysis to form a more complete model of each scenario.
- **c)** In the third phase, the answers to the two main research questions were synthesized to create three empirical models that formed a realistic representation of the three scenarios.
- **d)** In the fourth phase, these empirical models were evaluated and compared to one another.

3.4 Ethical Considerations

Ethical considerations were made during the research process. Informed consent was obtained from all participants in the interview process. Participation in interviews was entirely voluntary and confidential, and under no circumstances will any information obtained be used against the participants to cause harm or otherwise. The anonymity of the participants will be respected, and only data and information relevant to the research were requested. The data and information obtained from the interviewees will be safeguarded in a secure location only accessible to the researcher and will, if necessary, be deleted after the completion of this research period. This thesis follows all ethical guidelines set by the University of Twente and has been approved by the ethics committee of the university.

3.5 Limitations

This study was limited to the implementation of UF systems in the pulp and paper industry. The benefits and risks are specific to the Brazilian mill. UF systems may also be applied in other industries, which may face other market considerations and governance conditions. Access to interviews and data was also limited by the Covid-19 pandemic. Though the interviewees consisted of a broad spectrum of actors involved in the implementation process, the limited number of interviews conducted may exclude some relevant information. Finally, complex chemical interactions that could occur due to compounds entering process water via the UF permeate or concentrate were outside the scope of this study and may require further modelling to assess risks.

4. Scenario Analysis

This chapter is dedicated to an analysis of each UF implementation scenario. As discussed previously, the Brazilian pulp mill is located in the Doce River basin, where 100% eucalyptus wood species are used. The mill produces 1.2 million tons of bleached kraft eucalyptus pulp each year (Silva et al., 2018). Deriving pulp from eucalyptus is hardwood pulping, which is distinct from softwood pulping. Eucalyptus pulping generally contains less organics than softwood pulping and has a higher pulp yield with less solids in the generated black liquor. Additionally, eucalyptus pulping requires less chemicals in the production process, and the black liquor generated has a lower heating value than softwood black liquor (Tran & Vakkilainnen, 2016). Therefore, conditions for UF implementation in the pulp mill are generally favorable, as there are less chemicals present in the production process to affect the UF membrane compared to softwood pulping mills. Furthermore, in certain scenarios the resulting UF concentrate has high potential for pulp recovery and energy generation with less heating required in the recovery boiler. The UF technology can be applied in several areas of the production process, however this research focuses on three specific scenarios as identified in previous pilot studies (Silva et al., 2018; van Leeuwen & Cappon, 2020). The first scenario involves using UF to treat the EP-stage alkaline bleaching effluent. The second scenario uses UF to treat the whitewater from pulp drying, and the third scenario considers using UF to replace sand filters at the WTP (van Leeuwen & Cappon, 2020). The analysis in this chapter will include an overview of the technical benefits and risks of each scenario along with an estimation of the potential environmental and economic impacts.

4.1 Scenario 1: UF Treating EP-stage Alkaline Bleaching Effluent

Implementing UF to treat the ep-stage alkaline bleaching effluent comes with numerous benefits. As discussed in Chapter 2 of this research, UF reduces COD significantly along with BOD and color concentrations. The system has a low energy footprint and can be easily integrated into this process stream. However, several technical challenges are present as discussed in the following section.

4.1.1 Technical Assessment of Scenario 1

The flow rate for the EP-stage alkaline bleaching effluent line is 1150 m^3/h, with the UF membrane demonstrating a recovery rate of 90%. This produces a permeate stream of 1035 m^3/h and a concentrate stream of 115 m^3/h. Table 4 shows physiochemical characteristics of the ep-stage effluent stream prior to UF treatment, while Table 5 presents the characteristics of the resulting permeate after UF treatment.

Table 4: Characteristics of EP-stage bleaching effluent (Silva et al., 2019)

Parameter	Unit	(EP)
Temperature (T)	ºC	70-85
Flux (Q)	m^3/h	1000-1200
Total COD	mg/L	1024
pH	-	12,0
TSS	mg/L	30
Turbidity	NTU	60
Color	CU	276
Electrical Conductivity (EC)	mS/cm	3,37
Chloride	mg/L	194
Potassium	mg/L	16,3
Silica	mg/L	14
Sodium	mg/L	921

Table 5: Ep-stage bleaching UF permeate parameters (Silva et al., 2019; van Leeuwen & Cappon, 2020)

Parameter	Unit	EP Bleaching Permeate
Temperature	°C	30
Flux	m^3/h	1035
COD removal efficiency	%	61
Permeate COD	mg/L	398
pH	pH	<10
TSS removal efficiency	%	97
TSS in the Permeate	mg/L	1.3
Turbidity removal efficiency	%	51
Permeate turbidity	NTU	4.7
Color removal efficiency	$	51
Permeate color	CU	133
Electric conductivity	mS/cm	1.98
Chloride	mg/L	175
Potassium	mg/L	14.2
Calcium	mg/L	10.25
Copper	mg/L	3.35
Iron	mg/L	0.1
Magnesium	mg/L	0.52
Manganese	mg/L	0.03
Silica	mg/L	14
Sodium	mg/L	541

Reducing water usage by reusing process water is a challenge made especially difficult in this scenario due to the composition of the EP-stage bleaching effluent. As discussed in the Chapter 2, UF does not remove potassium and chloride ions as their molecular masses are smaller than the UF membrane pore size. Therefore, high concentrations of these ions in the filtrate have a potential to affect other processes sensitive to those ions. For example, recovery boilers are at risk of corrosion and fouling when high levels of potassium and chloride ions are present. High concentrations of potassium ions can also form a gel that obstruct filters, especially in the causticizer. However, because most of the potassium and chloride ions pass through the UF and are not abundantly present in the concentrate, the risk of experiencing these issues by reusing the concentrate in the recovery boiler is low. The composition of the EP-stage effluent is also harsh for the UF membrane, and this raises the potential for membrane fouling and may necessitate pretreatment and future maintenance. Periodic backwashing of the flux is essential to prevent membrane fouling (Rudolph et al., 2018; Silva et al., 2019b; van Leeuwen & Cappon, 2020). Temperature must also be taken into consideration as effluent in this phase reaches temperatures of 70-85°C, yet the UF membrane in the pilot tests could only handle temperatures of 40°C. According to C. Silva (personal communication, August 20, 2020), pH is also an important issue as this effluent has a higher pH than the UF membrane could stand. Therefore, pH would need to be regulated accordingly. Pressure must be regulated to control for temperature. Color concentration is also a potential issue. Pilot plant test results showed a color removal efficiency of 46-48%. This means that color content in the mill emissions to the river may still be a potential risk after UF, especially in dry seasons. This will be further discussed in the Section 4.4. Finally, unknown chemical reactions may take place as the permeate is reused due to the complexity of the compounds in the process water across the mill. Further studies are necessary to model these unknown reactions (van Leeuwen & Cappon, 2020). The best reuse of the EP-stage bleaching UF permeate, therefore, is to send it to the WWTP which can most benefit from the ultrafiltrate's reduced COD, TSS, and turbidity values, resulting in less overall sludge production and better effluent quality. The concentrate, in turn, can be sent to the evaporators where the concentration of solids is elevated in preparation for the recovery boiler where steam energy can be generated.

4.1.2 Economic Assessment of Scenario 1

The main economic benefits of scenario one come from water savings of 500m^3/h , reducing sludge generation up to 20%, and generating energy from the recovered organics in the concentrate (Silva et al., 2018, 2019). UF has the potential to concentrate the solids content of weak black liquor to more than 30%. This would lower the energy cost for evaporating black liquor, as the boiling point of the UF concentrate would be lower (Kong et al., 2016; Wallberg et al., 2005). The concentrate being sent to the recovery boilers in this scenario lacks the potassium and chloride ions that cause corrosion as they pass through the UF membrane, therefore additional equipment to protect the boilers would not be necessary. A preliminary economic assessment completed by Berghof Membranes reveals the potential capital and operating costs of the system in scenario one, which is shown in Table 6 (Sousa & Berghof Membranes Technology, 2020).

Table 6: Budgetary overview of Scenario 1 (Sousa & Berghof Membranes Technology, 2020)

CAPACITY	Feed Capacity (m^3/d)	27600
	Permeate Capacity (m^3/d)	24840
	Recovery	90%
SYSTEM SETUP	Technology	B-Smart ECO
	Design Flux (L/ (m^2.h))	77
	Number of single loop skids	1
	Number of double loop skids	12
	Number of modules/loop	8
	Total Number of Modules	200
	Number of CIP stations	2
OPEX	kWh/m^3	0.8
	Energy[1] and Maintenance (€)	**18,405**
CAPEX	Investment (€)	5,105,500
CAPEX (after infrastructure)	Total Investment (€)	**5,616,050**

According to pulp mill engineers (personal communication, May 21, 2020), the mill produces 95% of its energy in house. The remaining 5% is contracted at a rate of 0.29 Brazilian Reais/kWh, or €0.05/kWh. For the UF system in Scenario 1, the kWh usage is 0.8/m^3 while the permeate capacity is 24,840m^3/d. The system therefore requires 7,253,280 kWh per year, 95% of which is produced in house. The remaining 5% of this, or 362,664 kWh, is contracted at €0.05/kWh for a total annual operating cost of €18,133. The total investment, or capital cost, of installing the system in this scenario is €5,105,500 based on plug-and-play skids, including testing and excluding transportation costs (Sousa & Berghof Membranes Technology, 2020). According to top management at the mill (personal communication, July 28, 2020), an additional 1.5% should be added to the operating costs for maintenance costs and an additional 10% should be added to the capital for infrastructure costs. This brings the total capital expenditure of the first scenario to €5.6 million.

