

Deinking sludge waste management

A feasibility study of a novel demineralisation process of deinking sludge with the objective of reducing waste material.

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This document provides an overview of the research as designed by L.T. Kloekke for the Master Research Project for MSc Industrial Engineering and Management at the University of Groningen. The research entails a technical and economic feasibility study on a novel sludge waste management concept provided by the Centre of Competence of Paper and Board in Arnhem. The main objective of the introduction of this concept is the elimination of a specific component in waste streams of the paper recycling industry. Through this purification process, the remaining waste stream is perhaps even eligible for reuse. The overall concept is placed in a business context by designing several basic conceptual plants and including an economic feasibility study of these potential methods of processing.

List of abbreviations

°SR	-	<i>Degrees Schopper-Riegler</i>
A	-	<i>Sample 1 of processed deinking sludge, dewatered.</i>
C	-	<i>Sample 2 of processed deinking sludge, dewatered.</i>
BBC	-	<i>Best Case</i>
BC	-	<i>Best Best Case</i>
CaCO ₃	-	<i>Calcium carbonate</i>
CaO	-	<i>Calcium oxide</i>
CaCl ₂	-	<i>Calcium chloride</i>
CE-index/CEPCI	-	<i>Chemical Engineering Plant Cost Index</i>
CO ₂	-	<i>Carbon dioxide</i>
CPVC	-	<i>Chlorinated polyvinyl chloride</i>
DAF	-	<i>Dissolved Air Flotation</i>
DC	-	<i>Dry content</i>
EU	-	<i>European Union</i>
EURAL	-	<i>Europese Afvalstoffen Lijst</i>
EWG	-	<i>European Working Group</i>
HCl	-	<i>Hydrochloric</i>
ISBL	-	<i>Inside Battery Limits</i>
CCPB	-	<i>Centre of Competence of Paper and Board</i>
NIWO	-	<i>Nationale en Internationale Wegvervoer Organisatie</i>
OSBL	-	<i>Off-site Battery Limits</i>
P&ID	-	<i>Pipeline and Instrumentation Diagram</i>
PM7	-	<i>Paper pulp retrieved from Paper Machine 7 at ESKA Hoogezand.</i>
PM7/HCl	-	<i>Paper pulp retrieved from PM7 at ESKA Hoogezand, processed with hydrochloric acid.</i>
PVC	-	<i>Polyvinyl chloride</i>
RUG	-	<i>Rijksuniversiteit Groningen</i>
ROI	-	<i>Return On Investment</i>
SHE	-	<i>Safety, Health and Environment</i>
USGC	-	<i>United State Gulf Coast</i>
VIHB	-	<i>Vervoerders, inzamelaars, handelaren en bemiddelaars</i>
VNP	-	<i>Koninklijke Vereniging van Nederlandse Papier- en kartonfabrieken</i>
VROM	-	<i>Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer</i>
WC	-	<i>Worst Case</i>
WRV	-	<i>Water Retention Value</i>
Wt %	-	<i>Weight percentage</i>
WWC	-	<i>Worst Worst Case</i>

List of figures

Figure 1 Generic overview of the main process units of a paper recycling mill.....	14
Figure 2 A schematic arrangement of the Ahlstrom flotation cell used for deinking sludge material during the paper recycling process (Kemper, 1999).....	15
Figure 3 A typical flow diagram of a dissolved air flotation process, where air is injected from below. Unwanted particles attach to the air bubbles, and rise to the surface of the suspension, where it forms a foam layer. This foam layer can be mechanically removed (WaterIcon, 2012).	16
Figure 4 Overview of the main process steps production process of CPVC at Lubrizol. PVC is suspended in a slurry, and reacts with chlorine gas under UV-light. HCl acid is stripped from the CPVC through centrifuges, and the CPVC is finally dried and stored for transport.	17
Figure 5 Average reaction times in terms of pH for each sludge sample at 95% moisture content, ambient conditions, and laminar flow with no stagnant zones during the neutralisation reaction on lab scale (~100mL). Measurements start when HCl acid is added to suspended sludge sample and end at pH=6.	26
Figure 6 Average pH course for each sludge sample T=50 degrees Celsius, 95% moisture content and laminar flow without stagnant zones on lab scale (~100 mL).	26
Figure 7 Two average progressive values of pH of sample B1, under ambient conditions. One of the two is the average pH where air flow is induced at pH =5. This indicates the impact of dissolved CO2.....	28
Figure 8 The equilibrium balance of carbonates across pH, indicating the production of carbonic acid from around pH =4 (O. Pedersen, 2013).....	28
Figure 9 Block diagram demineralisation process hydrochloric acid and deinking sludge.	38
Figure 10 Overview of the equipment list of the base design, 20 metric ton/hr HCl 8wt%. This includes the purchasing cost of each piece of equipment according to the framework of Sinnott & Towler.	41
Figure 11 Overview of the calculations of the total investment cost of the base design, 20 metric ton/hr HCl 8wt%. This includes the purchasing cost of each piece of equipment according to the framework of Sinnott & Towler.	42
Figure 12 P&ID Suspension phase, created in MS Visio.....	61
Figure 13 PI&D Neutralisation phase, created in MS Visio.	61
Figure 14 P&ID Dewatering phase, created in MS Visio.	62
Figure 15 P&ID Neutralisation Air flow, created in MS Visio.	62
Figure 16 P&ID Neutralisation Vacuum, created in MS Visio.....	63
Figure 17 P&ID Neutralisation Water Spray, created in MS Visio.	63
Figure 18 P&ID Neutralisation phase, created in MS Visio.	64
Figure 19 Process Flow Diagram Paper mill Variant I, generated in Aspen Plus 8.	64
Figure 20 Process Flow Diagram Variant II, generated in Aspen Plus 8.	65
Figure 21 P&ID overview Base Design, created in MS Visio.....	67
Figure 22 Process Flow Diagram Base Design, 20 ton/hr HCl 8wt%, generated in Aspen Plus 8.	67
Figure 23 P&ID Water spray design.	68
Figure 24 Process Flow Diagram water spray, 20 ton/hr HCl 8wt%, generated in Aspen Plus 8.	69
Figure 25 P&ID Air flow design, created in MS Visio.....	71
Figure 26 Process Flow Diagram Air flow, 20 ton/hr HCl 8wt%.	71
Figure 27 P&ID Vacuum design.	73
Figure 28 Process Flow Diagram Vacuum design, 20 ton/hr HCl 8wt%..	73

List of tables

Table 1 Overview of the generic composition of deinking sludge waste in weight percentages as provided by the CCPB.	11
Table 2 Average conversion of calcium carbonate, where only sample PM7 conversion goal was set at 90% (A and C were set at $X_A = 100\%$) at ambient conditions. Samples were washed and dewatered before testing. Average conversion for samples A & C is 98.6%.	25
Table 3 Drainability of two sludge samples in °SR (Adjusted).	30
Table 4 Overview Water Retention Values of four samples of paper pulp. Each treated sample is compared to the current standard of PM7. Any higher deviation regarding water retention can be regarded negative in terms of the rate of papermaking.	31
Table 5 Overview results of TABER Abrasion Test displaying the loss in mass after 30 rotations on the TABER device.	31
Table 6 Average particle size distribution of processed sludge of both samples C1 and A1, performed in duplo.	33
Table 7 Overview of differences in scenarios by varying concentrations of main components of feedstock. Resulting mass equivalencies for required feedstock and output material of the neutralisation process are described per metric ton of HCl acid solution in kg.	36
Table 8 Estimated initial capital investments for each scenario based on the framework of Sinnott and Towler and the designs as portrayed in section 10.4 in the appendix.	40
Table 9 Projected Net Return on Investment for each design and scenario based on a period of fifteen years with an annual inflation of two percent compared to the current standards and practices.	43
Table 10 Estimated break-even prices for processed sludge material per metric ton for each scenario. This value has to be attained in order to break even the introduction of the demineralisation process compared to the current situation.	43
Table 11 Overview composition input sludge for demineralisation process (Maat & Rexwinkel, 2012).	44
Table 12 Overview annual cost of waste management for Variant I & II. The cost per year is the potential margin which can be gained by the introduction of the demineralisation process.	44
Table 13 Overview annual cost of neutralisation of HCl acid which is required for the demineralisation process for Variant I&II. The cost per year is the potential margin which can be gained by the introduction of the demineralisation process.	45
Table 14 Annual cost of sludge waste management versus expected cost of sludge waste management for Variant I&II.	45
Table 15 Approximate distance covered for which required HCl acid can be transported from Lubrizol within expected cost savings in kilometres for each variant.	45
Table 16 Projected initial capital investment required for the introduction of a demineralisation process for Variant I & II based on the framework of Sinnott and Towler.	45
Table 17 Expected ROI for each variant and scenario over a period of fifteen years with an average inflation of two percent compared to the current situation.	46
Table 18 Estimated required break-even prices of output sludge material per metric ton for each scenario of both Variant I & II. This would be the value of output sludge to break even the cost of introducing the demineralisation process at a paper recycling mill compared to the current situation.	46
Table 19 Overview properties deinking sludge samples (A and B), and a sample collected from a DAF unit (C). Each sample is stored at 4-7°C in an airtight container.	56
Table 20 Average produced CO ₂ in litres in relation to 100G of sludge sample (dry content).	57
Table 21 Mass balance base design 1 ton/hr HCl 8wt%, translated from Aspen Plus 8.	58
Table 22 Mass balance neutralisation phase base design, translated from Aspen Plus 8.	59
Table 23 Overview sizing main process equipment 1-20 metric ton per hour of hydrochloric acid 8wt%.	60
Table 24 Overview mass balance Variant I, generated in Aspen Plus 8.	65
Table 25 Overview mass balance variant II, generated in Aspen Plus 8.	66
Table 26 Mass balance Base design, 20 ton/hr. HCl 8wt% , generated in Aspen Plus 8.	68
Table 27 Mass balance Water spray design generated in Aspen Plus 8.	70
Table 28 Mass balance Air flow design, 20 ton/hr HCl 8wt%.	72
Table 29 Mass balance Vacuum design, 20 ton/hr HCl 8wt%.	74
Table 30 Overview ISBL estimation based on framework of Lang.	78
Table 31 Overview framework Sinnott & Towler for calculating ISBL/OSBL.	79
Table 32 ISBL of each design and scenario according to the framework of Sinnott and Towler for 20 metric ton per hour HCl solution.	79
Table 33 Overview ISB + OSBL of each design in each scenario according to framework Sinnott and Towler.	79

Table 34 Adjusted capital investment for each design and scenario according to CEPCI index.	80
Table 35 Adjusted initial capital investment based on location factor of the Netherland (=1.19) according to Sinnot and Towler.	80
Table 36 Adjusted initial capital investments for each design and scenario to Euros.	80
Table 37 Overview fixed and variable capital costs of each design and scenario based on the framework of Sinnot and Towler.	81
Table 38 Overview initial capital investment required for Variant I & II according to the framework of Sinnot and Towler. .	81
Table 39 Estimated variable cost of Variant I & II according to the framework of Sinnot and Towler.	81
Table 40 Estimated fixed capital cost of Variant I & II according to the framework of Sinnot and Towler.	81

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Table of Contents

List of abbreviations	2
List of figures	3
List of tables	4
Table of Contents	6
Management summary	8
1.0. Problem Definition	9
1.1. Incentives Project	9
1.2. Waste Origins	10
1.3. Management Question	12
1.4. Overview Build-up Report	13
2.0. Emergence of waste	14
2.1. Paper Recycling Process	14
2.2. Flotation Processes	15
2.3. Lubrizol Advanced Materials Resin B.V.	17
2.4. Stakeholder Analysis	18
3.0. Research Objective	20
3.1. Research Approach	21
4.0. Demineralisation process	24
4.1. Theory & Experimentation	24
4.2. Feedstock	29
4.3. Products	29
4.4. Potential Cost Savings	34
5.0. Cost Estimation – Scenarios	35
5.1. Scenarios	35
5.2. Design options	36
5.3. Lubrizol	39
5.4. Paper mill	44
6.0. Conclusions	47
7.0. Discussion	49
7.1. Final products and waste	49
7.2. Feed products	50
8.0. Further Research	52
9.0. Bibliography	53

10.0.	Appendices	55
10.1.	Experiments Lubrizol Advanced Materials & Resins	55
10.2.	Base Design & Simulation.....	57
10.3.	P&IDs	61
10.4.	Overview Simulations Aspen Plus	64
10.5.	Assumptions Economic Model	75
10.6.	Complementary Process Design.....	76
10.7.	Health & Safety.....	82
10.8.	Utility needs and costs	85

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Management summary

This document describes a feasibility study regarding the removal of mineral fillers, specifically calcium carbonate, from deinking sludge generated from paper recycling mills through a neutralisation reaction with specific concentrated hydrochloric acid. With the removal of mineral fillers, the sludge material has the unverified potential of being reused in the papermaking process. The hydrochloric acid is produced by a PVC-processing plant as a by-product, and is considered waste. The goal of this process is to lower the overall mass flow of waste material of paper recycling mills and a PVC processing plant by combining waste streams. The chosen method of this exploratory research to verifying the viability of such a process is done via a rudimentary case study. This case study concerns the neutralisation of HCl acid solution onsite, meaning sludge waste material is to be transported and assumed to be in sufficient supply. Several basic concepts of processing are created in order to overcome initial process shortcomings, and are further analysed to deduce their economic feasibility. In short, it would be possible to reduce the amount of mineral filler by a significant margin, but the costs of current disposal techniques are too low to cover the initial capital investment required for such an operation. The concept of reusing sludge material of papermaking was deemed improbable.

A waste stream originating from the deinking process at a paper recycling mill is currently incinerated for a significant fee. This fee is estimated to be approximately 25 euros per metric ton on average. With a national production of more than 100,000 tons of waste, the paper recycling industry seeks to find new methods in waste management in order to reduce overall incurred cost. By reducing the mass flow of this waste stream, it is possible to reduce the total cost of processing waste. One of the solid components of the deinking sludge stream is calcium carbonate, which is a mineral filler component. One option is to dissolve calcium carbonate with an acid. The acid used for this research is from a waste HCl acid stream from Lubrizol Advanced Materials Resin B.V. in Delfzijl. Lubrizol produces, neutralises, and discards roughly 20 metric tons of hydrochloric acid 8wt% per hour.