[1] Based on €0.05/kWh (0.8 kWh/m^3 * 24,840 m^3/day * 365 * 0.05)

4.2 Scenario 2: UF Treating Whitewater from the Pulp Dryer

In the second scenario, UF is applied to treat the whitewater from the pulp drying process. The stream is relatively simple in composition, consisting mainly of process water and fibers. The application of UF along this stream is especially attractive due to the potential to recover fibers along with a variety of reuse options for the permeate (van Leeuwen & Cappon, 2020). The technical and economic aspects of this scenario are discussed in the following sections.

4.2.1 Technical Assessment of Scenario 2

The whitewater from the pulp drying process consists of two streams with a combined inlet flow rate of 1,126 m^3/h. The first stream contains high organic load effluent with a flow rate of 481 m^3/h, and the second stream consists of low organic load effluent with a flow rate of 645 m^3/h. The difference in the streams concerns mainly temperature, with the low organic stream having a temperature below 40°C and the high organic effluent having a temperature above 40°C (Silva et al., 2019a). The recovery percentage of both streams is 90%. UF may be applied to either or both streams, however the high organic stream would need to be cooled to an appropriate temperature before UF. The permeate flow rate from the high organic load effluent stream is 432.9 m^3/h, and the permeate flow rate from the low organic load effluent stream is 580.5 m^3/h. Combining these permeate streams results in a permeate flow rate of 1013.4 m^3/h. The concentrate flow rate for the high organic load effluent stream is 48.1 m^3/h and that of the low organic load effluent is 64.5 m^3/h, or 112.6 m^3/h when combined. Table 7 provides an overview of the physicochemical properties of the whitewater from the pulp drier before UF treatment, while Table 8 shows the characteristics of the whitewater permeate after UF according to pilot tests (Silva et al., 2019).

Table 7: Characteristics of whitewater from pulp drier (Silva et al., 2019)

Parameter	Unit	Whitewater
Temperature	°C	50-65
Flow	m^3/h	900-1200
Total COD	mg/L	656
Soluble COD	mg/L	308
BOD	mg/L	52
pH		4.79
TSS	mg/L	75
Turbidity	NTU	35
Color	CU	132
Electric conductivity	mS/cm	1.75
Chloride	mg/L	128
Potassium	mg/L	13
Calcium	mg/L	14.6
Copper	mg/L	8.9

Iron	mg/L	0.57
Magnesium	mg/L	2.36
Manganese	mg/L	0.15
Silica	mg/L	11
Sodium	mg/L	364

Table 8: Whitewater permeate parameters (Silva et al., 2019; van Leeuwen & Cappon, 2020)

Parameter	Unit	Whitewater Permeate
Temperature	°C	40
Flux	m^3/h	1013.4
COD removal efficiency	%	79
Permeate COD	mg/L	140
pH		5.5
TSS removal efficiency	%	99
Permeate TSS	mg/L	0.5
Turbidity removal efficiency	%	90
Permeate turbidity	NTU	1.7
Color removal efficiency	%	81
Permeate color	CU	6
Electric conductivity	mS/cm	0.94
Chloride	mg/L	66
Potassium	mg/L	4.8
Calcium	mg/L	5.7
Copper	mg/L	5.2
Iron	mg/L	1.3
Magnesium	mg/L	1
Manganese	mg/L	0
Silica	mg/L	10
Sodium	mg/L	2.7

Pilot tests show that applying UF to whitewater greatly reduces TSS and turbidity, having average removal efficiencies greater than 98%. Lower dissolved compound retention was also observed, as expected. COD and color reduction were high, with removal efficiencies reaching 97% and 75% respectively. Sodium, potassium, calcium, copper, iron, magnesium, and manganese levels were considerably decreased in the permeate following UF, however silica and chloride levels were not affected. Increasing the concentration of the effluent in the pilot tests led to better removal efficiencies, however higher fouling mechanisms were also experienced. A balance among effluent concentration, permeate recovery and membrane fouling, along with appropriate periodic backwashing to control for this fouling, should be reached to achieve the best removal efficiencies at a constant transmembrane pressure (van Leeuwen & Cappon, 2020).

The main draw of this scenario is the potential to recover fibers from the concentrate, which would be sent to the drying machine. Humpert et al. (2016) explain that membrane technology provides an economic and environmentally friendly platform for recovering fibers. Meanwhile, the permeate stream has the potential to be reused in many processes as service water, including replacing industrial water in the evaporation surface condensers, cooling the bottom of the digestor, and cooling woodyard equipment. It may also be sent to a holding tank, otherwise known as the 'Mineirão' tank, to be later mixed with industrial water and reduce freshwater intake.

4.2.1.1 Sending the Whitewater Permeate to the 'Mineirão' tank

Sending the whitewater permeate to the Mineirão tank has the potential to increase the electrical conductivity, potassium ion, and chloride ion concentrations of the mill's industrial water. This is because the time the permeate spends in the Mineirão tank permits ions to accumulate. Pilot tests show that the electrical conductivity of the whitewater decreases from 1.75 mS/cm to 0.94 mS/cm after passing through UF. However, the overall electrical conductivity of the industrial process water when the permeate is reused from the Mineirão tank is high for normal use. Table 9 compares industrial water parameters before the addition of whitewater permeate and the parameters after whitewater is reused and added to the process stream from previous pilot tests (van Leeuwen & Cappon, 2020).

Table 9: Industrial water parameters before and after whitewater permeate reuse (Silva et al., 2019b; van Leeuwen & Cappon, 2020)

Units	Industrial Water Without Permeate Recycling	Industrial Water After Whitewater Permeate Reuse[2]
Flowrate (m^3/h)	9200	9200
EC (mS/cm)	118	202.7
Cl^- (mg/L)	9.8	16.8
K^+ (mg/L)	2.1	2.3
Color (CU)	1.0	0.9

Pilot tests show that higher recovery rates also equate to higher electrical conductivity (EC). Figure 13 below illustrates the relationship between EC and permeate recovery. Table 9 shows the EC assuming a 30% recovery rate, however the actual potential of the system according to BMT is 90%. This means that

[2] Assuming a 30% recovery rate

EC assuming whitewater reuse with a recovery rate of 90% would reach levels closer to 373 mS/cm (Sousa & Berghof Membranes Technology, 2020; van Leeuwen & Cappon, 2020).

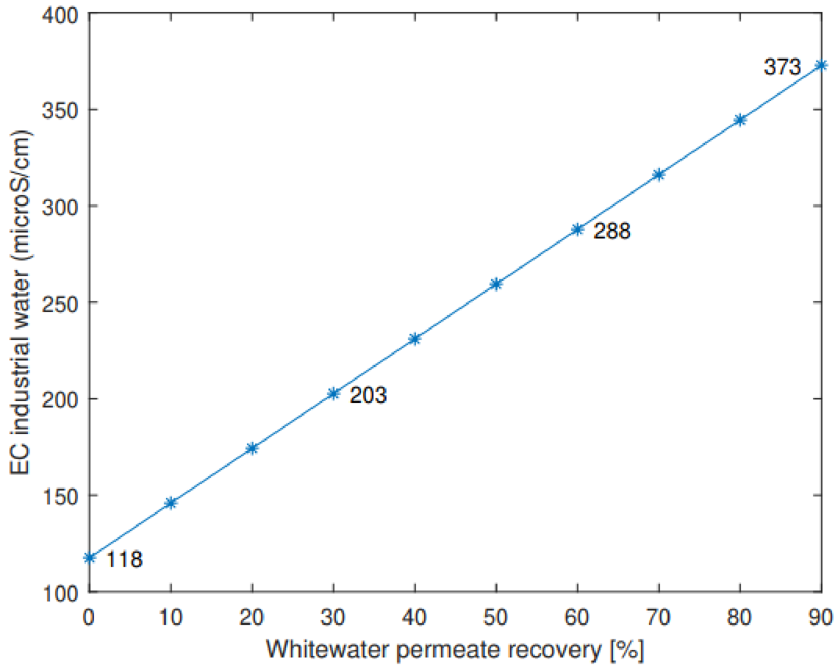

Figure 13: Industrial water EC at different whitewater permeate recovery rates (Silva et al., 2019b; van Leeuwen & Cappon, 2020)

The pulp mill technicians would need to define the maximum acceptable EC in the industrial water stream in order to determine if an ion exchange unit is necessary. For example, in the recovery boilers a maximum EC of 150 µs/cm is tolerated, which the industrial process water would exceed if whitewater is reused (van Leeuwen & Cappon, 2020).

4.2.1.2 Reusing Whitewater Permeate to Replace Industrial Water in the Surface Condensers

Aside from being sent to the Mineirão tank, the whitewater permeate may also be used to replace part of the industrial water intake for cooling purposes in the surface condensers. This would help reduce overall water usage. Figure 14 presents a map of the surface condenser water stream (van Leeuwen & Cappon, 2020).