The demineralisation process itself is divided into three basic sub processes. First stage is the adding of water to deinking sludge in order to create a suspension with 5wt% dry content. The next phase applies hydrochloric acid to this suspension, dissolving solid calcium carbonate and producing calcium chloride salts. The last process entails dewatering the demineralised sludge in order to create a material of the same consistency as the feedstock and separate the by-product, which is brine, for disposal. The reaction time of hydrochloric acid and calcium carbonate was monitored through pH levels and initially the reaction time was considered too extensive. Slight optimisation was established, although not always practical. For this exploratory research, this proves sufficient however, as further optimisation of the process can be developed in further stages, assuming that this research would indicate a positive viability of the overall process.

Even with an estimated shorter processing time, the initial capital investment in combination with the expected fixed annual capital cost seems stupendous. The estimated net return on investment would, under the current conditions as discussed in this report, be -44% at the most. For indicative purposes, the required breakeven price of the output of the demineralisation process should be more than €284,- per metric ton. This would be far from realistic.

1.0. Problem Definition

In the Netherlands, there are 22 paper mills responsible for the annual production of 2.6 million tons of paper and board of any grade and quantity (VNP, 2015). This can range from packaging material, to hygienic paper, to high quality graphic paper. Each paper mill differs in the type of paper that is produced and its quantity.

The amount of paper which is recycled in the Netherlands is roughly 82% of the total national production. This utilisation rate is in fact one of the highest in the world, which is convenient to say the least, as raw material, virgin fibres, for paper are not widely locally available in the Netherlands. However, the current overall recycling process of recovered paper does have some drawbacks. Before fibres can be reused, contaminants attached to the cellulose fibres need to be removed in order to create qualitatively sound paper. The final disposal of the generated waste stream usually is, unfortunately for a sizeable fee, incineration. Through incineration, energy can be recovered and the remaining fly ash can be utilized as, for example, concrete filler. According to the Centre of Competence of Paper and Board (CCPB) in Arnhem, an authority in terms of research and development in the Dutch paper industry, more than 100,000 tons of sludge waste from the paper industry is incinerated each year.

In short, this report will discuss the feasibility of a sludge treatment concept to reduce the quantity of this paper waste stream. This approach was initiated by the CCPB. The CCPB suggests a refinement process to reduce overall waste in the paper recycling industry involving an acid. This particular acid should ideally be a strong but inexpensive acid. A suitable source of this acid, the CCPB already identified for this research. This is hydrochloric acid currently regarded as a waste product by extra-chlorinated polyvinylchloride (CPVC) producer Lubrizol Advanced Materials Resins B.V. in Delfzijl, Groningen. Since this acid is considered a waste product, Lubrizol has expenses in waste management. The goal of Lubrizol is to adhere any form of value to counteract these costs. Therefore, as in the classical case of two birds and one stone, it may be possible to reduce the waste production from two entirely different industries through synergy, with on one hand, the paper recycling industry, and on the other, a specialty chemical producer.

The goal of this research is to investigate the feasibility of reducing the overall mass flow of paper waste by using this acid. This is done by studying both the technical and financial aspects of the proposed business case. This chapter will continue with establishing incentives of the CCPB to reduce the waste stream of the paper recycling industry before continuing with a brief summary of the origins of both the paper and acid waste stream. Furthermore, a problem definition is provided, and the related management question is stated. Lastly, a brief overview of the remaining components of this report is provided in this chapter.

1.1. Incentives Project

Besides the potential cost reduction in waste management for both paper mills involved in recycling recovered paper, and the producer of hydrochloric acid, Lubrizol, there are several other incentives for the treatment of waste sludge material from the perspective of the paper recycling industry.

The project is initiated due to several stimuli which have become apparent over the last decade. First and foremost is achieving environmental goals set by the branch organization Koninklijke Vereniging van Nederlandse Papier- en kartonfabrieken or VNP.

The first of these goals is the introduction of 100% closed biobased loops aimed for the total reuse of every component produced by the paper and board industry (VNP, 2015). To achieve 100% closed loops within the paper industry, waste streams must be zero. If possible, these waste streams must be rerouted into the main production process of paper. Although producing absolutely zero waste is not yet achievable or practical, as ink particles would have to be recyclable as well, thus always resulting in a small waste stream. But, a substantial step could be taken by the partial elimination of sludge through the proposed concept. An overall cost reduction regarding waste management for the paper recycling industry can be seen as the prerequisite for the introduction of new waste reduction techniques. It would be an admirable feat to lessen the negative impact on the environment and becoming more sustainable for any paper recycling mill, but any investment made should also be sustainable in a business sense.

More broad objectives can be generated under the realisation that the Dutch paper and board industry is suffering under the international market. Over the last 15 years, an average decline in overall annual revenue of 0.5% annually was established (VNP, 2015). This was also partly due to the decline of domestic demand, but this was counteracted by increased exports in high quality papers. Although some future prognoses have indicated a slight increase in the domestic consumption of paper, uncertainty rises as the number of paper mills in the Netherlands are still declining. An overall cost reduction may improve competitiveness of a Dutch paper recycling mill which are dealing with substantial cost due to the emergence of sludge waste.

1.2. Waste Origins

The objective of the recycling process of paper and board is to reclaim fibres, whilst upholding paper quality in terms of both mechanical and optical properties. As the range of quality of recovered paper is substantial, all used paper undergoes a rigorous recycling process. Each paper recycling facility upholds their own process design, depending on the final product (Göttsching & Pakarinen, 2000). This can range from the production of high-grade tissue paper to newspaper quality. The results are differences in starting material or resources and the level of efficiency of process equipment.

At certain points throughout the paper recycling process, waste emerges in the form of sludge. The differences in end-use translate to the composition of the sludge. According to the CCPB, over 100,000 tons of sludge waste from the paper industry is incinerated each year. Quantity and composition of waste material vary across recovered paper grades and the paper produced. Composition of sludge waste also varies at different stages of the paper recycling process. Sludge waste material is mainly recovered from flotation deinking, the cleaning of process water from wash deinking, and the clarification and biological treatment of wastewater.

According to the CCPB, besides incineration, sludge material has the potential to be used for a variety of different purposes. Examples are as composite filler material, or by retrieving biobased products through pyrolysis. Other options for sludge waste management are the prevention of the emergence of waste itself. This can be partially achieved by reducing the overall mass flow of sludge waste streams.

Table 1 Overview of the generic composition of deinking sludge waste in weight percentages as provided by the CCPB.

	Average wt%
Water	40%
Dry content	60%
○ Mineral filler	~60%
○ Fibres and fines	~40%
○ Process/functional chemicals, heavy metals, other contaminants	<1%

This project will mainly focus on paper sludge generated by the deinking process. Deinking sludge contains mostly water, a small amount of heavy metals, some functional and process chemicals, a decent amount of fibres and fines, and lastly a relatively large portion of mineral fillers. For this reason, deinking sludge is the primary focus of this research. The mineral fillers were added at the production stage of recovered paper to improve its mechanical and optical properties. An overview of the generic contents of a deinking sludge sample in weight percentages is provided in table 1. If the concept of treating deinking sludge is found viable, the introduction of demineralisation to other paper waste streams might also be applicable. A sample from a waste water treatment installation from a paper recycling mill is incorporated to indicate its potential regarding treatment with hydrochloric acid.

As deinking sludge waste contains a large portion of fillers, also in respect to other paper sludge waste material, if it is possible to remove these fillers, a stream containing mostly water, fibres, and residues of ink is left behind. This research focuses on the aspect of reducing the quantity of deinking sludge waste. And due to the presence of fibres in processed deinking sludge, efforts can be made to recover the remaining, potentially valuable, material. The removal of filler material could also benefit other sludge waste streams of the paper recycling process, but focus is laid on deinking sludge to verify the potential of reducing overall waste through the removal of mineral fillers.

A large portion of fillers comes in the form of calcium carbonate. Calcium carbonate is used, besides as filler, mainly for its optical properties and the amount of CaCO_3 in most recovered paper is growing (Göttsching & Pakarinen, 2000). Calcium carbonate can be present in the following configurations in regards to paper fibre:

- 1) As a coating on the surface of a sheet of paper.
- 2) In between the fibres
- 3) Inside of the fibre

According to the CCPB, calcium carbonate presented in the first two forms can be removed by current separation methods, whereas the latter configuration is rather difficult to remove. In theory, an acid can react with calcium carbonate in any of these configurations. In the past, using an acid to remove the presence of alkaline mineral fillers was investigated, but quickly abandoned due to the enormous costs accompanying the use and transport of highly concentrated acids. The concept of neutralising calcium carbonate was given new life as a partnership was sought after where acid could be purchased cheaply, leaving transport cost as perhaps a vital variable.

Luckily, a third-party supplier of such an acid offered their assistance in this research. Lubrizol Advanced Materials Resins B.V. have a waste acid stream, which now is neutralised and the resulting

products are discarded which overall costs of a little more than 9 euros per metric ton of HCl solution. The hydrochloric acid produced by Lubrizol could be an ideal material for the elimination of deinking sludge waste, as it is quite strong and could be relatively cheap, as CaO has to be purchased for its neutralisation and, ultimately, its elimination. One of the main reasons for using the acid from Lubrizol would be the low cost, as it entails a waste product, and it has a relatively large availability. A minor drawback of incorporating this acid is that Lubrizol uses calcium oxide as a neutralisation agent which is purchased from a supplier. Thus, any CO₂ released with this process would be additional greenhouse gas emissions. However, for the production of CaO, CO₂ is generated as well, resulting in a zero net increase in the production of carbon dioxide across the entire production chain.

1.3. Management Question

The problem of paper waste management is one of the many issues currently investigated by the CCPB in Arnhem. The main goal of the CCPB is to generate and/or disclose knowledge to the paper and board industry, and it was the CCPB who indicated the large portion of mineral fillers which is present in paper sludge. If mineral fillers would to be removed from the deinking sludge, at least a significant portion could be prevented from incineration, depending on the source and the effectiveness of the used method. The remaining fibres could even possibly be rerouted to the initial suspension phase of the recycling process, reusing those same fibres again for the production of paper.

The initial concept for this research designed by the CCPB focuses on finding a feasible method or process of separating components and to reduce the final volume of waste. This could be achieved by thus focussing on the alkaline properties of one of its larger components, calcium carbonate. The following management question can describe the problem stated by the CCPB:

'Would it be feasible to separate and remove calcium carbonate from deinking sludge and thus reduce the mass flow of deinking sludge in terms of dry content through a neutralisation reaction, using hydrochloric acid as produced by Lubrizol?'

Furthermore, in addition to the reduction of the mass flow in terms of dry content of incinerated sludge waste, it might be possible to recover the remaining fibres. These fibres might be suitable for the production of paper. The fibres suspended in deinking sludge cannot be utilized without any treatment, as the high mineral filler content heavily impacts the binding capacity and thus the quality of these fibres in a negative manner. Simply, when fibres are substituted by fillers, strength properties will decline also because there are fewer fibres in the network per unit volume (Neimo, Yhdistys, & Industry, 1999).

By exposing sludge material to an acid, it could be possible that the binding capacity of cellulose fibres may be restored through the removal of mineral filler. On the other hand, it is difficult to determine the effects of the acidic environment on the cellulose structures of the fibres through acid hydrolysis. Overall, it is true that potential value to the product stream can provide additional cost saving and even revenue, thus having a massive positive influence of the economic feasibility of this concept. But this requires a meticulous economic analysis of the proposed new situation. The possible end use(r)s for these fibres must be found through determining crucial properties. The

mechanical properties of paper composed from demineralised fibres will define the value of the product stream.

The overall goal of the CCPB can ultimately be divided into the following objectives;

1. Remove CaCO₃ from industrial sludge
2. Through neutralising acid waste, possibly
3. Reclaiming fibres from industrial sludge

1.4. Overview Build-up Report

The report will continue with a detailed description of the emergence of the relevant waste materials before continuing with a breakdown of the overall research objective. The third chapter will mainly concerns itself with the proposed process of demineralising deinking sludge, whereas the fourth chapter provides an overview of different scenarios and possible designs. The fifth chapter provides an estimation of the required capital for each proposed scenario and design. The report is finalised with an overview of the conclusions based on these cost estimations.

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2.0. Emergence of waste

In this chapter, both a brief description of the current situation regarding waste streams at paper recycling mills is provided, as well as additional incentives from the CCPB. The first section will discuss the relevant processes from which waste material originates in more detail. Starting with an overview of the generic paper recycling process, a step-by-step description will be provided on why a specific type of paper sludge is chosen, and how this waste stream is generated. Lastly, a short description of the production process at Lubrizol Advanced Materials and Resin is provided, clarifying how their acid waste stream is generated.

2.1. Paper Recycling Process

Recycling begins with municipalities collecting otherwise paper waste under the general European Waste Guideline 91/156 EWG of 1991 and the EU Packaging Directive 94/62 EG of 1994 (Göttsching & Pakarinen, 2000). These guidelines are there to prevent packaging waste, and reuse packaging material under the assumption that polluters reimburse the municipalities.

Göttsching and Pakarinen provide insight on the difficulties regarding the processing of recovered paper. 'The technology of recycling fibres is more complex than that of virgin fibres because the composition of the raw materials precludes any defined quality equivalence to primary pulps. Besides contaminants, recovered paper always contains some fillers and coating pigments that can vary according to type and composition. Due to the technical outlay and stock losses involved, complete removal of these components is not cost-effective' (Göttsching & Pakarinen, 2000). Separation techniques in the recycling process of paper to remove a significant portion, but as a trade-off, some valuable components are removed as well.

The recycling process of paper can be broken into the several main process steps as displayed in figure 1 below (Göttsching & Pakarinen, 2000).



Figure 1 Generic overview of the main process units of a paper recycling mill.

One of the main process units of paper recycling are separation processes. Separation processes vary according to the type and quantities of contaminants for removal. The same processing units can be used multiple times in a stock preparation line in order to provide better effectiveness and increased reliability depending on the type and quantity of contaminants. Besides screening, washing, and centrifugal cleaning, the process of flotation is one of the major separation processes. Flotation is based on surface properties and the size of particles. It is able to remove hydrophobic particles with great efficiency over a wide size range. One of the purposes where flotation excels is the deinking of paper fibres.

2.2. Flotation Processes

Flotation is the most commonly separation process used due to its high efficiency, meaning a high yield of fibres and a low amount of rejects. However, a large factor regarding efficiency are the properties of the ink and paper quality used (Göttsching & Pakarinen, 2000).

The basic principle of the flotation process is the removal of hydrophobic particles through air injection to which these particles can attach. The air bubbles move towards the surface of the suspension where it forms a foam layer which can be removed mechanically. Hydrophilic particles can be removed as well through the addition of surfactants. Flotation is based on probability mechanism, where different stages of the process each have their own probability. First, air bubbles must come into contact with the particles which are to be removed. These particles then have to attach themselves properly to these bubbles, and then rise to the surface as a stable particle-bubble aggregate. Lastly, it must undergo removal with the foam.

The flotation process can be used for the deinking of recovered paper. The purpose of deinking is thus to remove ink and other substances that might affect the quality in terms of dewatering and strength properties of the final paper product or the papermaking process. In a deinking process, the ink should first be detached from the cellulose fibre. A flotation process, as discussed before, can then separate the ink particles from the fibres.

Various flotation deinking cells can be utilised for the processing of recovered paper. Although all cells are based on the flotation principle, primary differences are concerned between aeration systems, where dynamic or static mixer can be used. A schematic example of an Ahlstrom flotation cell is displayed below.

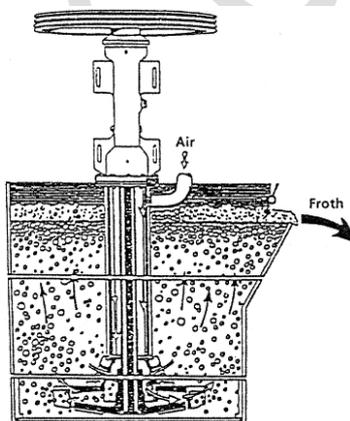


Figure 2 A schematic arrangement of the Ahlstrom flotation cell used for deinking sludge material during the paper recycling process (Kemper, 1999).

Besides ink particles, the resulting sludge contains fibres, fines and ash (mineral fillers and coating pigments). Flotation targets these fillers and pigments to some extent. This means that the ash content is fairly high.

Currently, deinking sludge is a waste product due to its high content of ash. The sludge is dewatered down from 0.1wt% dry content to about 60wt%. After which, it is transported and incinerated for a certain fee. This fee is estimated to be around €25,- per metric ton of sludge waste of average composition.

For the treatment of waste water in a paper recycling mill, another flotation based process is utilised. Dissolved air flotation (DAF) is a water clarification process. It is a technology which allows for effective treatment of large water volumes. Anionic particles and fine material agglomerate into more treatable clusters through the addition of flocculants. The agglomerates can be disposed in clarification tanks by flotation. Different flocculants can be used to minimize costs, as well as dual dosing these flocculants. Salt additives such as alum or poly-alum chloride with polymer and inorganic adsorbents such as bentonite are possible.

Before entering the clarification tank, untreated water or the corresponding amount of clarified water is saturated with air after raising the pressure to about 7 bar. No air bubbles may remain after aeration since these bubbles would collect smaller bubbles and reduce flotation efficiency. After depressurizing, miniscule air bubbles within a limited size range will appear. Then, after mixing the aerated water with unsettled process water, agglomerates already formed will adhere to the air bubbles and rise to the surface. This will form a layer of sludge material which can be removed mechanically with for example a paddle. Below is a typical flow diagram of a DAF process. The goal of DAF is water clarification, processing waste water in order to remove as much solid particles as possible. Usually, the resulting sludge material is rerouted into the main process stream. This research additionally investigates the slight possibility of using hydrochloric acid to clean the sludge produced by DAF to increase the potential value, or loss in value, of the main process stream by adding this sludge material. If the concept of removing mineral fillers with hydrochloric acid can be indicated as potentially viable for deinking sludge, it might be possible to introduce this concept to DAF as well.

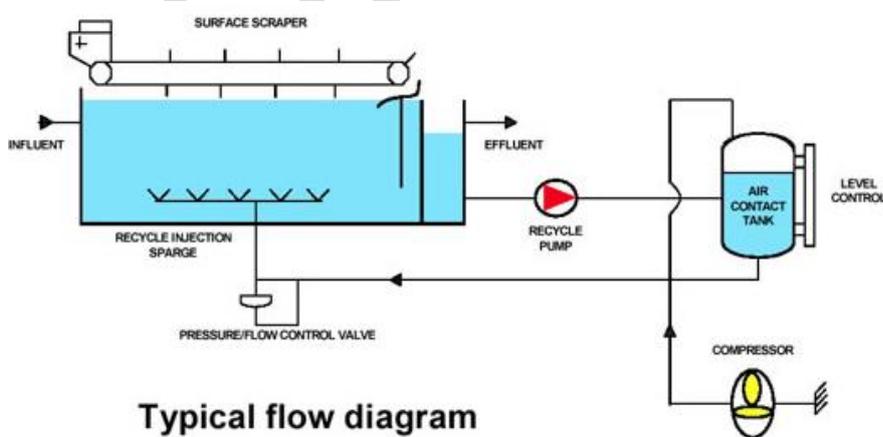
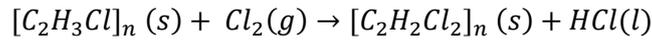


Figure 3 A typical flow diagram of a dissolved air flotation process, where air is injected from below. Unwanted particles attach to the air bubbles, and rise to the surface of the suspension, where it forms a foam layer. This foam layer can be mechanically removed (Watericon, 2012).

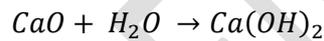
2.3. Lubrizol Advanced Materials Resin B.V.

Lubrizol Advanced Materials Resin B.V. in Delfzijl produces CPVC material for the production of high quality pipelines which are a cheap alternative to steel or copper pipelines (Lubrizol, 2017). Examples for uses are sprinkler systems, water conduits in buildings, and industrial pipe systems.

The general production reaction at Lubrizol is as follows:



PVC is mixed with water to create a slurry, which is then batch-mixed with chlorine in UV-exposed reactors. CPVC is produced by adding an additional chlorine atom to the standard PVC molecule under the influence of the ultraviolet light. The reaction thus splits a proton from the PVC chain, which reacts with the remaining chlorine atom in order to form hydrochloric acid. From a storage tank, the slurry is then centrifuged to separate the HCl acid. After this step, the slurry is neutralized, stripped and again centrifuged, before being dried and stored into silos. The end products are CPVC and HCl (8wt%), the latter being considered a waste product. This concentration is too low for any commercial use, and therefore the acid is neutralised by using calcium oxide according to the following reaction scheme.



The resulting brine, containing $CaCl_2$, is transported to sea.

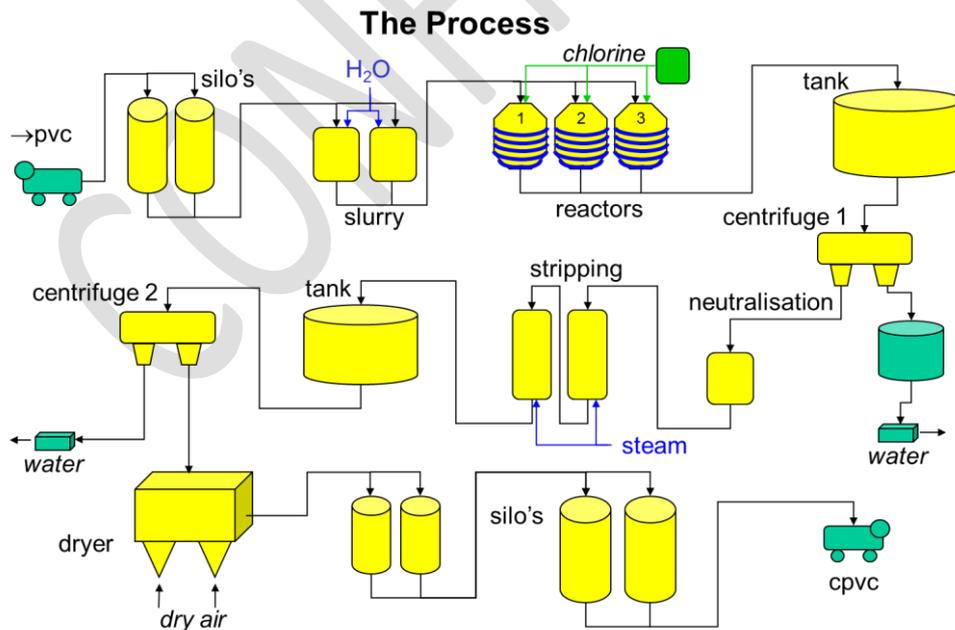


Figure 4 Overview of the main process steps production process of CPVC at Lubrizol. PVC is suspended in a slurry, and reacts with chlorine gas under UV-light. HCl acid is stripped from the CPVC through centrifuges, and the CPVC is finally dried and stored for transport.

The onsite storage of HCl acid at concentrations around 8-9wt% is in silo TK8F. After neutralisation and the discharge of water and salts to sea, any remaining solids are settled and centrifuged until as much process water is removed. Any recovered solids are placed in big bags and transported to a treatment facility.

2.4. Stakeholder Analysis

The following section will describe stakeholders actively involved in the project, or who are affected by its outcome. First, a short overview of the stakeholders is given before going into detail on their specific stake in the project.

- Centre of Competence Paper and Board (CCPB)
 - Ir. M. Adriaanse
 - MSc S. Bousios
- Lubrizol Advanced Materials Resin B.V.
 - BAsC. R. de Jonge
 - Operators at Lubrizol Delfzijl facility
 - Management at Lubrizol Delfzijl facility
- Rijksuniversiteit Groningen
 - Prof. Ir. M.W.M. Boesten
 - Prof. dr. G.J.W. Euverink

2.4.1. Kenniscentrum Papier & Karton

The Centre of Competence of Paper and Board or CCPB in Arnhem can best be illustrated as the knowledge bank for the paper and board industry in the Netherlands. It is an initiative by the association of Dutch Paper and Board producers to generate, disclose and disseminate knowledge to the Dutch paper and board industry by reinforcing the knowledge infrastructure. Founded in 1998, the CCPB performs collective research on various subjects which are in relation to the industry. Projects are performed in (inter)national consortia in which universities, knowledge institutes, paper and board producers and suppliers jointly work on mutual interests. This project required information from paper and board suppliers which was attained through the CCPB. Results are most likely provided by the CCPB to these paper and board producers if applicable.

This project is established by the CCPB in order to gain insight in possible solutions to separate valuable components of paper sludge generated from the paper recycling industry. The CCPB can indicate this as a possible solution to paper recycling mills, if requested, customising the designs and other solutions to the individual paper mill.

For this particular project, the CCPB is represented by Ir. M. Adriaanse and MSc S. Bousios. Both have provided excellent insights and background information regarding the paper recycling process, the difficulties when dealing with the waste emerging from this process, and provided possible solutions regarding this waste and throughout the proposed demineralisation process.

2.4.2. Lubrizol Delfzijl

Lubrizol Advanced Materials Resins B.V. is part of a larger American conglomerate which produces various substances ultimately used in a range from personal care products to high performance coatings. The main process of Lubrizol in Delfzijl is the production of CPVC resin used in industrial piping systems. CPVC piping has excellent chemical resistance and high-temperature performance for any type of fluid.

The main interest of Lubrizol is to decrease current costs in processing one of their waste streams by either using their waste acid for increasing the value of paper sludge or cutting costs for the treatment of their waste by purchasing a neutralising agent which is much cheaper than CaO.

Lubrizol is represented in this project by BAsc. R. de Jonge, who supervised the experimental work performed at Lubrizol Delfzijl. Additionally, difficulties which arose during this period were relayed, discussed, and placed into context with R. de Jonge in order to come to an optimal solution.

2.4.3. Rijksuniversiteit Groningen

The university has numerous guidelines and/or constraints on a master research project. The main stake of the RUG in this research is the graduation of the researcher. Professor M.W.M. Boesten will monitor the research on its conformity to the stated guidelines as the supervisor of this project. Professor G.J.W. Euverink will confirm the overall assessment of Professor M.W.M. Boesten and will provide the final evaluation and judgement of the finished report.

Professor Boesten has also provided support regarding difficulties which arose throughout the project and supplied design options and resolutions pertaining to increasing the overall reaction rate.

Overall, it can be stated that there is no actual conflict of interest amongst the stakeholders of the project. All aim towards the same common goal, which is to reduce the amount of waste that is produced, or adding value of the same flow of waste. The acid treatment process can definitely be seen as a potential tool for achieving this goal.

3.0. Research Objective

Now that the origins of the relevant waste streams are depicted, as well as the involved stakeholders, we can continue with the research objective of this research project. The research objective must be clearly defined, have a quantifiable constraint, and must be agreed upon by all involved parties. The main research objective of this project can be described as:

'Design a demineralisation process to reduce the amount of deinking sludge in terms of weight of ash content using hydrochloric acid ~8wt% for removing calcium carbonate and evaluate this design by approximating its economic prospect.'

The main research question which can be formulated based on this research objective as follows:

'Is it both technically and economically feasible to reduce the ash content of deinking sludge by removing calcium carbonate using hydrochloric acid 8wt%?'