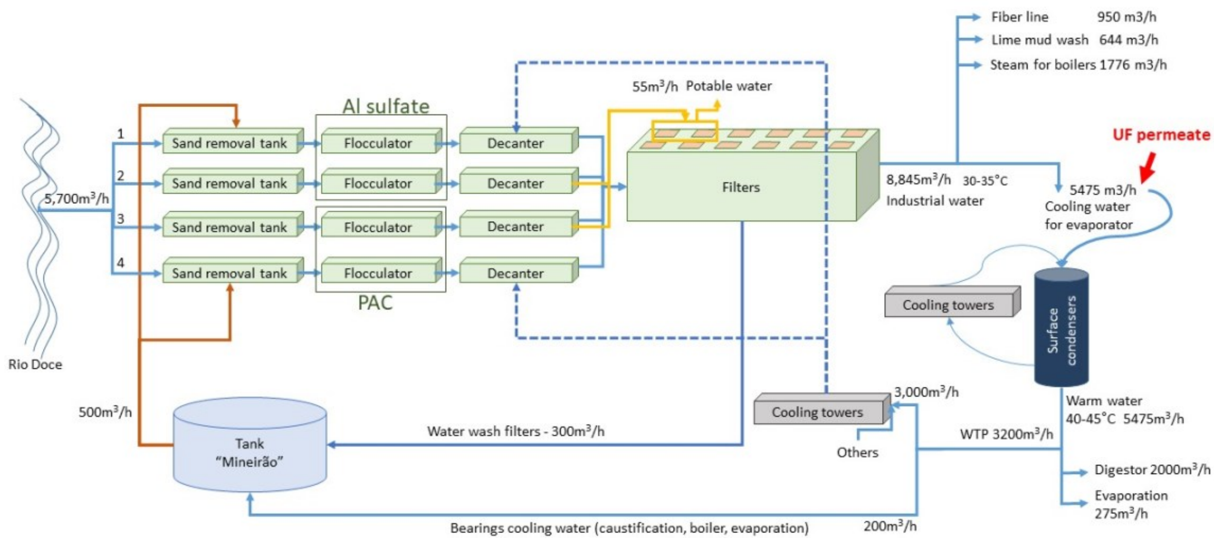

Figure 14: Map of surface condenser water streams (Silva et al., 2019a; van Leeuwen & Cappon, 2020)

The risks associated with reusing the whitewater permeate in the surface condenser include EC increase, potassium and chloride ion increase, and heat overload. Industrial water quality is better in this case as opposed to sending the permeate to the Mineirão tank. This is because 2000m^3/h of permeate exits the system to the digestor, avoiding ion accumulation within the loop. Table 10 compares the industrial water quality when sending the permeate to the Mineirão tank and when sending the permeate to the surface condenser.

Table 10: Industrial water quality after sending whitewater permeate to the surface condenser and to the Mineirão tank (Silva et al., 2019b; van Leeuwen & Cappon, 2020)

Units	Industrial Water After Sending Permeate to Surface Condenser	Industrial Water After Sending Permeate to Mineirão Tank [3]
Flowrate (m^3/h)	5500	9200
EC (mS/cm)	160.8	202.7
Cl^- (mg/L)	13.1	16.8
K^+ (mg/L)	2.2	2.3

While the EC of industrial water is lower after sending the permeate to the surface condenser, the condenser itself may still be sensitive to higher levels of EC, Cl^- and K^+. As for heat overload, pilot tests also show that small increases in temperature that come from reusing permeate streams do not pose much risk to pulp mill operations (Silva et al., 2019b; van Leeuwen & Cappon, 2020).

[3] Assuming a 30% recovery rate

4.2.1.3 Reusing Whitewater Permeate to Cool the Bottom of the Digestor

The bottom of the digestor is cooled with a mix of 2000 m^3/h of warm water and 900 m^3/h of industrial water. Part of this industrial water may be replaced by the whitewater permeate to contribute towards a reduction in the mill's freshwater intake. However, after cooling the digester this stream flows into the digester itself and then to the recovery boilers. Figure 15 shows where the UF permeate may replace industrial water in the water streams associated with the digester.

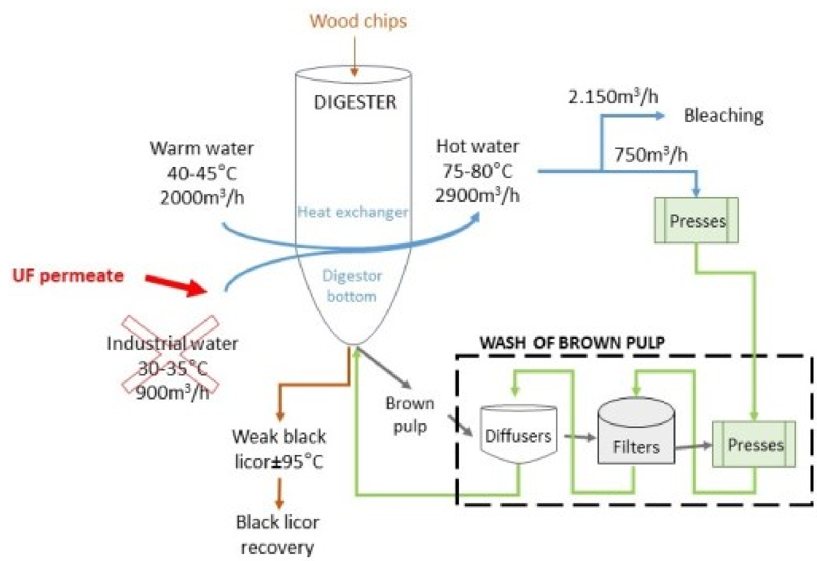

Figure 15: Water map of streams associated with the digester (Silva et al., 2019a; van Leeuwen & Cappon, 2020)

Both the digester and boilers are at risk of corrosion and fouling from the increased EC and Cl^- and K^+ concentrations added to the black liquor by the whitewater permeate (Tran & Vakkilainnen, 2016). Pilot tests have shown how these concentrations change when mixing the UF permeate with the industrial water and warm water streams. Table 11 presents a summary of these values.

Table 11: Ion concentration in digester industrial water stream before and after mixing with whitewater permeate (Silva et al., 2019; van Leeuwen & Cappon, 2020)

Units	Industrial Water Base Case	Industrial Water After Mixing with Whitewater Permeate
Permeate Flowrate (m^3/h)	0	374
Mix of Industrial Water and Warm Water Flowrate (m^3/h)	2900	2526
EC (mS/cm)	117	223.4
Cl^- (mg/L)	9.9	17.2
K^+ (mg/L)	2.2	2.5

It is important to note that reducing water consumption in cooling the digester may also be achieved by cooling the warm water using heat exchangers instead of cooler industrial water. Doing so would eliminate the need to utilize the UF permeate and industrial water overall, which would also eliminate the risks to the digester and the boilers (van Leeuwen & Cappon, 2020).

4.2.1.4 Reusing Whitewater Permeate to Cool Woodyard Equipment

Woodyard equipment is cooled using an industrial water stream from the pump house tank with a flow of 195 m^3/h. Figure 16 displays a map of the water streams associated with cooling the woodhouse equipment.

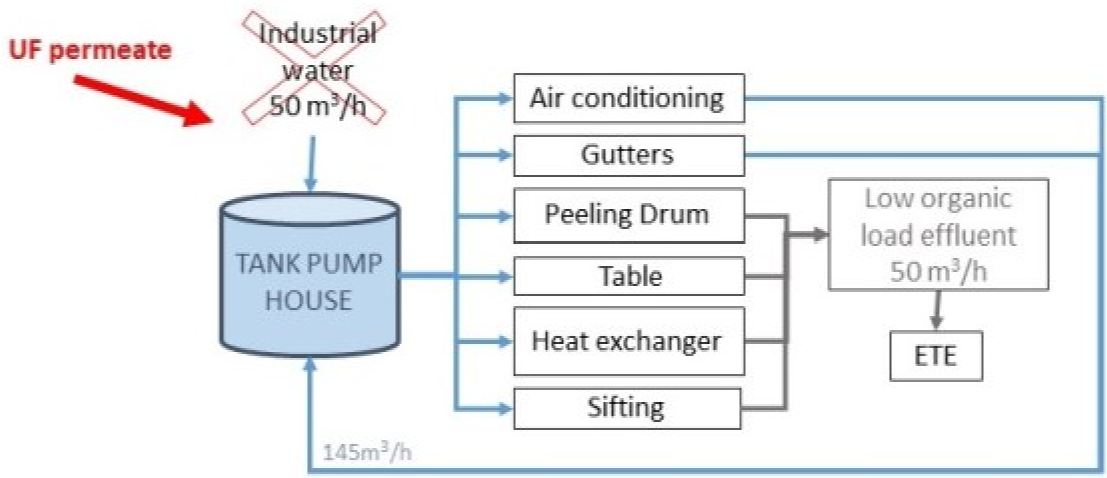

Figure 16: Water streams for cooling woodyard equipment (Silva et al., 2019a; van Leeuwen & Cappon, 2020)

As shown in Figure 16, a 50 m^3/h stream of low organic load effluent from the peeling drum, heat exchanger, table, and sifting is discarded, while a stream of 145 m^3/h from the air conditioning and gutters is sent back to the pump house tank. This leaves a stream of 50 m^3/h for cooling the woodyard equipment that can be replaced by the whitewater UF permeate. The only potential issue with this is an increase in EC, which could corrode pipes and equipment. However, the whitewater permeate stream results in a relatively low EC increase which would not be further increased by the stream from the air conditioning and the gutters. Table 8 shows the EC would remain around 942 mS/cm, against which the limits for the woodyard equipment should be checked (van Leeuwen & Cappon, 2020).

4.2.2 Economic Assessment of Scenario 2

This scenario has two main economic benefits, the first of which is the profitable recovery of pulp fibers. Economic models have shown that pure lignin may be recovered using membrane-technologies at a cost of €46-€120 per ton (Humpert et al., 2016). Pulp mill engineers (personal communication, May 21, 2020) report that the cost of pulp fibers fluctuates year to year, and that a medium price of pulp may be used to estimate the benefits of pulp recovery. The average price has fallen over the last few years from €850/air-dried ton to around €350-380/adt. Considering that the cost to recover the fibers is currently less than the cost of the fibers on the market, implementing UF in this scenario has the potential to be profitable. The second main economic benefit of this scenario is a reduction in the use of freshwater. According to Silva et. al. (2018), about 500 m^3/h of water may be saved.

BMT has conducted a preliminary economic assessment of the Scenario 2 (Sousa & Berghof Membranes Technology, 2020). This assessment consists of three sub assessments. The first concerns utilizing UF to treat both the high organic effluent and low organic effluent, which is Scenario 2a. Scenario 2b and 2c concern using UF to treat the high and low effluent individually. These preliminary assessments are presented in Table 12, Table 13, and Table 14.