The research objective can then be separated into three sub goals;

- 1) Reduce the amount of deinking sludge through confirming its potential value in the neutralisation of hydrochloric acid.
- 2) Design a process which is able to remove the mineral filler from fibres of the deinking sludge using hydrochloric acid.
- 3) Determine whether the potential investment and any additional costs are greater than the current induced costs of processing hydrochloric acid and deinking sludge.

In turn, these goals can be achieved by answering the following research questions:

- What is the effectiveness of 8wt% hydrochloric acid on the removal calcium carbonate from cellulose fibres?
- Which parameters are of importance in the treatment of deinking sludge with an acid?
- What is the effect on the quality of the fibres which are present in the deinking sludge?
- What is the optimal arrangement of process conditions and equipment for the removal of calcium carbonate form cellulose fibres with hydrochloric acid?
- Is the implementation of acid treatment for deinking sludge economically feasible?
- What is the environmental impact of neutralising calcium carbonate in deinking sludge with hydrochloric acid?

If these research questions have been answered, it would be possible to relay back to the main research objective to state it has been achieved.

3.1. Research Approach

The following section will shortly cover the methodology of the proposed research. It will start off with a description of the character of this research, before shortly discussing the experimental approach.

3.1.1. Character Research

According to literature study, the neutralisation reaction with calcium carbonate would be possible, but proof has to be found that calcium carbonate can be removed efficiently from the network of cellulose fibres using acid. A proof-of-principle can be established through experimentation. Process optimisation can be performed on certain crucial process parameters to conclude whether it would be theoretically possible and practical to include this certain process to the paper recycling industry. In this way, it would assist practitioners at the CCPB and at paper recycling mills to find alternatives for reducing the amount of sludge waste.

This research is to be described as a practice-orientated research. The knowledge on a specific technique, the paper sludge waste treatment process, is provided to the practitioners of the CCPB. This knowledge aims at carefully assessing possible solutions to sludge waste generated by the paper industry, coordinated by the CCPB.

3.1.2. Knowledge gaps

To adequately depict the research design and research approach for appropriately answering the research questions, it is important to identify the gaps in literature. The plan of action regarding the literature search is defined in the following section.

First, the application of hydrochloric acid at this specific concentration on the treatment of paper deinking sludge has not been investigated before. Although the interaction of calcium carbonate as a material with hydrochloric acid is generally known, as it is a basic neutralisation reaction, the gap mainly exists in the interaction of hydrochloric acid with calcium carbonate which is present within a cellulosic structure and with the presence of other components. Although obvious reaction parameters can be thought of when dealing with such an interaction, it is important to investigate the exact impact of certain process conditions. These conditions can be taken into account when designing a refinement process in regard to process equipment, variable costs, and their eventual impact on the potential cost savings. The potential cost savings of any design developed during this research project can eventually be compared to the current expected cost. By comparing the two, a net return on investment can be generated over a set period of time.

To determine the net return of investment of an acid treatment process for deinking sludge, other factors besides the optimal process conditions will affect the final process design. Issues such as environmental impact, legislation, and the introduction of an entirely new logistical system have to be considered as well. These factors will be determined through the development of multiple design scenarios. These scenarios will include primarily the location of the proposed plant design(s), and its corresponding production capacity. These two factors mainly impact the final process design and the accompanying capital investment within a certain range of accuracy. Then other factors, such as environmental impact, can be incorporated into the final process designs, allowing alterations when

necessary or financially viable. A continuous cycle is applied to achieve a process design considering all crucial factors whilst maintaining the optimal required investment.

Based on the present knowledge gaps, it is determined that laboratory research is required to generate sufficient knowledge on the interactions of various basic process parameters on the reaction of calcium carbonate with hydrochloric acid, as well as identifying possible practical complications involved in such a neutralisation process.

3.1.3. Experimental approach

The amount of possible experiments depends on the wanted accuracy of the results. As the final process design will be an exploratory depiction for the economic analysis, the final range of costs will be in a range of $\pm 15\%$ accuracy (Sinnott & Towler, 2009). The experiments leading up to the range of optimal process conditions will therefore be depicting a range in which an optimized reaction can take place up to a particular degree of accuracy. Therefore, it is chosen that a certain range of various process conditions will be regarded, considering practicality and large incremental differences. Not enough time and space is available to deliver a 100% accurate value of each parameter. A pragmatic approach has been chosen, where each condition is examined briefly and individually, before continuing onward to the subsequent step.

The results of the experiments will be translated into a preliminary optimal setup, where it is established that the neutralisation reaction itself will be a trade-off between speed and cost-effectiveness. Again, this depends on practicality which is depicted by the researcher. In general, it is possible to introduce the demineralisation process in two different ways. One being a large scale operation facility, capable of processing large amount of waste material, and the second a custom designed process at a paper recycling mill. Both have advantages and disadvantages in terms of efficiency, both technical and economical. However, the starting point of this research is to design a large scale process. Several issues can be addressed in this manner:

1. A detailed market analysis of paper sludge waste is not required.
2. A large factor in this decision is that Lubrizol have stated that their acid has no economic potential due to its low concentration and heavy transport cost. As we are dealing with waste products, the impact of these transport cost will be high on the overall potential cost savings. This factor was already proven by research done by Lubrizol through the Rijksuniversiteit Groningen (Schrotenboer, 2015).
3. Paper sludge waste is already transported to incendiary plants, it can therefore also be brought to Lubrizol.
4. Output product (brine) can be discharged without additional permits, as this is already done by Lubrizol.
5. The process design at Lubrizol can be relocated anywhere else with the addition of the transport of HCl acid.

However, there are also disadvantages which have to be taken into account:

1. Location is in Delfzijl, not a strategic location in the middle of the paper industry sector producing sludge.
2. Permits for waste treatment will be required.
3. Transport distance of sludge material is assumed to be a nonfactor.

4. Sludge material has to be dewatered at a paper mill, then transported to Lubrizol, where it is suspended again, treated with HCl acid, and then dewatered again before finally being incinerated.

The latter remark seems very inefficient. But as stated before, the transport of acid deems the small scale neutralisation process at a paper mill as unfeasible. Therefore, the starting point of this research will be a case-specific study for the implementation of a demineralisation process at Lubrizol in Delfzijl. If ultimately found that the large scale process design does not deliver the required effectiveness, the scenario of installing a small scale neutralisation process at a paper mill can be investigated.

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4.0. Demineralisation process

In the previous chapter, both the research objective and the research approach were defined. In this chapter, the development of the demineralisation process of deinking sludge is portrayed. Starting off with basic theory and the proof-of-principle regarding the neutralisation reaction itself, it will then discuss the feedstock and expected product variety before ending with the identification of potential cost savings.

4.1. Theory & Experimentation

The neutralisation reaction of calcium carbonate and hydrochloric acid is almost an instantaneous reaction, meaning that the majority of hydrochloric acid has disappeared within a few seconds if added equivalently. The rate of dissolution of calcium carbonate mainly depends on temperature, pH, and particle size. If an acid is added, the hydroxyl ions become neutralised, resulting in the formation of calcium ions and carbon dioxide. The bicarbonate equilibrium is affected by temperature and moves to the product side as temperature increases (Neimo, Yhdistys, & Industry, 1999).

The main reaction of calcium carbonate with an acid is as follows;



During experimentation on hydrochloric acid and paper sludge material, the reaction itself has been monitored through the pH value of the suspension using a pH-electrode. The reaction time of experiments are depicted as the time starting from the addition of HCl acid to sludge waste material, to until the suspension has reached neutral pH value (>6). The latter prerequisite would be in concurrence with current standards of Lubrizol regarding their specifications of waste disposition.

Three sludge samples were tested, depicting the effectiveness of HCl acid for the removal of calcium carbonate. Sample A1 and B1 are deinking sludge samples, C1 was recovered from a wastewater treatment facility of a papermill, and sample PM7 was retrieved from papermachine PM7 at ESKA Hoogezand. Additional information regarding the properties of each sample can be found in table 19 in chapter 10.1.1. of the appendix.

4.1.1. Proof-of-principle

The technical feasibility concerns most about the ability of hydrochloric acid to dissolve calcium carbonate within a cellulose structure. By heating a sample of pulp of known mass and dry content to 550°C, it is weighed and heat to 900°C, both for two hour periods. The weight difference between the weight of pulp at 550°C and 900°C is the amount of CO₂ released through decomposition of calcium carbonate.

Table 2 Average conversion of calcium carbonate, where only sample PM7 conversion goal was set at 90% (A and C were set at $X_A = 100\%$) at ambient conditions. Samples were washed and dewatered before testing. Average conversion for samples A & C is 98.6%.

Sample	A1	C1	PM7
X_A	98.0%	99.3%	87.3%

The amount of carbon dioxide released indicates the amount of calcium carbonate which was still present in the sample. From this, the total conversion of calcium carbonate can be estimated. Three samples were tested to confirm the potential of hydrochloric acid for the removal of calcium carbonate from deinking sludge. The results are displayed in table 2 at the top of this page.

To monitor the reaction time of hydrochloric acid and calcium carbonate, the pH value of the suspension is monitored using a pH-electrode. By monitoring the pH, the concentration of hydrochloric acid can be monitored directly, and thus the concentration of calcium carbonate indirectly as well. Unfortunately, the values of the pH at specific intervals have to be recorded manually, as the pH-meter HI 9017 microprocessor did not support the function of recording data digitally. An inherent unknown margin of error is thus established, as the time intervals between points of measurement will not be 100% consistent. The pH provides an indication of the concentration of HCl during the reaction. Unfortunately, there are a few drawbacks of using a pH-electrode. First, is the deviation during the bubbling phase in the suspension is due to the production of CO_2 . Pockets of gas will hit the electrode, and will affect its measurements. Second, because of the large impact of only the smallest surplus in concentration of hydrochloric acid, the aimed conversion rate of calcium carbonate is set at 90%. This conversion rate is chosen due to the deviation in the concentration of calcium carbonate of smaller sludge samples compared to the average concentration. To avoid a surplus of hydrochloric acid, which is also undesirable in the final product, the amount of hydrochloric acid added to the suspension of sludge is set at 90%. This aimed conversion is strongly comparable to when an exact amount of HCl is added to completely neutralise all calcium carbonate, but opinions on this matter may differ. This method of testing at least provides an insight in the amount of time required to neutralise a large portion of calcium carbonate, providing an indication of equipment required size, and can be perfected on pilot plant scale under influence of pH-controllers, should this milestone be reached. By only monitoring the concentration of hydrochloric acid, it is quite possible deviations occur that the actual amount of calcium carbonate which is neutralised is not finally settled at 90% of its original contents.

4.1.2. Base reaction time

As described above, a 90% conversion of calcium carbonate is set due to variation in concentration of CaCO_3 in the acquired deinking sludge. Additionally, the final pH value of the suspension is preferably neutral (≥ 6) as expressed by stakeholders, whilst conversion is set as high as possible.

A remark has to be made regarding the first few minutes of the monitoring of the pH of the suspension after adding HCl. During these few minutes, over 99% of the added HCl is converted, releasing significant amounts of CO_2 , possibly influencing the accuracy of the pH-electrode. The results during these first five minutes are not incorporated into the final figures. After five minutes, the foam is removed as much as possible by manual stirring.



Figure 5 Average reaction times in terms of pH for each sludge sample at 95% moisture content, ambient conditions, and laminar flow with no stagnant zones during the neutralisation reaction on lab scale (~100mL). Measurements start when HCl acid is added to suspended sludge sample and end at pH=6.

As can be seen in the figure above, the time for each sample to arrive at a neutral pH (>6.0) differs greatly. A shift in reaction rate can be observed between pH 4 and pH 5, leading to believe that the rate determining step alters in regard to pH. Methods of optimisation were investigated to reduce the overall reaction time.

4.1.3. Temperature

The effects of increasing temperatures have been tested to decrease the overall reaction time. Although the pH reaches 5 much faster overall at higher temperatures as displayed in the figure below, the overall reaction time does not conclusively change with increasing temperature for each sludge sample. It must be stated that some samples, especially sample C, did not reach a neutral pH. It would be unnecessary and, above all, unpractical to alter any process conditions beyond ambient. Additional focus can be put on the slow shift in pH after the pH reaches 4-5, in order to make this neutralisation more viable in terms of overall reaction time.

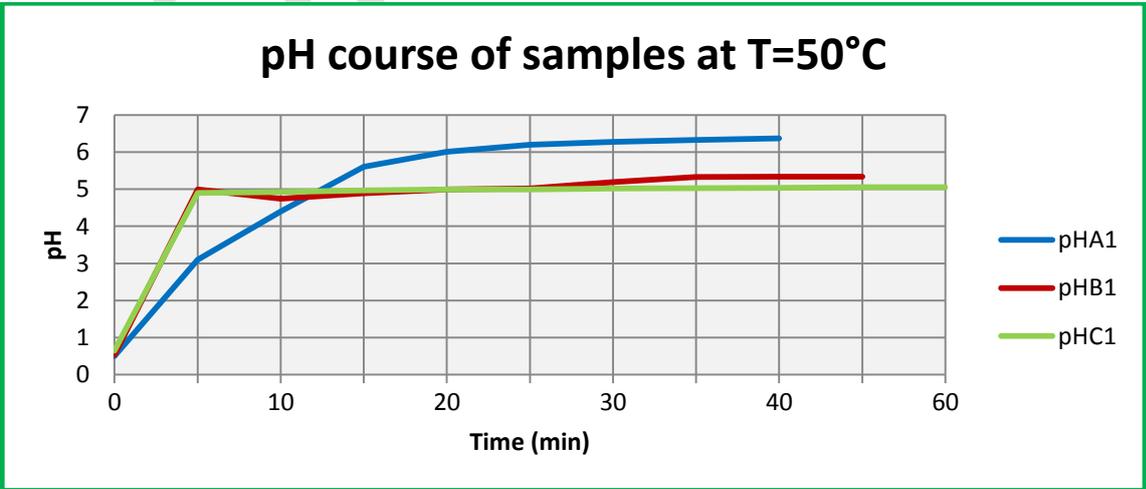


Figure 6 Average pH course for each sludge sample T=50 degrees Celsius, 95% moisture content and laminar flow without stagnant zones on lab scale (~100 mL).

Additionally, in regards to temperature, the overall increase in temperature due to the exothermal reaction is found to be minimal, that meaning of such a low impact on the overall temperature that the consequences are omitted.

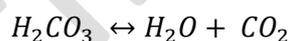
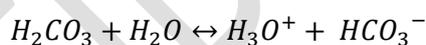
4.1.4. Pressure

The experiments were performed without altering the pressure due to practical reasons. The experiment only determined the effects of temperature on the reaction time. The effects of altering temperature were established, although any alteration in temperature is considered unpractical in regards to hydrochloric acid and unnecessary considering dealing with large-volume waste streams.

4.1.5. Carbonic acid

At lower pH of the suspension, the rate determining step is the concentration of hydrochloric acid, as this concentration should be relatively lower than the concentration of calcium carbonate. The possibility of dissolved CO₂ affecting the pH in the form of carbonic acid at pH >5 is indicated by Ter Maat and Rexwinkel (Maat & Rexwinkel, 2012). The ambient pressure and the concentration of produced CO₂ could limit the rate of neutralisation of calcium carbonate. The carbon dioxide in solution must be diffused through the surface as fast as possible to increase the reaction time. According to the research of Cadogan, Maitland and Trusler, the diffusivity of CO₂ in water increases with increasing temperature (Cadogan, Maitland, & Trusler, 2014), but this is deemed unpractical. The correct balance has to be found at which the CO₂ is removed from the solution as calcium carbonate is dissolved at the highest rate possible both technically and economically (Yunzhao, Xingfu, C. Guilan, Yanxia, & Jianguo, 2014).

Side reactions of the main neutralisation reaction form carbonic acid according to;



At a pH of 4-5, an increase in concentration of carbonic acid is suspected to take over as the rate determining step, in terms of shifting pH. This issue was confirmed by blowing air through the suspension after this point in pH has been reached. The pH is monitored after blowing air (~2.0 bar) through the suspension. The pH rapidly returned to neutral values after initiating air flow. This phenomenon has also been hinted by research of M.G.E. Bos where focus lay on using calcium carbonate as an alkaline for the neutralisation of hydrochloric acid at Lubrizol (Bos, 2015). The next figure describes the theoretical balance of the different forms of carbonates across a pH-scale. Although expressed as theory, this phenomenon could impact the overall reaction time of HCl acid and calcium carbonate.

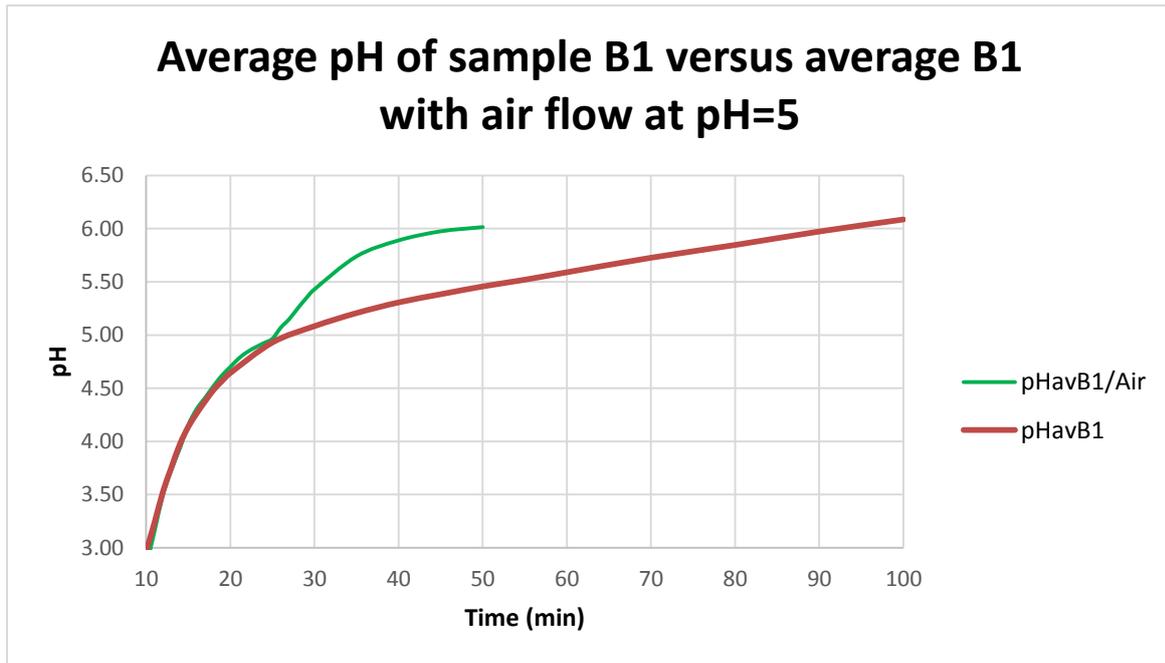


Figure 7 Two average progressive values of pH of sample B1, under ambient conditions. One of the two is the average pH where air flow is induced at pH =5. This indicates the impact of dissolved CO₂.

The theory states that the concentration of CO₂ clearly diminishes at pH 4, and the concentration of the bicarbonates increases. In this case, it could mean that the reaction between HCl acid and calcium carbonate at this pH level is no longer the rate determining step in terms of shifting pH levels. This is an indication that the reaction of carbonic acid and calcium carbonate becomes the rate determining step around a pH of 4. Thus, there is a potential of shortening the overall reaction time. A method of verification of this mechanism is provided in the next chapter.

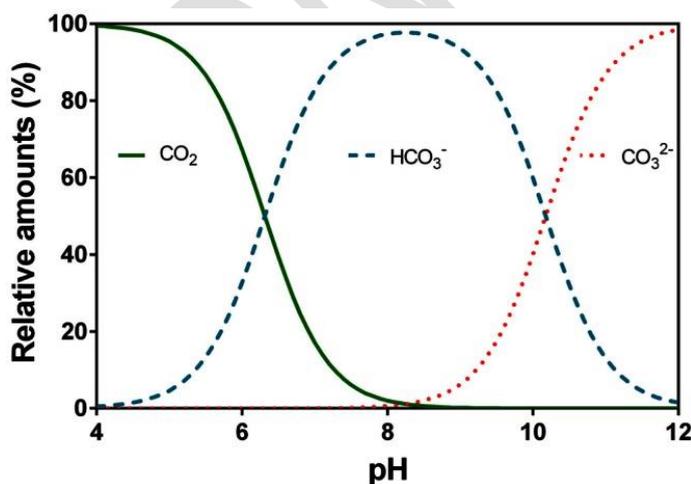


Figure 8 The equilibrium balance of carbonates across pH, indicating the production of carbonic acid from around pH =4 (O. Pedersen, 2013).

The ambient pressure and concentration of produced CO₂ could limit the removal of calcium carbonate. In terms of improving the overall reaction time in a larger scale process, several solutions are possible regarding a reduction in the influence of CO₂ on the overall reaction time. There are several avenues to explore regarding the removal of CO₂. According to the research of Cadogan, Maitland and Trusler, the diffusivity of CO₂ in water increases with increasing temperature (Cadogan, Maitland, & Trusler, 2014). This might provide an initial solution but it seems not very cost-effective to alter process conditions beyond ambient in terms of temperature and pressure of large process flows. Especially considering produced CO₂ is the largest determining factor regarding overall reaction time. Other rudimentary options would for example be inducing air flow, or reducing pressure above the suspension. The correct balance has to be found at which the CO₂ is removed from the solution as calcium carbonate is dissolved at the highest rate possible both technically and economically.

4.2. Feedstock

The most important properties of deinking sludge regarding neutralisation are dry content, and calcium carbonate content. Deinking sludge encountered during testing were analysed to hold a calcium carbonate content of 21-26wt% based on dry content. This heavily influences the required amount of sludge per metric ton of hydrochloric acid. A representative deinking sludge content as portrayed by the CCPB is regarded as the average (21.6wt%).

The concentration of hydrochloric acid also varied based on analysis, varying between 7-9wt%. Overall, both these differences lead to slightly different process designs regarding overall fixed capital and accompanying fixed and variable cost of production, as initial fixed capital investments would be different across these designs.

Concentrations of both calcium carbonate and hydrochloric acid were determined using an autotitrator system. Details on this method and specifications of the device are discussed in the appendix.

4.3. Products

The dewatering stage of the proposed designs is assumed to be capable of producing the same dry content regarding to weight as the feedstock sludge. The only difference is the calcium carbonate content being diminished, resulting in a loss of water as well. The demineralised output is, however, determined to be unsuitable in terms of reuse for papermaking. An explanation of this statement is provided in the following section. Therefore, it might be possible that output sludge is only suitable for incineration.

The average cost for the incineration of deinking sludge is estimated to be around 25 euros per metric ton. At the time of writing, it is assumed that the output sludge, holding either none or miniscule amounts of calcium carbonate, can be incinerated for the same amount of costs. The issue is that without calcium carbonate, the output of incineration (fly ash) is depleted of calcium oxide, a valuable material for the application of fly ash to its current main endproduct, cement. It is therefore possibly an assumption that demineralised sludge is incinerated for the same price as standard

deinking sludge. A possibility to resolve this issue is the reuse of demineralised sludge in the production of paper.

The current value of high-end recycled paper fibre would be somewhere near €700 per ton (Maat & Rexwinkel, 2012). Generally, as stated by the KPCK, the value of virgin fibres is €500 per metric ton, and for low-end quality this would come down to €50-100 per metric ton. The fibres generated from the demineralisation process may be reused for papermaking as well. For fibres of lower quality, the value may be much less. According to expert opinion, the processed fibres used in this research probably have no, or negative value in terms of reuse in papermaking. However, this is only an indication on fibres which were exposed to both a possible slight surplus of acid, and were stored for three to twelve weeks before analysis. It would be still be possible that fibres without such exposures have some value after all. But further research would be required. Further explanation on the factors determining value of paper fibres will be discussed next.

4.3.1. Fibre Quality

The following section provides more insight in the probability of utilising fibres originally reclaimed from a deinking process and then treated with hydrochloric acid to reduce the calcium carbonate content as much as possible.

Only samples A and C had sufficient material left after initial experimentation and were tested on fibre usability. It seems that certain strength properties of paper actually improve with the addition of processed fibres. However, drainability and the water retention were very poor, rendering the fibres of processed deinking sludge worthless.

4.3.1.1. Drainability

The drainability of fibres is the rate at which a dilute suspension of pulp may be dewatered, ultimately affecting machine rates (ISO, 1999). Drainability is related to the surface conditions and the amount of swelling of fibres. This amount to a useful index of the degree of mechanical treatment to which pulp has been subjected to. Recovered fibres usually have higher drainage resistance than virgin fibres, which ultimately limit both paper quality and thus operating rate of paper machines. The results of the Schopper Riegler drainability test are shown in the figure below. The drainability of sample C was impossible to determine. After drainage, the substance left behind was not suitable for the formation of a sheet. This phenomenon was confirmed on multiple occasions.

Table 3 Drainability of two sludge samples in °SR (Adjusted).

	A	C	PM7	PM7/HCl
°SR	76.3	NA	45.0	44.7

The drainability of sludge sample A in degrees Schopper-Riegler (SR) is higher than the value found for the fibres present in PM7. Any difference is most noticeable in the production of paper sheets of sample A, but whether paper quality is affected and if so, by what degree, is difficult to state.

The fibres which were retrieved from PM7 and treated with hydrochloric acid show minor difference in °SR compared to the difference between sample A and the untreated fibres of PM7. The real question is then whether this difference is due to the removal of mineral filler, or whether the fibres are affected by hydrochloric acid during neutralisation. The answer to this question is impossible to answer with the data provided through this research.

4.3.1.2. Water Retention Value

The water retention value (WRV) provides an indication of the ability of fibres to take up water and swell. The WRV of various samples of fibres is displayed in table 4. Provided that the fibres retrieved from PM7 act as a benchmark, the other samples have poor water retention as expressed by expert opinion at ESKA Hoogezand. This means that paper machines have significantly lower machine rates when producing paper involving these treated fibres.

Table 4 Overview Water Retention Values of four samples of paper pulp. Each treated sample is compared to the current standard of PM7. Any higher deviation regarding water retention can be regarded negative in terms of the rate of papermaking.

	A	C	PM7	PM7/HCl
WRV	1.39	3.03	0.87	1.02

PM7 fibres treated with HCl acid had a higher WRV than untreated fibres. The cause of this difference is unknown as well as the exact impacts on the quality of the fibres.

4.3.1.3. TABER Abrasion Test

The next section portrays the data received during the TABER abrasion test. First remarks considering these results is that the added percentage of each sample is given as the relative dry weight ratio as a specific sample regarding fibres supplied directly by the PM7 in Hoogezand.

Table 5 Overview results of TABER Abrasion Test displaying the loss in mass after 30 rotations on the TABER device.

Sample	Δm (mg)	m_0 (mg)	Index
100%PM7	164	2434	6.7%
100%PM7/HCl	120	2881	4.2%
100%A	16	1851	0.9%
100%A+	20	2505	0.8%
5%A	155	2438	6.3%
10%A	150	2428	6.2%
15%A	153	2565	6.0%
5%C	135	2220	6.1%
10%C	113	2318	4.9%
15%C	98	2438	4.0%

The first result is the base result made from paper retrieved from PM7. The others samples are treated with HCl acid or are a mixture of the sample with PM7 paper in mass percentages respectively. What can be seen immediately is the increased toughness of the surface of the paper sheets treated with hydrochloric acid. The relative mass loss after 30 rotations is less when involving treated fibres in any degree. Treating the same PM7 fibres with hydrochloric acid results in a different surface toughness. Whether this difference is due to the loss of calcium carbonate or a change in the fibre itself by exposing it to an acid is difficult to determine.