Table 12: Budgetary overview of Scenario 2a (high and low effluent UF treatment) (Sousa & Berghof Membranes Technology, 2020)

CAPACITY	Feed Capacity (m^3/d)	27024
	Permeate Capacity (m^3/d)	24321.6
	Recovery	90%
SYSTEM SETUP	Technology	B-Smart ECO
	Design Flux (L/ (m^2.h))	75
	Number of single loop skids	1
	Number of double loop skids	12
	Number of modules per loop	8
	Total number of modules	200
	Number of CIP stations	2
OPEX	kWh/m^3	0.8
	Energy[4] + Maintenance (€)	**18,021**
CAPEX	Investment (€)	5,105,500
CAPEX (after infrastructure)	Total Investment (€)	**5,616,050**

[4] Based on €0.05/kWh (0.8 kWh/m^3 * 24,321.6 m^3/day * 365 * 0.05)

Table 13: Budgetary overview of Scenario 2b (high organic load effluent UF treatment) (Sousa & Berghof Membranes Technology, 2020)

CAPACITY	Feed Capacity (m^3/d)	11544
	Permeate Capacity (m^3/d)	10389.6
	Recovery	90%
SYSTEM SETUP	Technology	B-Smart ECO
	Design Flux (L/ (m^2.h))	77
	Number of single loop skids	1
	Number of double loop skids	5
	Number of modules per loop	8
	Total number of modules	80
	Number of CIP stations	2
OPEX	kWh/m^3	0.8
	Energy[5] and Maintenance (€)	**7,700**
CAPEX	Investment (€)	2,254,000
CAPEX (after infrastructure)	Total Investment (€)	**2,479,400**

Table 14: Budgetary overview of Scenario 2c (low organic load effluent UF treatment) (Sousa & Berghof Membranes Technology, 2020)

CAPACITY	Feed Capacity (m^3/day)	15480
	Permeate Capacity (m^3/day)	13932
	Recovery	90%
SYSTEM SETUP	Technology	B-Smart ECO
	Design Flux (L/ (m^2.h))	77
	Number of single loop skids	0
	Number of double loop skids	7
	Number of modules per loop	8

[5] Based on €0.05/kWh (0.8 kWh/m^3 * 10389.6 m^3/day * 365 * 0.05)

	Total number of modules	112
	Number of CIP stations	2
OPEX	kWh/m^3	0.8
	Energy[6] and Maintenance (€)	**10,323**
CAPEX	Investment (€)	2,851,500
CAPEX (after infrastructure)	Total Investment (€)	**3,136,650**

As discussed previously, the Brazilian pulp mill produces 95% of its energy in house. The remaining 5% is contracted at a rate of 0.29 Brazilian reals/kWh, or €0.05/kWh. For the UF system in scenario 2, the kWh usage is 0.8/m^3 while the permeate capacity is for both lines 24,321.6m^3 per day. The system therefore requires 7,101,907 kWh per year, 95% of which is produced in house. The remaining 5% of this, or 355,095 kWh, is contracted at €0.05/kWh for a total annual operating cost of €17,755. The total investment, or capital cost, of installing the system in this scenario is €5,105,500 based on plug-and-play skids, including testing and excluding transportation costs (Sousa & Berghof Membranes Technology, 2020). According to top management at the mill (personal communication, July 28, 2020), an additional 1.5% should be added to the operating costs for maintenance costs and an additional 10% should be added to the capital costs for infrastructure. This brings the total capital expenditure of the second scenario to €5.6 million. Tables 14 and 15 break down the costs of implementing Scenario 2b and 2c. For the high organic line in Scenario 2a or 2b, additional costs for a heat exchange unit may be necessary to reduce the temperature of the effluent to 40°C before passing through the UF membrane. This is not necessary in Scenario 2c.

4.3 Scenario 3: UF Replacing the Sand Filters at the Water Treatment Plant

In Scenario 3, UF is used to replace sand filters at the WTP to produce potable water for human consumption. This is the simplest of the three scenarios, as UF would be used to treat river water from the Doce River, and the resulting concentrate could either be returned to the river or sent to a landfill. The technical and economic aspects of this scenario are summarized in the following sections.

4.3.1 Technical Assessment of Scenario 3

River water enters the mill's WTP through four lines at a flow rate of 5,700 m^3/h. This is shown in Figure 17.

[6] Based on €0.05/kWh (0.8 kWh/m^3 * 13932m^3/day * 365 * 0.05)

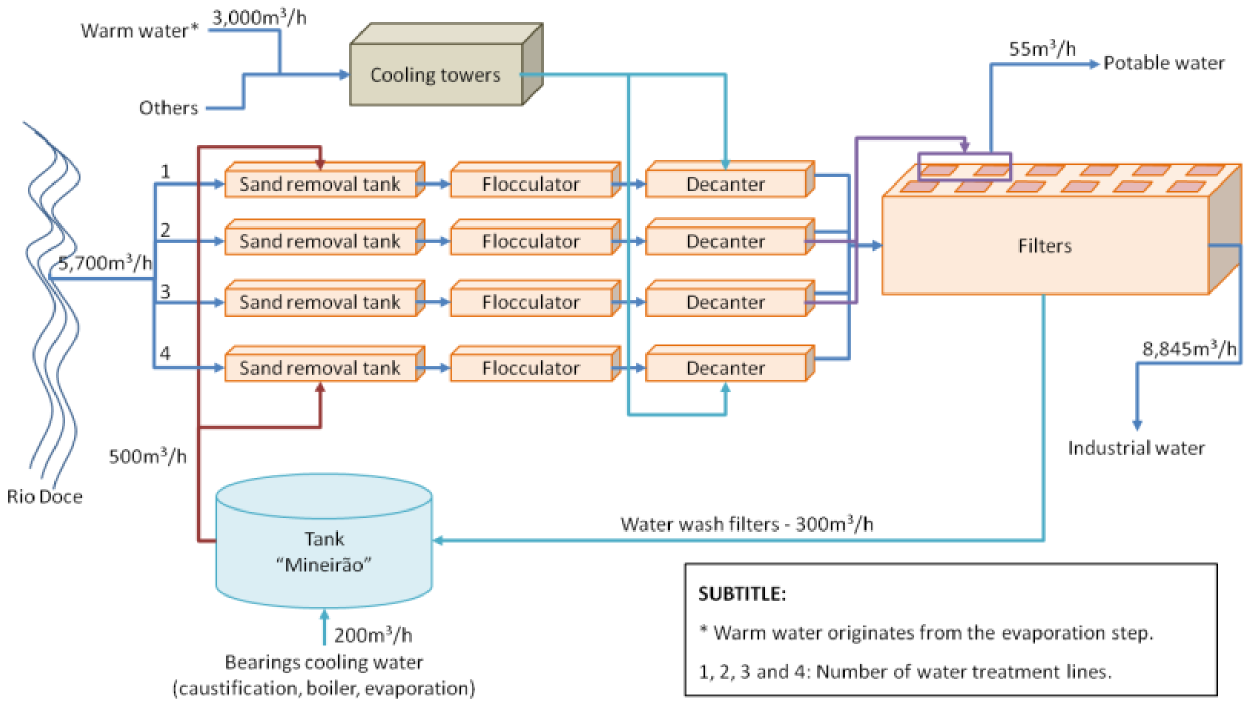

Figure 17: Water flows in the pulp mill's water treatment plant (Silva et al., 2019a)

The second and third lines are used specifically for drinking water, and pass the river water through sand removal, flocculation and decanting. After this, the water from the second and third lines is sent to the filtration stage where two quick filters are used to treat the water for human consumption at a flow rate of 55 m^3/h (Silva et al., 2019a). At this flow rate, UF could easily be used to replace the filters with a 90% or greater recovery rate (Sousa & Berghof Membranes Technology, 2020). Table 15 presents a summary of the river water parameters.

Table 15: Doce River water parameters (van Leeuwen & Cappon, 2020; Viola, 2020)

Parameter	Unit	Doce River Water
Flux	m^3/h	55
Total COD	mg/L	8-22
pH	pH	7.28
TSS	mg/L	~100 (50 - 200)
Turbidity	NTU	100
Color	CU	154
Electric conductivity	mS/cm	~80 (45-100)
Chloride	mg/L	5.63
Potassium	mg/L	2.09
Calcium	mg/L	5.69
Copper	mg/L	0.05

Iron	mg/L	74.88
Magnesium	mg/L	1.61
Manganese	mg/L	0.38
Silica	mg/L	11.54
Sodium	mg/L	7.02
Aluminum	mg/L	10.56

The resulting permeate would be used for human consumption, while the concentrate would be returned to the river or landfilled. Because the streams in this scenario do not mix with any industrial water lines, there is no risk to production and virtually no additional environmental impacts. The concentrate would be returned to the river as it entered the mill. Meanwhile the quick filters would be freed up to treat industrial water. BMT offers two different UF technologies to treat the river water, which differ slightly in costs as explained in the next section.

4.3.2 Economic Assessment of Scenario 3

BMT offers two UF technology options to replace the drinking water filters in scenario three. One is the B-Smart Performance UF system and the other is the B-Smart ECO UF system (Sousa & Berghof Membranes Technology, 2020). Each option has a different capital and operating cost. These options are summarized in Table 16 and Table 17.

Table 16: Budgetary overview of scenario 3a (B-Smart Performance system) (Sousa & Berghof Membranes Technology, 2020)

CAPACITY	Feed Capacity (m^3/d)	1320
	Permeate Capacity (m^3/d)	1188
	Recovery	90%
SYSTEM SETUP	Technology	B-Smart Performance
	Design Flux (L/ (m^2.h))	92
	Number of single loop skids	0
	Number of double loop skids	1
	Number of modules per loop	4
	Total number of modules	8
	Number of CIP stations	1
OPEX	kWh/m^3	1.6

	Energy[7] and Maintenance (€)	**1,760**
CAPEX	Investment (€)	340,000
CAPEX (after infrastructure)	Total Investment (€)	**374,000**

Table 17: Budgetary overview of scenario 3b (B-Smart ECO system) (Sousa & Berghof Membranes Technology, 2020)

CAPACITY	Feed Capacity (m^3/d)	1320
	Permeate Capacity (m^3/d)	1188
	Recovery	90%
SYSTEM SETUP	Technology	B-Smart ECO
	Design Flux (L/ (m^2.h))	74
	Number of single loop skids	0
	Number of double loop skids	1
	Number of modules per loop	5
	Total number of modules	10
	Number of CIP stations	1
OPEX	kWh/m^3	0.8
	Energy[8] and Maintenance (€)	**880.25**
CAPEX	Investment (€)	419,500
CAPEX (after infrastructure)	Total Investment (€)	**461,450**

There are small tradeoffs between the two systems. The B-Smart Performance system, for example, has a lower capital cost and a higher operating cost than the B-Smart ECO system. This higher operating cost has the benefit of providing a higher design flux of 92 L/(m^2.h) vs the B-Smart ECO's 74 L/(m^2.h). However, the operating costs of the B-Smart ECO system are about half as much as the B-Smart Performance system, which is better for long-term cost savings. There is no need for ion exchange units or heat exchangers as the water comes directly from the river and does not mix with any process streams.

[7] Based on €0.05/kWh (1.6 kWh/m^3 * 1188m^3/day * 365 * 0.05)
[8] Based on €0.05/kWh (0.8 kWh/m^3 * 1188m^3/day * 365 * 0.05)

4.4 Environmental Assessment

As discussed previously, the Brazilian pulp mill has been operating in the Doce River basin for over 20 years. The environmental disaster that occurred in 2015 related to a mining company severely impacted the quality of the river. Studies show that mill closure is one of the best ways for pulp mills to reduce impacts on freshwater sources (Mänttäri et al., 2010; Oliveira et al., 2007; Tran & Vakkilainnen, 2016). Mill closure reduces freshwater intake, which translate into less water discharged back into the river. Preliminary studies of the Brazilian pulp mill have shown that both Scenarios 1 and 2 can contribute to water savings of up to 500 m^3/h each (Silva et al., 2018). If both scenarios are implemented, the mill could reduce freshwater consumption by up to 8,760,000 m^3 per year. The principle benefit of scenario three is in its low capital and operating costs and energy savings, thus water savings are not as significant as in the first two scenarios.

The UF systems also greatly reduce COD, BOD, TSS, color, and turbidity as shown in the technical sections above. This would help the mill comply with Brazilian legislation regarding wastewater discharge standards. The current standards and limits are presented in Table 18.

Table 18: Wastewater discharge standards for the State of Minas Gerais (Deliberação Normativa Conjunta COPAM/CERH-MG N.º 1, 2008)

Parameter	River Water Quality Standards and Wastewater Discharge Limits
Color	75 CU
Turbidity	100 NTU
BOD	60 mg/L
Dissolved Oxygen in River Water	Not less than 5 mg/L O_2
TSS	100 mg/L
COD	180 mg/L (or 15 kg/air-dried ton for kraft pulp production wastewater)

Table 19 shows the Doce River water parameters measured in the fourth quarter of 2019 by the government of the state of Minas Gerais at points before and after the mill (Viola, 2020).

Table 19: Doce River water parameters before and after Pulp Mill (Viola, 2020)

Month (2019)	Parameter	Before Pulp Mill	After Pulp Mill
October	Turbidity (NTU)	12.3	6.07
	BOD (mg/L)	<2.0	<2.0
	DO (mg/L)	7.9	8.2
	TSS (mg/L)	7	40

	COD mg/L	8.7	14
November	Turbidity (NTU)	55.4	57.7
	BOD (mg/L)	<2.0	<2.0
	DO (mg/L)	7.8	7.7
	TSS (mg/L)	26	39
	COD (mg/L)	31	14
December	Turbidity (NTU)	243	287
	BOD (mg/L)	<2.0	<2.0
	DO (mg/L)	8.0	8.2
	TSS (mg/L)	147	169
	COD (mg/L)	25	27

These parameters show that the mill generally complies with regulations. The UF systems could help future-proof the mill as these regulations become more stringent. Color content is also an important factor to be considered. Figure 18 shows the concentration of color (CU) in the river at points before and after the pulp mill from 2016 to 2019 (Viola, 2020).

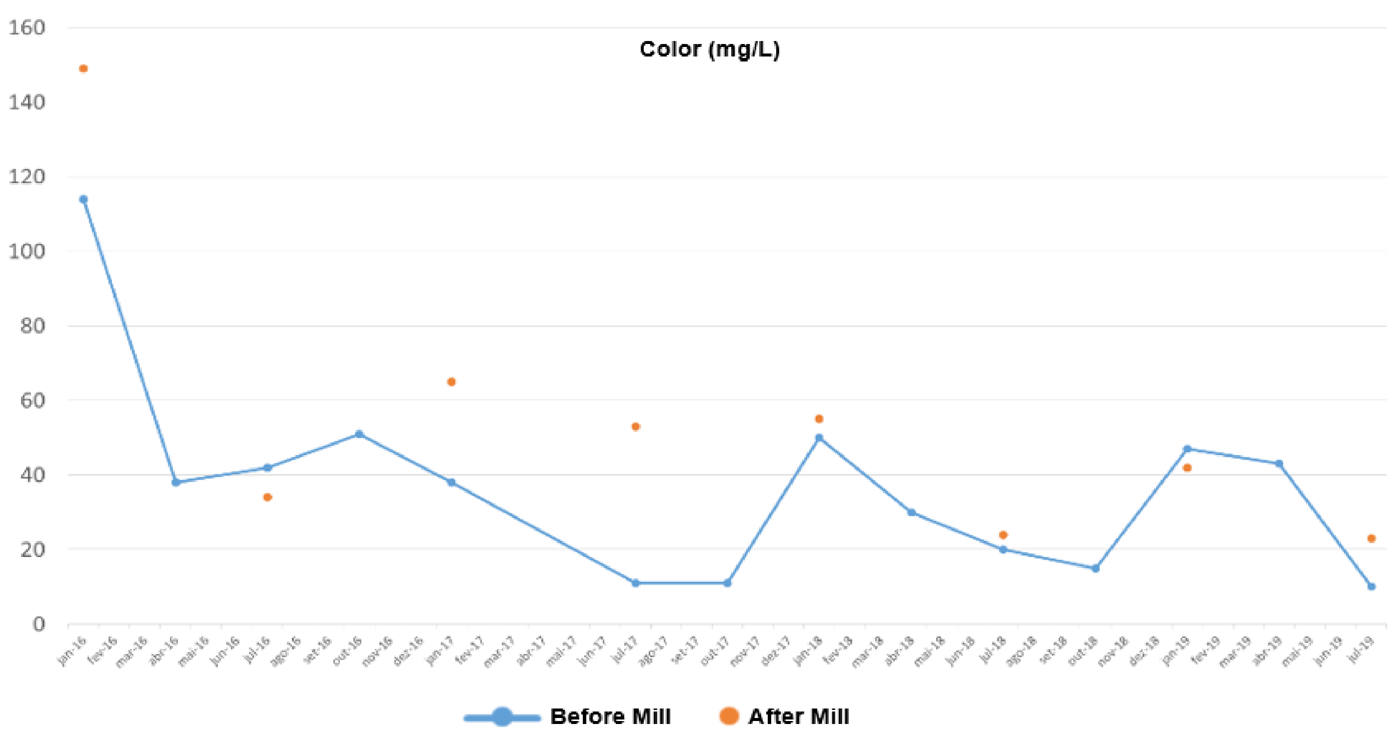

Figure 18: Color concentration in the Doce river from 2016 -2019 at points before and after the bleached kraft pulp mill (Viola, 2020)

The data shows that the pulp mill may sometimes contribute to a color content in the river that exceeds 75 CU, especially in dryer seasons. With high color removal efficiency, the UF systems in Scenarios 1 and 2 would contribute to lower color concentration in the mill discharge.

4.5 Summary of Results

In summation, each scenario has key benefits, risks, and impacts. Implementing Scenario 1 contributes to significant reductions in COD, BOD, TSS, turbidity, and color concentrations. The UF permeate may be sent to the WWTP, resulting in up to a 20% reduction in sludge generation. The concentrate may be sent to the recovery boiler, where the risk of corrosion due to potassium and chloride ions is low as these ions pass through the UF filter into the permeate. This permeate is not reused in the production process and therefore does not impact mill operations. The UF concentrate also reduces the energy costs associated with evaporating black liquor by contributing to a lower boiling point in the recovery boiler (Kong et al., 2016). The capital cost of implementing the UF system in Scenario 1 is €5.6 million while the operating costs are €18,400 per year. Water savings in this scenario can reach up to 500m^3/h. These water savings and a reduction in color concentration are the principle environmental benefits of Scenario 1.

In Scenario 2, UF is applied to treat whitewater from the pulp drying process. The two whitewater streams are relatively simple in composition, and therefore the UF system is easy to implement to treat either stream with the added benefit of profitably recovering pulp fibers from the concentrate. The UF permeate may be reused in several areas of the production process, contributing to water savings of up to 500m^3/h. Higher recovery rates are needed for the profitable recovery of pulp fiber, however this leads to electrical conductivity increase which may impact the operation of the mill. EC increases must therefore be balanced against recovery rates. The capital cost of implementing UF to treat both streams is €5.6 million while the operating costs are €18,000 per year. The capital and operating costs of implementing UF to treat only the high organic load effluent are €2.5 million and €7,700 per year respectively. The capital and operating costs of using UF to treat only the low effluent stream are €3.2 million and €10,300 per year respectively. Temperature is the main difference between the two streams, with the high organic load effluent having a temperature above 40°C. This means that treating this stream with UF would require a heat exchanger. The principle environmental benefits of Scenario 2 are water savings and COD, TSS, and turbidity reduction.