Although the influence of adding fibres from sample C is evident, the consequences of adding A in the quantities of 5-15% weight ratio in terms of dry content is almost insignificant between the different concentrations. The required loading of A where a difference in terms of abrasion would noticeably be different is unknown.

Overall, the treatment of fibres with hydrochloric acid does not significantly impact the overall bulk density of the paper, as expressed by expert opinion at ESKA Hoogezand. Adding treated sludge fibres to the fibres retrieved from PM7 have impact to a certain degree. Sludge sample A does not impact the bulk in any way at these concentrations, whereas C does seem to lower the bulk at a concentration of 15%.

4.3.2. Value treated fibres

The overall value of fibres retrieved from deinking sludge treated with hydrochloric acid is determined to be zero or even slightly negative. This was stated by expert opinion at ESKA Hoogezand. Overall, the mechanical properties do not change or improve slightly, whereas the expected machine rate producing paper with processed sludge fibres will most definitely be less than desired. Therefore, adding these fibres would be considered filler material, not as actual fibres.

4.3.3. Factors affecting quality output fibres.

One of the factors affecting the value is the salt content of the sludge. Although most of the produced calcium chloride will be removed from the sludge through dewatering, a portion is most likely left behind. By neutralising calcium carbonate, the resulting calcium salts can reduce the possible swelling of the treated fibres by covering the charged groups on the surface of fibres, ultimately affecting bonding capability (Neimo, Yhdistys, & Industry, 1999).

Again, fibres tested for their quality regarding papermaking were at least three weeks old, as was the time necessary for processing, demineralising, washing, dewatering and transporting the sludge to the testing location with the required equipment for further analysis on the quality of the samples. Storage conditions were airtight plastic containers under a constant temperature of 7°C. The overall processing time could be much shorter in the case of a larger scale operation.

Main factors influencing the average fibre length are:

1. Acid hydrolysis.
2. Bacterial degradation.
3. Inherently shorter fibre length from the DAF process.

Besides acid hydrolysis, there is the probable impact of bacteria on the degradation rate of processed fibres. Bacteria cut the cellulose polymer fibres, leaving behind a smaller fibre fraction over a period of time. This will certainly impact the final value and possible end uses of these fibres. Most

degradation due to bacteria is likely to occur before exposure to an acidic environment in the neutralisation process. The time of collecting sludge material, transport and storage plays a crucial role in the degree of degradation of cellulosic fibres due to bacteria.

Lastly, there is the possibility the sludge retrieved from DAF-unit are fibres with a relatively short length. As the basic concept of the DAF process is to collect small particles through agglomeration, it is most likely that relatively smaller fibres are collected, although incidentally, as well. The exact impacts of acid hydrolysis, bacteria, and the average length distribution of fibres collected from the DAF process need to be researched.

4.3.4. Degradation

The following section will provide some deeper insight in the mechanisms behind the degradation of fibres. This mainly concerns the degradation through acid hydrolysis and bacterial degradation. The particle size distribution of the tested samples was considered to be small. Comparison material from a high consistency separation unit at ESKA provides some insight in the usability of processed fibres. The fibres treated with hydrochloric acid were considered to exist mostly of fines. Expert opinion also regarded the sludge material as fines, which do improve strength properties, but worsen dewater properties, and do not add significant weight regarded to added volume when used in combination with PM7 fibre material.

Table 6 Average particle size distribution of processed sludge of both samples C1 and A1, performed in duplo.

Mesh	Size (mm)	Average fraction wt%	HC First Stage
<14	>1.41	0.6%	7%
<35	>0.5	11.9%	34%
<50	>0.297	3.3%	21%
<100	>0.149	20.9%	12%
<200	>0.074	1.0%	6%
>200	<0.074	62.3%	20%

4.3.4.1. Bacteria

The deinking sludge samples used in the tests described previously has most likely been impacted by the degradation through bacteria. Due to the presence of water (>15%), bacteria are able to react with molecules on surface of the fibres, transforming them into sugars, and finally fatty acids. The result is the 'snipping' of fibres, creating a larger fraction of smaller fibres, which, can result into fines. This can possibly explain the small fibre fraction of the tested sludge samples.

The reason behind this phenomenon is that the molecule of pure cellulose is comprised of β -glucose units linked to form long chain (Boswell, 2006). Recorded molecular weights range from 100-1200 glucose units per chain. Before cellulose can be utilized by any organism, it must be broken down into water-soluble molecules, allowing diffusion into the cells. This breakdown is enzymatic, mainly hydrolytic through the enzymes cellulase and cellobiase. The first step is to break down the chain into single cellulose units, thus breaking any bonds which unite the cellulose molecules into macro-units. Secondly, the linkages which unite the glucose units into the cellulose chain must be hydrolysed, resulting in individual glucose units. These two steps cannot be examined separately as both occur simultaneously in different parts of the same tissue, macro-unit, or micelle series.

To compare the degree of degradation in terms of the fibre fraction of the examined fibres from deinking sludge, it would be most logical to first determine the fibre fraction right at the moment at which the sludge samples were attained and before introducing hydrochloric acid to the sludge. As these moments of testing were omitted due to the unavailability of equipment and sufficient testing material.

4.3.4.2. Acid hydrolysis

Adding hydrochloric acid to cellulosic material leads to acid hydrolysis, reducing the degree of polymerization. Cellulose introduced to an acidic medium in general will split into glucose through the addition of water molecules. This addition leads to fragments of short chain lengths but preserves the basic structure. Specifically, the β -1,4-glucosidic bonds of a cellulose chain molecule are split. The rate of depolymerisation depends on the concentration of the acid.

Although it is most likely that hydrochloric acid will react mainly with the presented calcium carbonate. It is difficult to depict the amount of hydrolysed bonds broken during the neutralisation of calcium carbonate. Aimed at 100% conversion of calcium carbonate during experimentation, the amount of hydrochloric acid present at the end of the experiment remained relatively high (pH >2) and stable most likely due to inconsistencies in the concentration of calcium carbonate. Thus, with a surplus of hydrochloric acid relative to the amount of calcium carbonate present in the treated sludge, the rate of depolymerisation due to acid hydrolysis remained fairly low. However, for this particular case, resources were not sufficient to verify the actual degree of hydrolysis of cellulose in deinking sludge. Further research on the effects of hydrochloric acid at this specific concentration on the fibres present in deinking sludge is required.

4.4. Potential Cost Savings

Currently, the neutralisation process for hydrochloric acid is costing Lubrizol €9.28 per metric ton of acid solution on average, depending on concentration. This includes the disposal of remaining minor products. To calculate the potential cost saving, the required average amount of deinking sludge to neutralise a metric ton of HCl acid is to be calculated.

For a generic paper recycling mill, the cost of incinerating sludge material is estimated to be around €25,- per metric ton of sludge. For it is assumed that after the removal of calcium carbonate, the final product can be considered waste as well. The margin of cost saving is based on the removal of a portion of sludge material. It is assumed that removal of calcium carbonate would result in that a portion of water as well, as the final product after demineralisation would have the same dry content relatively to the input sludge material. It is estimated that this would reduce the overall mass flow of sludge by 30-50wt% based on dry content, depending on calcium carbonate content of input material. It was found that per metric ton of HCl acid 8wt%, a margin of €13.85-14.65 can be realized on average, depending on the required amount of sludge material related to calcium carbonate content. From this amount, the initial capital investment, the variable cost per ton of processed acid and sludge, and the annual fixed capital cost have to be covered. The economic feasibility study is portrayed in the next chapter.

5.0. Cost Estimation – Scenarios

The last chapter briefly discussed the potential cost savings which could be realised with the demineralisation of deinking sludge, as well which parameters are of importance during the neutralisation reaction itself. This chapter will focus on these parameters, and the variability of feedstock and products. The following sections will depict the economic analysis based on this information, starting with a depiction of several scenarios, from worst to best case. It will then discuss the possible design options regarding reaction optimisation based on the before mentioned process conditions before continuing with the exact implications of those designs at possible plant locations.

5.1. Scenarios

Five different scenarios were established in development of the economic analysis. These scenarios concern varying concentrations of reactants in available feedstock. The worst-case scenario holds into account that the most deinking sludge is needed to neutralise the relatively highest concentration of hydrochloric acid. The best-case scenario would be that the lowest amount of sludge is needed to neutralise the lowest concentration of HCl acid. These differences between scenarios does not only affect the variable cost of the proposed processes, but also the initial capital investment cost, as volumetric flow through these processes vary greatly. Also, this thus includes a basic sensitivity analysis for the proposed designs. A basic overview of the differences between scenarios is provided in table 7 at the bottom of this page.

Regarding a design options at a paper mill, the designed capacity is based on a model sludge and its average output per paper mill. A difference in cost estimation is based on transport distance from Lubrizol in Delfzijl, with specific radii at 50, 100 and 150 kilometres. The choice of these specific distances was based on the research done by K. Schrotenboer, who has indicated a break-even distance for the transport of HCl acid from Lubrizol to possible buyers (Schrotenboer, 2015). This break-even distance was determined to be within the proposed maximum range of 150 km. This maximum distance was chosen in order to cover the three northern provinces of the Netherlands. The cost of transport per ton of acid increases with every kilometre it needs to travel. Significant differences in variable costs were established, using this differentiation. These differences are displayed further on in this chapter.

Table 7 Overview of differences in scenarios by varying concentrations of main components of feedstock. Resulting mass equivalencies for required feedstock and output material of the neutralisation process are described per metric ton of HCl acid solution in kg.

Scenario	[HCl] wt%	[CaCO ₃ wt%	Required CaCO ₃ in kg	Required sludge in kg.	CaCl ₂ produced in kg.	Output sludge in kg.
WWC	9	21.0	124.5	592.1	137.0	377.5
WC	8	21.0	110.7	526.3	121.8	335.5
Average	8	21.6	110.7	512.5	121.8	328.0
BC	8	26.6	110.7	417.8	121.8	208.1
BBC	7	26.6	96.9	365.7	106.5	182.1

5.2. Design options

Initially, a base design was created with the minimal required main process equipment. The average reaction time was established during the experimentation phase at Lubrizol and depicted to average 60 minutes across all samples. The base average reaction time of each sample is displayed in figure 5 in chapter 4. The start of the reaction was the addition of 90% mol-equivalent HCl acid to suspended deinking sludge at 5wt% dry content. The pH of the suspension was continuously monitored. The end of the neutralisation reaction was depicted to be at a pH of 6. A neutral endproduct was determined to be prerequisite by all involved stakeholders.

It is suspected that the long reaction time of 60 minutes is due to the presence of carbonic acid and the any inconsistencies of these reaction times are due to the production of carbon dioxide causing a bubble formation phase. The reaction time could perhaps be much lower under different process conditions. For example, a decrease up to 50% of the base reaction time was found by inducing air flow through the suspension at pH 5 as displayed in figure 7. The reasoning behind blowing air through the suspension is to increase the effective surface contact of water with the atmosphere. The atmosphere is created inside the suspension in the form of air bubbles. As air bubbles come into contact with water, any dissolved gasses approach equilibrium with the partial pressures of the atmosphere. This phenomenon greatly increases the overall removal of dissolved CO₂ gas in the suspension. A major drawback blowing air through the suspension is that HCl gas can be released to the environment as well. It is unknown to what effect this will occur. Several other design options were also investigated to demonstrate the effects of both shortening the overall reaction time and downsized equipment. These variants on the base design are described in further detail in the appendix.

Of these proposed design options, all designs have a similar pulping and dewatering processes. For the suspension phase of the process, about half an hour of soaking and mixing was required for a small batch of 25-40 grams of sludge material. Shorter periods of fifteen minutes were tested and can be introduced, however, the reaction time becomes higher and less consistent, although differences between sludge samples were observed. This is due to the type of dewatering which has occurred to produce the sludge sample. It was found that the compact sludge sample derived from a pressing dewatering mechanism (sample A) would only break down around 30 minutes. Shorter mixing times would generally leave large chunks of fibre material on the bottom of the beaker. This is the opposite when comparing to a sludge sample derived from a thermal dewatering system (sample

B), which contained more 'loose' material. Longer suspension phases do not improve either the reaction time or its inconsistency across all sludge samples.

A minimal moisture content of 95wt% was established as at this concentration, no stagnant zones were observed throughout the experiments. A 90wt% moisture content resulted into a suspension which was not able to be stirred with a magnetic stirrer, and a moisture content higher than 95wt% was omitted due to impracticality and expected high accompanying cost in scaling up from the experimental phase.

Several proposals in terms of different process designs are provided. Four additional design options are included, all based on the single base design. This base design is based on stainless steel 316 material of construction, due to its increased resistance to both corrosion and pitting from chloride ions in comparison to carbon steel. If HCl acid would accidentally penetrate to the outside of the designated reactor, it would be a major safety hazard.

Two of the designs concern the inhibition of foam formation due to rapid carbon dioxide production, which increased the volume dramatically of the suspension. By introducing a lowered pressure above the suspension in which the neutralisation reaction of HCl acid takes place, carbon dioxide bubble formation is expected to a smaller impact, allowing for a more homogenous and shorter overall reaction time. The exact impacts on the reaction time are unknown, but an estimation of the additional required equipment provides an insight in its viability. The same principle applies when top down water spray system is introduced inside the neutralisation reactor. Water drops pierce the bubbles created by carbon dioxide, suppressing bubble formation. Overall bubble formation is expected to be much lower under continuous processing of sludge waste and hydrochloric acid but its exact effects are unknown beyond laboratory scale.

5.2.1. Base Design

The following section will display the process of creating process flow diagrams. The process flow diagram shows the arrangement of equipment, the stream connections, stream flow rates, stream compositions, and the operating conditions.

Flow-sheet calculations are carried out by using a commercial process simulation programme. The simulation program features models for most unit operations as well as thermodynamic and physical property models if available. For this specific case, Aspen Plus 8 is the simulation program of choice. As it is readily available for the researcher, as well as that the researcher has a basic understanding of operating this program.

The next step after flow-sheet is the preparation of piping and instrumentation diagrams, which show the engineering details of the process, and are based on the flow-sheet.