Finally, Scenario 3 replaces the filters at the WTP with two optional UF systems. Either system is easy to implement at relatively low capital and operating costs. The first system has a flux rate of 92 L/ (m^2.h), a capital cost of €374,000, and an operating cost of €1,700 per year. The second system has a lower flux rate of 74 L/ (m^2.h), a higher capital cost of €461,450, and a lower operating cost of €880 per year. The UF permeate is to be used as drinking water for human consumption, while the concentrate may be either landfilled or returned to the river. Technical and environmental risks in this scenario are low. The greatest benefit of implementing UF in this scenario would be achieved if it is combined with one of the options in Scenarios 1 and 2.

5. Governance Analysis

The implementation of new technology is more than simply a technical process, but a social process as well. A complex network of actors must coordinate and cooperate in order to reach a consensus and place plans into practice. This section will evaluate the governance conditions of implementing new technology in the pulp and paper industry to assess whether they are favorable or unfavorable. This evaluation is done according to a version of the GAT used by Bressers et al. (2016). The GAT is part of the CIT, which assesses decision-making from three main actor characteristics, namely: motivations, knowledge and resources. Motivations refer to external and internal pressures that drive individuals or groups to action. These pressures include values, goals, and norms. Knowledge, or cognition, refers to interpretations of reality that actors or groups hold to be true. These interpretations of reality are influenced not only by facts and information but also interactions with others, time frames, and levels or scales. Finally, resources refer to assets that provide actors with the power and capacity to act. These resources may be financial, institutional, or network based. According to CIT, the three main actor characteristics both influence and are influenced by the governance conditions that surround a decision-making process (Bressers, 2007). These conditions, described across five dimensions, ultimately support or restrict implementation as indicated by four quality criteria. These five governance dimensions are: levels and scales, actors and networks, problem perspectives and goal ambitions, strategies and instruments, and responsibilities and resources. These dimensions are assessed according to the criteria of extent, coherence, flexibility and intensity (Bressers et al., 2016). These governance dimensions and the four assessment criteria are further explained in Section 2.3.1 The Governance Assessment Tool To better understand the governance context surrounding the implementation of new technology in the pulp and paper industry, a series of interview questions were drafted according to the GAT matrix shown in Figure 10. These questions may be found in Appendix II.

Each section of this chapter will assess one of the five dimensions of the GAT matrix according to the four criteria of extent, coherence, flexibility and intensity. Supporting evidence from the interviews described in Section 3.2 was used to asses each criterion as low, moderate, or high according to the guidelines explained in Section 2.3.1 The Governance Assessment Tool Answers to the interview questions were found to be consistent across the interviews, as described in the following sections. This consistency provided validation for the results, which are presented in the final section of this chapter.

5.1 Levels and Scales

The first governance dimension refers to the administrative, geographical, institutional, and social levels existing internally and externally to a governance regime. According to the GAT, this governance dimension has high extent if several different internal and external levels are involved in the decision-making process. The levels must work together with a high level of trust, and mutual dependence among the different levels must be recognized if coherence is high. Flexibility is high if it is possible to communicate and shift focus effectively across the different levels, and intensity is high if certain level have a powerful impact on reforms or changes in behavior or management (Bressers et al., 2016).

5.1.1 Extent

All interviewees, which are summarized in Table 2 in Section 2.3.1 The Governance Assessment Tool, confirmed that both internal and external levels are involved in the decision-making process of implementing new technology in the pulp and paper industry. The extent of this involvement, however, varied slightly according to each interviewee. MG explained that licensing requirements determine the extent to which different levels are involved. Large companies often face stricter licensing requirements due to the size of their impact. The larger the company is, the greater the need to incorporate external administrative levels in government, academia, and society due to this impact and the need to comply with regulations. BMT, AD, PTM and PME all mentioned that the cost of implementing a project also impacts the administrative levels involved. The more costly a project is, the more administrative levels are involved both internally and externally. For example, PTM explained that a project exceeding €10 million requires the involvement of international shareholders at the top of the company and consultation from various organizations including academia, other companies, and technology providers. Due to the standardized involvement of these various levels according to the size, impact and cost of a project, extent for levels and scales may be considered high.

5.1.2 Coherence

All interviewees confirmed a hierarchical nature of communication and function across the different levels involved, both internally and externally. The mutual dependence among different levels is therefore highly recognized. If a decision needs to move up in the hierarchy, AD, BMT, PTM, PME and MG confirm that appropriate channels exist for this and are used with relative simplicity and standard procedure. However, PTM explained that due to this standard procedure, it takes a significant amount of time to follow all steps of approval before a decision may be reached. PTM also identified different languages as a potential barrier to coherence across levels, especially when higher administrative levels are international. Additionally, AD mentioned that lower internal levels may not always trust information coming from equivalent or higher external levels due to misunderstandings and lack of interest in collaboration. Thus, these lower levels, though important, are more difficult to reach out to and collaborate with from outside of the company. However, PTM and PME emphasize that standard procedures and strong hierarchical relationships mitigate these issues to an extent. Therefore, coherence may be considered moderate to high.

5.1.3 Flexibility

According to PTM and PME, lower levels in the hierarchy, such as technicians and engineers, are obligated to consult higher levels before making certain decisions in the production process. The larger the cost or the impact of a decision, the higher up the hierarchy it must reach before approval. AD added that external levels outside of the company often only communicate with their equivalent levels or lower. That is, a lower level government or academic representative would primarily interact with lower levels inside the company. PME also confirmed that it is relatively easy to send an idea up the hierarchy, but each level must decide to pass it up. Though it is possible to move up and down the hierarchy given the issue at stake due to standard procedures, specific individuals and circumstances determine this mobility. Therefore, flexibility may be considered moderate to high.

5.1.4 Intensity

All interviewees confirm that top levels in the hierarchy have the final say on where or not changes are implemented. MG, AD, and PTM also added that external factors such as social pressure, stricter legislation, and environmental impacts may also influence change, however the top levels in the company hierarchy must be convinced. Because the top of the hierarchy has such as strong influence on behavioral change and management reform, intensity may be considered high.

5.2 Actors and Networks

This governance dimension refers to all the relevant stakeholders involved in a governance regime. Figure 19 illustrates the typical stakeholder network of a pulp and paper company according to the interviewees.

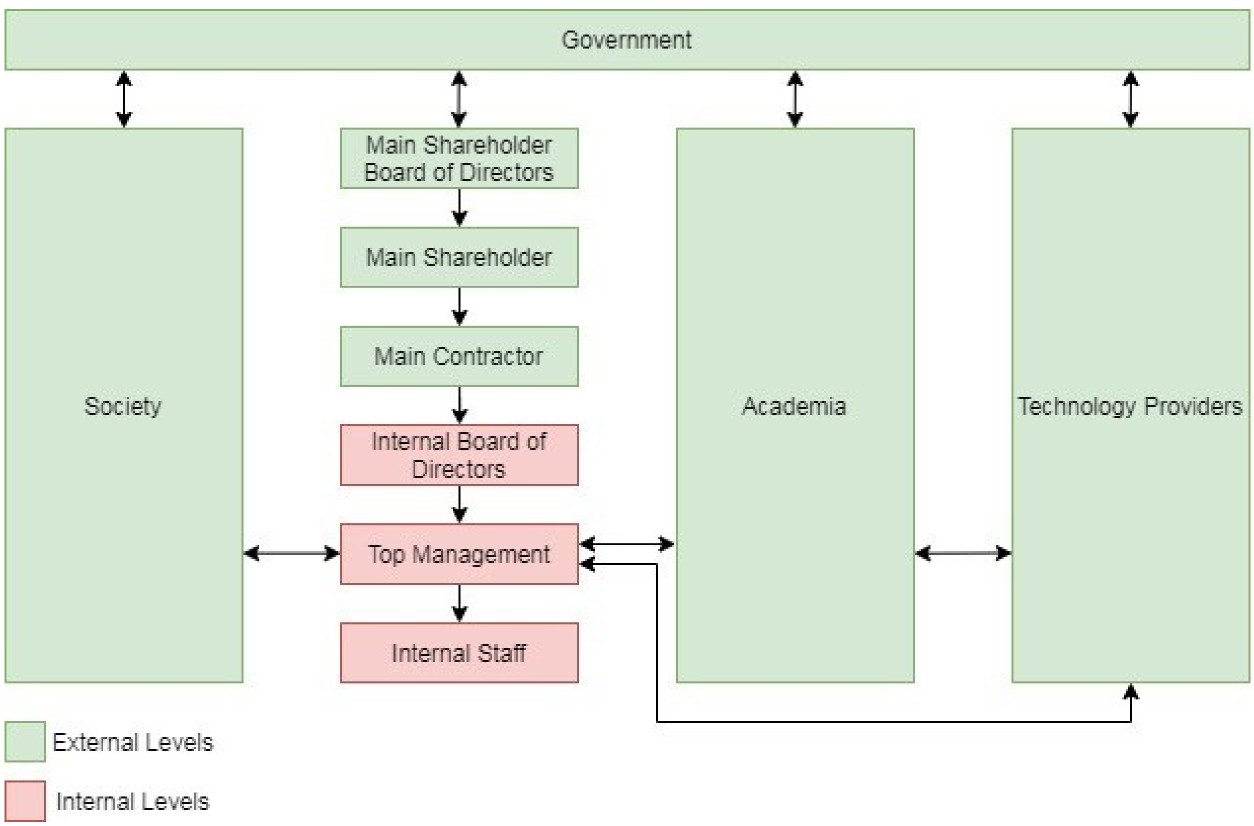

Figure 19: Pulp and Paper Industry actor and network hierarchy

The extent of this dimension is considered high if few stakeholders are excluded. Coherence is high if interactions among those involved are stable and institutionalized. Stakeholders should have experience working together and should respect and trust each other. Communication and cooperation among actors should be straightforward. Flexibility is high if new actors or leaders have the ability and opportunity get involved as needed, and it is easy for actors to support one another. Intensity is high if some actors should hold influence over others concerning behavioral or management changes (Bressers et al., 2016).

5.2.1 Extent

As with levels and scales, all interviewees confirm that the extent to which relevant stakeholders are involved depends on the size, costs, and impacts of a change. PTM, AD, and MG all explained that stakeholders at the very top of the hierarchy are only involved if a change exceeds €10 million in costs. AD further explained that it is often difficult for external actors to reach out to and collaborate with those at the lowest level of the internal hierarchy without first consulting their superiors. For most decisions, therefore, the middle levels of the internal hierarchy are most involved, often without the need for external actor input. Thus, the extent for actors and networks may be considered moderate to low.

5.2.2 Coherence

All interviewees mentioned the strong nature of the hierarchical relationship among different actors internally. PTM and PME emphasized this especially and added that the hierarchy must always be respected when decisions are made. Externally, coherence across actors varies. Between government and the pulp and paper industry, MG explained that communication among the different actors occurs primarily over the internet and is relatively easy. MG added that the local government is also the main link between the public and the industry. For example, the industry has a direct connection with the public ministry, and popular participation is organized when there are meetings for decisions that impact the public or the environment. Regarding the interactions between the industry and academia, AD mentions that communication lines are not always direct. For example, every pulp and paper company has its own research institute and academics often connect with stakeholders in those institutes. However, it is more difficult for stakeholders in academia to reach out to mill personnel directly. As AD explains, there is often some distrust between the mill personnel and researchers, as the mill personal often prefer consulting an engineer to solve problems rather than an academic researcher. Some companies also have stronger ties to academia than others. As for technology providers, BMT explains that actor involvement is also hierarchical and based on the size and cost of a project. Some conflicts may occur among stakeholders when sales managers reach an agreement on cost, design and function and engineers must deliver to the industry. Across all these different internal and external actors, all interviewees confirmed that interactions are standardized in stable structures and most stakeholders have experience working together. Considering that internally, coherence among actors in the hierarchy is straightforward and standardized, but externally interactions may sometimes be weak, actor and network coherence may be considered moderate to high.

5.2.4 Flexibility

According to PTM and PME, due to the hierarchical nature of most interactions internally and externally, new actors are consulted and included as needed. When a project increases in size, cost, or impact, the lead decision maker may shift, and more external actors may be involved. MG and AD both discussed how government and academia are always ready to support improvements in the industry. They also confirmed that strong historic ties across industry, academia and the government has created an environment that allows different stakeholders to place their input at the appropriate levels in the industry hierarchy. Due to these strong relationships and the standardized nature of shifting leads and involving different actors according to practical necessity, actor and network flexibility may be considered high.

5.2.5 Intensity

All interviewees expressed that stakeholders at the top of the hierarchy exert the most pressure towards implementing a decision. For example, BMT explained that the CEO of the company always has the final say in the decision-making process if a consensus cannot be reached otherwise. This is reflected by PTM and PME. MG also added that public interest groups may also foster behavioral changes in the industry, either by popular pressure or increased government regulations. Actor and network intensity may therefore be considered high.

5.3 Problem Perspectives and Goal Ambitions

The third governance dimension concerns how the actors involved perceive goals and objectives. Extent is high if multiple perspectives are considered and accounted for. Coherence is high if differing perspectives and goal ambitions support each other rather than conflict with each other. Flexibility is high if there are opportunities to change goals and perspectives when, for example, new information is obtained. Finally, intensity is high if there are opportunities for goal ambitions to differ from the status quo (Bressers et al., 2016).

5.3.1 Extent

PTM explained that the main driving factor for adopting and implementing new technology in the pulp and paper industry is improving the efficiency of production. For the shareholders, reducing production costs and increasing efficiency is far more important than increasing production capacity. PME, PTM and AD also explained that it is far easier to convince industries to implement proven technology that is known and has already been implemented with success by other companies or industries. MG and BMT also pointed to increasingly strict legislation and licensing requirement as drivers of technical change. MG explained that this legislation often comes into effect as a result of environmental and social pressures, which the industry pays significant attention to. BMT confirmed this and explained that the industry is motivated to comply with legislation to avoid fines and gain favor with society. Thus, multiple problem perspectives are taken into account by the industry, and extent may be considered high.

5.3.2 Coherence

Increasing efficiency in the production process of the pulp and paper industry means using less raw materials and conserving water. Achieving these objectives eases pressure on the environment, which, as MG and BMT explained, often translates into compliance with environmental legislation and social pressures to maintain operational licensing. PTM, PME, and AD each explained that if a new technology has not been tested it is less likely to be implemented. PTM did mention, however, that sometimes new technology is surprisingly easy to approve. For example, a new biological sludge drying system was approved and installed with little proof of application in other industries. This is evidence that social, legal, and environmental pressures may assist in the implementation of new technology in the industry even if it has not yet been fully proven. Coherence is therefore high.

5.3.3 Flexibility

PTM, MG, and BMT each confirmed that establishing objectives is a dynamic process that requires a lot of discussion and proof that solutions will function as intended. They also each mentioned that environmental, legal, and social pressures will continue to influence the decision-making process in the industry to an increasingly greater extent in the future. Therefore, there will be a necessity to optimize objectives to align with external and internal pressures, and flexibility may be considered high.

5.3.4 Intensity

PTM, PME, BMT and MG explained that the status quo encourages seeking constant improvements in the production process. For example, AD and PTM both explained that most pulp and paper companies have their own research divisions and regularly consult with technical companies and academia in the search for improvements. BMT and MG further explained that these improvements are often aligned with legal and environmental requirements. Because the status quo encourages innovation, intensity may be considered high.

5.4 Strategies and Instruments

This governance dimension concerns internal and external strategies and policy instruments that influence how the governance regime operates. Extent is high if multiple policy instruments are involved in the decision-making strategy, including enforcement and monitoring instruments. Coherence is high if incentive systems rarely conflict with one another and trade-offs are considered if they do. Flexibility is high when there is a choice to use different types of instruments and if there are opportunities to combine these different types. Finally, intensity is high when policy instruments are effective at influencing actors to behave in a certain way (Bressers et al., 2016).

5.4.1 Extent

Many policy instruments and incentives exist both internally and externally to encourage the implementation of new, more efficient technology in the pulp and paper industry. As PTM and MG explained, Brazil has policies in place to give tax breaks to companies that have a research and development team. MG also explained that the government allocates resources to companies that wish to make improvements that positively impact the environment and society. AD and MG mentioned that this is not the case in every country, though most forward thinking governments have recently begun to invest more in industry for this purpose. Internally, PME mentioned that it is normal for companies to monitor and enforce strict self-imposed limits on waste generation. PTM explained that legislation is often confusing, and companies are constantly on the lookout for changes. BMT confirmed that new legislation is often one of the driving factors for new technology demand. This shows that several policy instruments work in tandem to encourage the implementation of new technology, and extent is therefore high.

5.4.2 Coherence

None of the interviewees identified any conflicts in the incentive system. PTM, MG, and AD confirmed that government works closely with both academia and industry to facilitate the research, development, and implementation of new or improved technology. Synergies exist across these institutions. For example, AD and MG explained that the costs of researching new technology that improves the production process are offset by government incentives. Coherence is therefore high.

5.4.3 Flexibility

PTM and PME explained that the industry always seeks to comply with existing legislation through constant monitoring and enforcement. Should new laws be passed, appropriate channels exist to ensure that compliance is maintained. As MG and AD emphasized, the government has policies that encourage the industry to innovate. However, AD mentioned that incentives to implement new technology only exist when a company has a problem that it needs to solve. It is difficult to introduce new technology if a company does not require it to solve an existing problem first. The major driving force for change is economical above all else, followed by regulations and then social pressure. Flexibility is therefore moderate.

5.4.4 Intensity

All interviewees confirmed that compliance with regulations and constantly seeking opportunities for innovation is the norm for the pulp and paper industry. Practice therefore aligns with policy, especially because the government both passes stricter regulations and helps the industry innovate to comply. Intensity is therefore high.

5.5 Responsibilities and Resources

The fifth and final governance dimension concerns the distribution of power and information across the governance regime. Extent is high if all actors involved are aware of who is responsible for what and have the means to carry out these responsibilities. Coherence is high when responsibilities are validated by the main stakeholders, do not create conflicts, and facilitate cooperation among the actors involved. Flexibility is high when it is possible to combine different responsibilities and resources with little to no loss in accountability or transparency. Finally, intensity is high when the amount of resources allocated allow for the implementation of intended changes (Bressers et al., 2016).

5.5.1 Extent

The hierarchical nature of companies means that most responsibilities are clearly assigned, and the appropriate economic resources are allocated as needed. Clearly established communication pathways with government, academia, and technology providers provide access to knowledge, research and technological resources. PTM explained that yearly budgets determine which projects will be invested in. MG and AD added that governments also allocate resources to industries. MG also explained that top level company decisions determine if resources are utilized. Extent for responsibilities and resources is thus high.

5.5.2 Coherence

All interviewees confirmed that those at the top of the company hierarchy have the greatest responsibility. The greater the size and impact of a project, the more those at the top of the company must be involved. CMT explained that when a decision needs approval from the very top of the company, this takes a lot of time. Language barriers may also slow the process. AD added that it is sometimes difficult for researchers from external institutions to gain the trust of those at the bottom of the company hierarchy. This is because external actors such as researchers often communicate primarily with those higher in the hierarchy. According to AD, for example, mill technicians may not always fully trust external researchers and are sometimes reluctant to collaborate. Additionally, technicians are not always interested in research projects and prefer to implement quick, proven solutions when there is a problem. Responsibilities are therefore impacted to an extent by the strict nature of the hierarchy and the relationships it establishes, making coherence moderate.

5.5.3 Flexibility

PME explained that the implementation of any decision ultimately depends on shareholder strategy. Predefined goals along with technical and economic criteria must be followed. MG, AD, and BMT also mentioned that those at the top of the company hierarchy have the ultimate say on whether a decision is implemented. This leaves little room to pool assigned responsibilities, leaving flexibility low.