Block diagrams are a simple form of presentation, representing a process in a simplified form, but has a limited use as engineering documents. Stream flow rates and compositions can be shown alongside stream lines. Block diagrams are drawn using Microsoft Visio, as it is readily available for the researcher, as well as that the researcher has a basic understanding of operating this program.

The structure of the base manufacturing process is as follows:

1. Raw material storage
 - a. Storage for 3 days.
2. Feed preparation
 - a. Screened, broken down
 - b. Suspended
3. Reaction
 - a. Ambient process conditions
 - b. Reaction time of 1 hour
 - c. Excessive gas production
4. Product separation
 - a. Dewatering removes all soluble unwanted material
5. Product purification
 - a. Additional scrubbing might be required depending on end-use.
6. Product storage
 - a. Waste material is discarded.
 - b. Product material is saved until sufficient amount is achieved for optimal transport (~3).

The base design includes the base operations of the proposed neutralization process, based on the 'model' sludge as proposed by the CCPB. This includes the suspension phase, where moisture content is increased to 95wt%. The neutralization step initially uses a batch method, where hydrochloric acid is added. And finally the dewatering step, where the previously added water is recaptured. Collected water is at this point not recycled back into the process. The base of design is set to convert 20 metric ton of HCl 8wt% per hour.

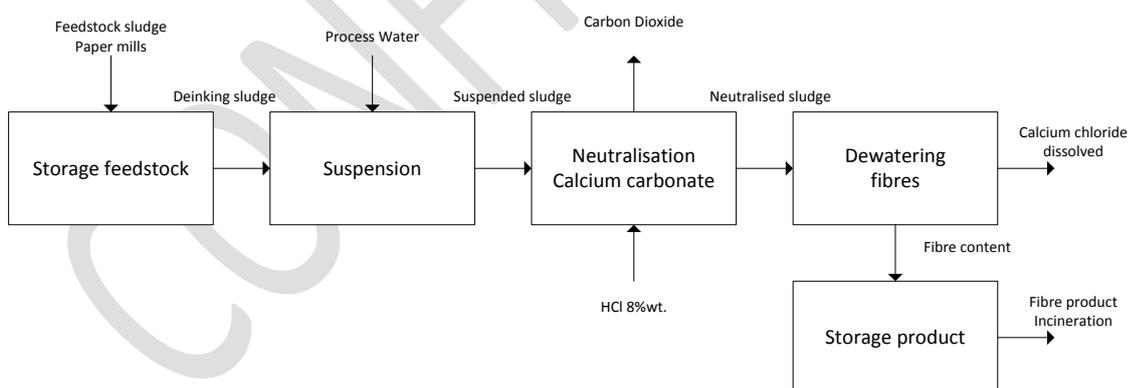


Figure 9 Block diagram demineralisation process hydrochloric acid and deinking sludge.

At the suspension phase, deinking sludge of known moisture and calcium carbonate content is transported into a reactor of sufficient size. With a content of mostly water, the required reactor size is set at 12 m³, allowing a 10% overcapacity. The exact dimensions have yet to be determined. Ordinary tap water is added until a total moisture content of 95% has been reached.

In the case of neutralizing 1 metric ton of HCl 8wt%, a mere total of 11.0 kg of calcium carbonate is needed per hour. This amount roughly translates into a required amount of 46.8 kg deinking sludge. At 40wt% moisture content, the required amount of water added is set at 515 kg to finally reach a moisture content of 95%. Sufficient mechanical force is to be applied for more efficient mixing of the suspension. During experimentation, a homogenous mixture is observed at various mixing times, depending on the sludge sample provided. For the model sludge, a minimal average mixing time of 30 minutes has been set. As the reaction time is supposedly greater than the mixing time, a mixing unit represents the suspension step in the simulation.

The next phase is the neutralization process itself. After the suspension has been homogenized sufficiently, the suspension is pumped into the next reactor. 20,000 kilograms of hydrochloric acid 8wt% is added to the suspension, initiating the neutralisation reaction. As the base design operates with an exemplary sludge, the actual overall reaction time is unknown. For the simulation, the time to process 20000 kg of HCl is set at 30 minutes. During this time, approximately 960 kg of CO₂ is produced. For simulation purposes, this amount is vented actively from the reactor.

The final process, the dewatering step, is simulated as a centrifuge, where fractions of liquid to solid are specified. The goal is to separate the fibres from salts produced in the previous process step. A mere 224 kilograms of fibres and the remainder of mineral filler are to be separated at this point, although it is next to impossible for these fibres to be completely dry. The aim is to have to the same final moisture content as the sludge which entered the process, which is 40%.

All designs described are visualized through Piping and Instrumentation Diagrams (PIDs) in Windows Visio and tested on practicality in Aspen plus 8. Tables, drawings and other figures of these designs are listed in the appendix chapter 10.3 and 10.4.

The designs were optioned at Lubrizol in Delfzijl, where the input HCl process stream is assumed to come directly from silo TK8F. As for designs regarding a paper mill, the connection of these designs depends on each variant and the method of dewatering either chosen or available.

5.3. Lubrizol

The following initial capital investments have been found for every design at a production rate of twenty metric tons of hydrochloric acid per hour at an operating time of 80%. The chosen plant location would be an adjacent plot next to Lubrizol at Chemiepark Delfzijl. The framework used for these calculations is designed by Sinnott & Towler (Sinnott & Towler, 2009).

Table 8 Estimated initial capital investments for each scenario based on the framework of Sinnott and Towler and the designs as portrayed in section 10.4 in the appendix.

Designs				
Scenario	Base	Air flow	Spray	Vacuum
WWC	M€ 37.4	M€ 29.8	M€ 28.5	M€ 30.6
WC	M€ 34.4	M€ 26.6	M€ 26.7	M€ 28.8
Average	M€ 35.1	M€ 26.6	M€ 26.6	M€ 28.8
BC	M€ 27.7	M€ 21.6	M€ 21.6	M€ 23.8
BBC	M€ 25.6	M€ 19.9	M€ 19.9	M€ 22.1

A brief example of the framework of Sinnott and Towler is provided in the set of tables on the next pages of this report. First, the required main process equipment is determined to perform the desired processes. Then, the main parameter of each piece of equipment on which the model is based is estimated. This is usually done based on the required volume or mass flow of the process, where a 10% surplus is included for contingency purposes. Based on this parameter, the purchasing cost of each piece of equipment can be calculated. Note that some equipment are split into multiple pieces of equipment. This is due to the constraints set by Sinnott and Towler on the size of each piece of equipment due to accuracy purposes. The assumption is that a multitude of the same piece of equipment more or less amount to the most accurate purchasing cost. The purchasing cost of each piece of equipment can be calculated using the formula:

$$C_e = a + bS^n$$

Adding all cost amounts to the purchasing cost of the proposed plant. Then, the Inside Battery Limit can be determined, which is the estimated cost of the plant itself. This includes erection of equipment, piping, controllers, electrical equipment etc. This is a multiplication factor, which is set at 3.2 for fluid-solid processing plants. Then, the Outside Battery Limit can be determined, which can briefly be described as the additional cost of actually placing the plant at a certain location. This includes offsites such as infrastructure, design and engineering and contingencies. Lastly, there is the 'time' correction factor of placing this model from 2009 into today's market. As well as including a 'location' correction factor for this model for the Netherlands.

Basic Design costs		20 ton HCl per hour							
Suspending phase									
	S		S lower	S upper	a	b	n	Ce	
Tank	1844.9 m3		100	10000	97000		2800	0.65 \$ 468,575.56	
Reactor	67.6 m3		0.5	100	53000		28000	0.8 \$ 868,383.22	
Stirring mechanism	67.6 kW		5	75	15000		990	1.05 \$ 97,680.41	
Pump	37.6 L/s		0.2	126	6900		206	0.9 \$ 12,287.05	
Conveyor2	33.8 m		10	500	40000		1160	1 \$ 79,235.81	
								\$ 1,526,162.05	
Neutralisation phase S			S lower	S upper	a	b	n	Ce	
Pump	43.7 L/s		0.2	126	6900		206	0.9 \$ 13,069.37	
Reactor1	25.0 m3		0.5	25	11000		76000	0.4 \$ 286,416.27	
Reactor2	25.0 m3		0.5	25	11000		76000	0.4 \$ 286,416.27	
Reactor3	25.0 m3		0.5	25	11000		76000	0.4 \$ 286,416.27	
Reactor4	25.0 m3		0.5	25	11000		76000	0.4 \$ 286,416.27	
Reactor5	25.0 m3		0.5	25	11000		76000	0.4 \$ 286,416.27	
Reactor6	25.0 m3		0.5	25	11000		76000	0.4 \$ 286,416.27	
Reactor7	7.3 m3		0.5	25	11000		76000	0.4 \$ 179,284.99	
Mixer1	25.0 kW		5	75	15000		990	1.05 \$ 44,071.82	
Mixer2	25.0 kW		5	75	15000		990	1.05 \$ 44,071.82	
Mixer3	25.0 kW		5	75	15000		990	1.05 \$ 44,071.82	
Mixer4	25.0 kW		5	75	15000		990	1.05 \$ 44,071.82	
Mixer5	25.0 kW		5	75	15000		990	1.05 \$ 44,071.82	
Mixer6	25.0 kW		5	75	15000		990	1.05 \$ 44,071.82	
Mixer7	7.3 kW		5	75	15000		990	1.05 \$ 22,977.53	
Pump HCl	5.4 L/s		0.2	126	6900		206	0.9 \$ 7,835.36	
								\$ 2,206,095.80	
Dewatering phase S			S lower	S upper	a	b	n	Ce	
Pump1	36.4 L/s		0.2	126	6900		206	0.9 \$ 12,134.90	
Pump2	7.3 L/s		0.2	126	6900		206	0.9 \$ 8,130.98	
Storage tank	1180.8 m3		100	10000	97000		2800	0.65 \$ 375,012.37	
Vacuum drum	180.0 m2		10	180	-63000		80000	0.3 \$ 316,902.14	
Centrifugefilter, sus	19.7 kW		2	20	57000		660	1.5 \$ 114,542.02	
Pump3	34.6 L/s		0.2	126	6900		206	0.9 \$ 11,898.48	
								\$ 838,620.88	
							Total	\$ 4,570,878.73	

Figure 10 Overview of the equipment list of the base design, 20 metric ton/hr HCl 8wt%. This includes the purchasing cost of each piece of equipment according to the framework of Sinnott & Towler.

Methods of estiatiing ISBL fixed capital costs			
The Lang factor is an installation factor			
C	\$ 16,592,289.80	ISBL capital cost	
F	3.63	Lang Factor	
Σce	\$ 4,570,878.73	total delivered cost	
c			
Typical factors for estimation of project fixed capital cost			
Equipment erection		fer	0.5
Piping		fp	0.6
instrumental and control		fi	0.3
Electrical		fel	0.2
Civil		fc	0.3
Structures and buildings		fs	0.2
Lagging and paint		fl	0.1
Offsites		OS	0.4
Design and Engineering		D&E	0.25
Contingency		X	0.1
Material cost facto	316 SS	fm	1.3
C	\$ 4,570,878.73		
Ce	\$ 16,820,833.74		
CFC2009	\$ 31,791,375.76		
CFC2017	\$ 34,822,689.99		
Location factor Netherlands relative to USGC installation			
LFA	1.19		
CFC	\$ 41,439,001.09		
ISBL	\$ 20,016,792.15	ISBL adjusted	
Estimated total fixed capital cost			
ISBL		\$	16,820,833.74
ISBL+OSBL+D&E+X		\$	41,439,001.09

Figure 11 Overview of the calculations of the total investment cost of the base design, 20 metric ton/hr HCl 8wt%. This includes the purchasing cost of each piece of equipment according to the framework of Sinnott & Towler.

With the initial capital investment known of each design, it would be possible to determine the approximate net return on investment. This can be one by estimating the cost of current practices over a period of time with a set average inflation rate, and comparing this to the estimated cost induced by each proposed design, including an estimation of variable and fixed costs.

The net returns on investment for each design across each scenario have been determined based on a period of fifteen years with 2% inflation regarding variable and fixed capital cost are displayed in table 9 on the next page.

For indicative reasons, a break-even price was calculated for output sludge material of the demineralisation process, if found this product has any value. The prices portrayed in table 10 on the next page are break-even prices for output sludge material per metric ton for twenty metric tons of hydrochloric acid solution per hour at an operating time of 80% of each design. As can be seen in table 10, even if value could be attributed to the output fibres of the demineralisation process, it

would not be sufficient to cover the estimated additional costs of this process, as low-grade recovered paper material would only be worth €75-100 per metric ton, which has a much higher dry content at that.

Table 9 Projected Net Return on Investment for each design and scenario based on a period of fifteen years with an annual inflation of two percent compared to the current standards and practices.

Projected ROI				
Scenario	Base	Air Flow	Spray	Vacuum
WWC	-57%	-51%	-49%	-51%
WC	-57%	-49%	-49%	-52%
Average	-58%	-50%	-50%	-53%
BC	-52%	-44%	-44%	-47%
BBC	-52%	-44%	-44%	-47%

Table 10 Estimated break-even prices for processed sludge material per metric ton for each scenario. This value has to be attained in order to break even the introduction of the demineralisation process compared to the current situation.

Designs								
Scenario	Base		Air flow		Spray		Vacuum	
WWC	€	511	€	370	€	338	€	377
WC	€	500	€	330	€	330	€	375
Average	€	526	€	338	€	338	€	385
BC	€	534	€	321	€	321	€	395
BBC	€	514	€	284	€	286	€	369

5.4. Paper mill

Another avenue to explore would be the introduction of a demineralisation process downstream of the flotation process at a non-specific paper recycling mill. The main advantage would be the relatively small initial capital investment requirement and additional variable and fixed cost, as pulping and dewatering equipment are already in place. A disadvantage would be the transport of hydrochloric acid from Delfzijl to any participating paper mill. The matter on where to situate a demineralisation process of hydrochloric acid with deinking sludge would be after the first stage of dewatering of the sludge. This helps to reduce overall process flow and thus equipment sizes whilst not introducing additional pulping and dewatering processes.