5.5.4 Intensity

All interviewees expressed that standard operating procedures ensure that resources are sufficiently allocated for the implementation of any decision. Top company management closely collaborates with government and academia to ensure this. Intensity is therefore high.

5.5 Results

The GAT assesses whether a governance regime is favorable or unfavorable towards the implementation of a given objective (Bressers et al., 2016). In this case the favorability of implementing new technology in the pulp and paper industry was assessed. The results are shown in Table 20.

Table 20: Favorability of implementing new technology in the pulp and paper industry

Governance Dimension	**Quality of the Governance Regime**			
	Extent	Coherence	Flexibility	Intensity
Levels and Scales	High	Moderate-High	Moderate-High	High
Actors and Networks	Moderate-Low	Moderate-High	High	High
Problem Perspectives and Goal Ambitions	High	High	High	High
Strategies and Instruments	High	High	Moderate	High
Responsibilities and Resources	High	Moderate	Low	High

The results show that the governance regime of the pulp and paper industry is indeed favorable to the implementation of new technology. This sheds light on the motivations, knowledge, and resources of the stakeholders involved. Across all five governance dimensions, most of the criteria are moderate to high. Problem perspectives and goal ambitions are especially favorable as they are high across all four evaluation criteria. The industry is generally motivated to seek technological improvements that align with the goals of both internal and external stakeholders, namely: increased production efficiency, reduced costs, and decreased environmental impacts. Only flexibility of responsibilities and resources is low, since most decision-making responsibilities reside at the top of the hierarchy. Facilitating more communication lines to the chief decision-makers could increase this flexibility.

All interviewees recognized the impact of environmental, legislative, and social pressures on the decision-making process. Actor cognitions are therefore also favorable to implementing new technology. However, some small improvements could be made to streamline this process. For example, actors at the bottom and top of the industry hierarchy could be involved more often. Currently, specific individuals and circumstances internal to a company decide which actors and networks are involved, making actor and network extent moderate-low. Opening communication lines across the actor network both internally and externally could facilitate the transmission of new ideas. As mentioned, this could also help the flexibility of responsibilities and resources by allowing more knowledge and ideas from other stakeholders to influence decisions. Collaboration could be more encouraged among internal engineers and technicians and external researchers. More international actors could be involved and more time could be saved if the language of international communication is standardized.

Many of the interviewees explained that trends are leaning towards greater international cooperation and expanded resources. Therefore, the resources that provide the main stakeholders with the capacity to act on their motivations and knowledge exist and are plentiful. However, it is interesting to note that this has been impacted somewhat by the global Covid-19 pandemic. As one interviewee mentioned, international funding is more difficult to obtain since countries are directing resources internally to manage the pandemic. It remains to be seen if the pulp and paper industry becomes more efficient and has less of an environmental impact in the future due to the implementation of new technology.

6. Conclusion

This research combined a technical approach with a social science approach to assess the implementation of new technology in the pulp and paper industry. This industry is a huge consumer of freshwater and energy resources, resulting in a large environmental footprint. Studies show that reducing environmental impacts by increasing water and energy efficiency in the pulp production process is paramount for companies in the industry to remain competitive and sustainable (Corcelli et al., 2018; Deshwal et al., 2019; Ghosal, 2015; Johakimu et al., 2016). The case of the Brazilian bleached kraft pulp mill in the Doce River basin provided an opportunity to investigate the implementation of UF systems in practice, which contributes to reduced water usage by permitting the reuse of process water (Chen et al., 2015). In this case, the need to reduce water usage was intensified by a mining disaster that occurred in 2015. This disaster severely impacted the quality of the Doce River, the mill's main freshwater resource.

This research answered two main research questions. The first concerns the technical, economic, and environmental benefits, risks, and impacts of implementing UF systems in three different scenarios. The results show that UF implementation can greatly benefit the Brazilian bleached kraft pulp mill by contributing to reduced freshwater intake and reduced COD, BOD, TSS, and turbidity values. In Scenario 1, the principle benefits of the UF system are water savings of 500 m^3/h, higher energy efficiency in the recovery boiler, and 20% sludge reduction from reduced color, COD and TSS concentrations. The options in Scenario 2 provide the opportunity to profit from the recovery of pulp fibers, as well as several water re-use options that also contribute to water savings of up to 500 m^3/h. The options in Scenario 3 are the simplest to implement with the lowest risks at the lowest costs, freeing up sand filters in the WTP for other uses and providing drinking water fit for human consumption. However, the third scenario does not provide many other environmental or technical benefits. It is therefore recommended to combine Scenario 3 with one of the options in Scenarios 1 and 2. The greatest water savings can be achieved if both Scenarios 1 and 2a are implemented, however this has the highest economic impact. Scenario 2b or 2c may be alternatively combined with Scenario 1 to balance water savings and financial costs.

It is important to note that both Scenarios 1 and 2 may contribute to increased electrical conductivity as well as calcium and potassium ion concentrations in the industrial water stream. This may impact recovery boilers as well as other processes in the mill sensitive to these changes. If the proper measures are taken, however, these risks appear low. Further modeling may also be necessary to account for unknown chemical reactions, which are outside the scope of this study. Reducing freshwater intake is an important goal for the pulp and paper industry, as this reduces environmental impacts and increases production efficiency (Ghosal, 2015; Tran & Vakkilainnen, 2016). Implementing UF in the Brazilian mill would contribute to reduced freshwater intake as well as reduced COD, TSS, turbidity, and color concentrations in the mill's wastewater discharges. This can greatly benefit the recovery process of the Doce River.

The second research question concerns the favorability of governance conditions in the pulp and paper industry towards the implementation of new technology. Previous research suggests that implementing new technology such as UF in the industry is difficult due to high upfront costs and limited access to financial resources (Adnan et al., 2010; Mänttäri et al., 2010; Song et al., 2015). However, increased pulp demand, the need to remain competitive, and stricter environmental regulations place pressure on companies in the industry to increase production efficiency (Ghosal, 2015; Kong et al., 2016). Governance assessment results suggest that the governance conditions surrounding the implementation of new technology in the pulp and paper industry are favorable. Overall, there is significant support from international governments, technology providers, and academia towards research, development, and implementation. Meanwhile, companies are indeed motivated to implement new technology in order to increase production efficiency and comply with government regulations as well as social and environmental pressures. Governance assessment results also show that companies in the industry are more likely to implement new technology if it has been previously applied in other mills or in other industries. Thus, implementing UF in the Brazilian mill could contribute to the application of UF in other mills, especially if the resources and knowledge are readily available and accessible.

Notably, there is evidence that resources and motivations may be impacted by global disasters, especially at the international level. Future studies may be therefore conducted to assess the impact of global crises such as the Covid-19 pandemic on industrial technology implementation. Additionally, future studies could monitor the quality of Doce River after UF has been implemented in the Brazilian kraft pulp mill to further assess the environmental impacts.

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Appendix I

BMT Preliminary Budgetary Assessment

	Capacity			System setup							OPEX		CAPEX
Scenario	Feed capacity	Permeate capacity	Recovery	Technology	Design flux (LMH)	# of skids single loop	# of skids double loop	# of modules / loop	Total number of modules	# of CIP stations	kWh/m3	Energy (€)	Total investment (€)
1	27600	24840	90%	B-Smart ECO	77	1	12	8	200	2	0.8	€725,328	€5,105,500
2a	27600	24840	90%	B-Smart ECO	77	1	12	8	200	2	0.8	€725,328	€5,105,500
2b	27024	24321.6	90%	B-Smart ECO	75	1	12	8	200	2	0.8	€710,191	€5,105,500
2c	15480	13932	90%	B-Smart ECO	77	0	7	8	112	2	0.8	€406,814	€2,851,500
3a	1320	1188	90%	B-Smart Performance	92	0	1	4	8	1	1.6	€69,379	€340,000
3b	1320	1188	90%	B-Smart ECO	74	0	1	5	10	1	0.8	€34,690	€419,500
Remarks													
NOTE: This overview is based on a preliminary design and to be used for budgetary approaches only.													

Appendix II

GAT Interview Questions

Levels and Scales

1. Internally, what administrative levels are generally involved in the decision-making process to upgrade the production process or install new technology? Are any external levels involved as well?

2. Are these decisions made at different internal and external levels independently, or must there be communication at all levels before a final decision is made? Is it generally easy or difficult to communicate across different levels?

3. Is there anything that could be improved regarding the communication involved across different internal and external levels to reach a final decision?

Actors and Networks

4. Who is generally involved in the decision-making process. Who are the people (teams, organizations, etc.) you most communicate with? Is it difficult or easy to get involved?

5. Generally, are there any conflicts that you have noticed among these different groups? If there are, how do these conflicts generally get settled?

6. Does any one group seem to have more influence in the decision-making process? If so, does this ever vary or is it static?

Problem perspectives and goal ambitions

7. How do you view the process of implementing new technology or changing/upgrading the production process in the pulp and paper industry? Is the process generally dynamic or bound by set procedures and restrictions?

8. What are the main factors driving these decisions? Would you say standard procedures encourage or discourage change?

9. Do you think these factors will change in the foreseeable future? Are there opportunities to reassess goals or problems in the decision-making process?

Strategies and instruments

10. Are there any policies or incentives in place that make it easier to adopt new technology? Are there any conflicts that come to mind regarding these policies or incentives?

11. Are there any laws that factor in to this decision-making process? What provides the most incentive to make changes?

12. Is this likely to change in the foreseeable future? Why or why not?

Responsibilities and resources

13. Who is ultimately responsible for the decision to upgrade or change the production process? Is this responsibility clear? Are there any struggles or conflicts created by this responsibility?

14. How are resources generally obtained and allocated towards this objective? Is this a static or a dynamic process?

15. What determines if the decision is ultimately implemented? Is there a standard procedure or does this vary on a case-by-case basis?