Two points are depicted by Ter Maat and Rexwinkel in their paper 'Chemische scheiding van calcium carbonaat en papiervezels'. Two variants exist according to Ter Maat and Rexwinkel. Both are situated behind the water treatment facility. Variant I concerns the output of a vibrating sieve unit. The purpose of this sieve unit is to dewater sludge, and creates an output with a relatively high concentration of calcium carbonate. In variant II, a standard thickener processes the sludge. The output of this separation unit also includes relatively high calcium carbonate content. Ter Maat and Rexwinkel provide the a consistency regarding input of the proposed neutralisation reactor, which is portrayed in table 11 at the bottom of this page.

The following table, table 12, describes the expected cost savings of treating deinking sludge with 8wt% hydrochloric acid. The assumption is made that the product of the demineralisation process is to be incinerated. Besides the initial capital investment and annual fixed costs, these cost savings have to cover additional variable cost, mainly transport cost of HCl acid. According research done by Lubrizol, the transport fee will be €0.30 cents per ton of HCl acid 8wt% per kilometre. By comparing the annual requirement of HCl acid for each variant and the expected transport cost, it is possible to deduce the breakeven range of transport, where the transport cost are covered by the expected cost savings of the demineralisation process.

Table 11 Overview composition input sludge for demineralisation process (Maat & Rexwinkel, 2012).

	Variant I	Variant II
Dry content wt%	2.3%	4.2%
Fibre content wt% dc	77.9%	40.9%
Calcium carbonate wt% dc	22.1%	59.1%
Average volumetric flow m3/day	87.4	83.7
Required HCl acid 8wt% m3/day	3.9	18.5

Table 12 Overview annual cost of waste management for Variant I & II. The cost per year is the potential margin which can be gained by the introduction of the demineralisation process.

Produced sludge in tons per hour	Yearly cost of sludge incineration in euros		
	Tons/yr.	Cost per year	
Variant I	0.1	978	k€ 24.5
Variant II	0.2	1710	k€ 42.8

Table 13 Overview annual cost of neutralisation of HCl acid which is required for the demineralisation process for Variant I&II. The cost per year is the potential margin which can be gained by the introduction of the demineralisation process.

Required HCl 8wt% in tons per hour	Yearly cost of neutralisation in euros		
	Tons/yr.	Cost per year	
Variant I	0.2	1153	k€ 10.7
Variant II	0.8	5520	k€ 51.2

Table 14 Annual cost of sludge waste management versus expected cost of sludge waste management for Variant I&II.

	Current yearly cost		Expected yearly sludge cost	
Variant I	k€	35.2	k€	10.7
Variant II	k€	94.0	k€	51.2

Table 15 Approximate distance covered for which required HCl acid can be transported from Lubrizol within expected cost savings in kilometres for each variant.

Transport of HCl 8wt%	Max range (km)
Variant I	60
Variant II	40

The maximum range of transport of hydrochloric acid 8wt% would be around 40-60 km. Again, initial capital investment and annual fixed cost would still have to be covered. This calculation provides only an indication of the impact of the transport of hydrochloric acid and the narrow capital margin in which this new concept has to operate.

The initial investment displayed in table 16 applies for each process design of both variants. This includes a basic initial design but adds an air flow system to improve overall reaction time.

As with the previous calculations of ROI, table 17 represents the ROI of Variant I & II based on a period of fifteen years with 2% inflation regarding variable and fixed capital cost. As can be seen from the table, the most important factor, variable cost of transportation, does not impact the final return on investment in any significant way. This means the initial capital investment and accompanying fixed capital cost heavily outweighs the variable cost, and thus in fact the potential cost-saving margin.

Table 16 Projected initial capital investment required for the introduction of a demineralisation process for Variant I & II based on the framework of Sinnott and Towler.

Projected Capital Investment			
Variant I		M€	1.3
Variant II		M€	1.4

Table 17 Expected ROI for each variant and scenario over a period of fifteen years with an average inflation of two percent compared to the current situation.

	ROI
Variant I	
50km	-95%
100km	-95%
150km	-95%
Variant II	
50km	-89%
100km	-89%
150km	-89%

Lubrizon depicted the cost of transportation of HCl acid to be quite significant, 0.30 euro per metric ton of acid per kilometre within a range of 94 kilometres, and 4.6 cents per metric ton per kilometre plus an additional fee of €455,- for distances greater than 94 kilometres (Schrotenboer, 2015). This results in the following break-even price for output sludge per metric ton. Again, this far exceeds the common value of recovered paper of €75-100 per metric ton.

Table 18 Estimated required break-even prices of output sludge material per metric ton for each scenario of both Variant I & II. This would be the value of output sludge to break even the cost of introducing the demineralisation process at a paper recycling mill compared to the current situation.

Variant	50km	100km	150km
I	€745	€754	€ 773
II	€1379	€1388	€1407

6.0. Conclusions

The last chapters discussed and portrayed the steps taken to answer the research questions of this research project. This chapter will discuss the final conclusions of this research by answering the overall main research question. The main research question of this project is:

'Is it both economically and technically feasible to reduce the ash content of deinking sludge by removing calcium carbonate using hydrochloric acid 8wt%?'

Thus, to answer the main research question, several sub questions were listed. Below, each research question is listed and an answer is provided, depending on the results of this research and in a fair and comprehensive manner.

- What is the effectiveness of 8wt% hydrochloric acid on the removal calcium carbonate from cellulose fibres?

It was found that the average conversion of calcium carbonate from deinking sludge with hydrochloric acid 8wt% is 98.6% based on weight. This conversion should be sufficient to depict hydrochloric acid of this concentration as an effective agent for the removal of calcium carbonate. However effective, hydrochloric acid still is a hazardous substance. Therefore using it for the scrubbing of paper fibres retrieved from deinking processes induces a fair amount of practical issues.

- Which parameters are of importance in the treatment of deinking sludge with an acid?

Besides common parameters in terms of basic reaction kinetics, concentrations, temperature, and pressure, one of the products of the neutralisation reaction, CO_2 , seems to have the most influence on the overall reaction time and reactor design. Inducing an air flow to increase the contact surface of the suspension with the atmosphere allows more CO_2 to be removed, resulting in a significant decrease in overall reaction time. Other more practical solutions might apply, such as a belt filter to increase the contact surface area of the suspension to the atmosphere whilst dewatering the suspension, but only will be of significance beyond exploratory research.

- What is the effect on the quality of the fibres which are present in the deinking sludge?

In short, the quality of the fibres in deinking sludge which were treated in this research with hydrochloric acid was poor in terms of mechanical properties. This was mostly due to a relatively short fibre length distribution. And whether this was due to acid hydrolysis or bacterial degradation is unknown. It is possible that shorter processing times might provide some value, but further research on this subject is required.

- What is the optimal arrangement of process conditions and equipment for the removal of calcium carbonate from cellulose fibres with hydrochloric acid?

Only the basic or minimal equipment was included within the initial designs, which was judged as sufficient for an exploratory research. Thus, little optimisation was included. Most significant improvement which was made is the introduction of an air flow inside the neutralisation reactor to

counteract the dissolution of carbon dioxide. Further information on the designs is present in the appendix.

- Is the implementation of acid treatment for deinking sludge economically feasible?

The net return on investment of a period of fifteen years is -44% at best. Additional output value is required in order to make this process currently economically viable. Perhaps future cost of waste management will increase, but no indication of any significant increase has been provided throughout this research.

- What is the environmental impact of neutralising calcium carbonate in deinking sludge with hydrochloric acid?

Besides the presence of organic material on site at Delfzijl or a tertiary plant location, which would require additional permits due to offensive odours, the production of enormous amounts of carbon dioxide would be an issue. Up to production of 500 m³ per hour of CO₂ is produced. This seems quite an enormous amount of greenhouse gas emissions; however, this would be equivalent to the combustion of 500m³ of methane gas. It is still uncertain what costs must be included and whether this would affect the viability of this process.

There is the case of transporting and processing waste material. According to the Dutch 'Wet Milieubeheer' a company has to apply for a permit to collect, transport and process waste material from either consumers or other businesses. In some scenarios, a permit for the processing of hazardous material has to be acquired according to the 'gevaarlijke afvalstoffen VIHB vergunningaanvraag' at the Nationale en Internationale Wegvervoer Organisatie (NIWO, 2017). A VIHB number has to be acquired through registration at the NIWO. A list of properties for hazardous material is provided in Article 1.1 section 6 in 'Wet milieubeheer' and a list of common waste material are listed in appendix 2000/532/EG of the Commission of the European Communities hence the 3rd of May 2000 (EURAL) (VROM, 2001). This list clearly states that waste hydrochloric acid from inorganic chemical processes is subjected to scrutiny by above stated permits. Further research has to be performed to assure the removal of calcium carbonate with hydrochloric acid is legal.

In short, the process as within the framework of Sinnott and Towler of neutralising hydrochloric acid with deinking sludge seems economically unfeasible. Even within a period of fifteen years, current costs of neutralisation and incineration even under most optimal conditions are almost doubled under this new process. The initial capital investment is thus deemed not cost-effective. But, results regarding the reuse of fibres recovered from deinking sludge are inconclusive. However, even if these fibres hold any value, it would most likely not be enough to cover the excessive amounts of additional costs.

7.0. Discussion

This chapter will discuss several assumptions and potential inconsistencies made throughout the research project. It has to be stated that the calculated initial capital investment of each design is regarded by stakeholders as excessive. Comparative projects are difficult to find, but based on experience, this project has shown extreme required investments. The accuracy of framework of Sinnott and Towler is debatable and has been verified continuously throughout the research. But nonetheless this model should be applicable to determine the potential of this case-study. Therefore, the following section will discuss the assumptions made throughout the development of the economic models. Even with these assumptions and inconsistencies, it is unlikely that the overall conclusions of this research project would change significantly if altered.

7.1. Final products and waste

The current disposal of deinking sludge for paper mills is incineration. Deinking sludge is delivered from paper mills to an incineration facility, with the aim of removing organic material. The remaining material is sold as fly ash to be added to cement. The costs of the entire process of disposing deinking sludge averages around €25,- per metric ton for a non-specific paper mill, depending on dry content, organic content and inorganic content. It is unclear whether deinking sludge after demineralisation is eligible for incineration. Calcium oxide is the main components of fly ash, which is produced from calcium carbonate. Without calcium carbonate, the value of deinking sludge is likely to change. The assumption is made that it would be possible to still incinerate processed sludge, in fact for the same average price per ton as current practice.

Not included in the overall consideration is the change in cost regarding the dewatering and transport of processed sludge material. The assumption is made that the endproduct of the demineralisation process has the same dry content relative to the feedstock. Transport cost of endproduct would diminish as well in this regard. It would be possible to match the dry content of output sludge material to feedstock sludge, however, it would be likely that additional costs are incurred as it would be more difficult to achieve sufficient dewatering, as water takes the place of any removed mineral filler. Thus additional dewatering is required and thus additional cost. The overall assumption made during this research is that it would be possible to gain equal dry content of output sludge at no additional expenses. Realistically, dewatering to an equal dry content would incur more cost, depending on feedstock sludge content, mainly calcium carbonate content.

In the scenario of using hydrochloric acid at a paper mill to neutralise sludge on site, several difficulties arise. First and foremost, the transport of hazardous hydrochloric acid from Delfzijl to various paper mills across the Netherlands. Permits must be attained for transports of acid, which may not be given out by the respective municipalities for a multitude of reasons. These reasons most likely tend to be focussed on safety as urban areas might have to be crossed for the deliverance of acid.

Another point of discussion is the (additional) carbon dioxide emissions at the site where the process of neutralisation of hydrochloric acid takes place. Along the entire production chain, the total emission of carbon dioxide remains constant, as calcium carbonate is processed to calcium oxide,

releasing carbon dioxide. Additionally, the calcium oxide currently used at Lubrizol for the neutralisation of hydrochloric acid is produced in the same manner of incineration, releasing carbon dioxide as well. By combining these two waste products, a large amount of carbon dioxide emissions can be omitted overall. But, by combining these two streams still produces a significant amount of carbon dioxide on the specific location of processing. For the neutralisation of the current production of hydrochloric acid at Lubrizol with calcium carbonate, almost one metric ton of CO₂ is emitted per hour. For any location where such a demineralisation process takes place means acquiring permits for the emission of these amounts of carbon dioxide.

Another issue is that paper fibres can be shortened through acid hydrolysis or bacterial degradation, and it would be crucial to know the average degradation rate of each phenomenon. But what is most important, it is still to be determined whether treated deinking sludge is usable for the production of paper. What has to be known is the usability of paper fibres in deinking sludge after treatment with hydrochloric acid, and the average length of time of which fibres are no longer usable due to degradation. This depicts the maximum allowable time for deinking sludge to be processed and added to the papermaking process. It is also possible that between sources of sludge, this rate of degrading value of fibres will deviate, depending on the initial average fibre length.

Another point of discussion is the amount of paper fibre samples which were tested on usability in regards to papermaking potential and the effects of treatment with hydrochloric acid. Only two paper sludge samples were finally tested at ESKA Hoogezand. An additional sample was collected at ESKA's main paper making machines. Halve of which was treated with acid, analysed and tested to compare against the fibres from the other halve of the sample to compare properties. The only test which was not completed on this specific sample was the depiction of the fibre length distribution of the specific sample due to time constraints. Data has been collected from ESKA depicting an average fibre length distribution of their product material. The accuracy of the proposed price of the fibres after treatment with acid is debateable, but certain is that although surface strength properties of paper material which included processed sludge material improved; dewatering was heavily negatively affected. Only one opinion concerning the value of processed sludge material was provided but this opinion came from a field expert with excellent understanding of the subject. The value mentioned is thus to be considered valid.

7.2. Feed products

Prices for calcium oxide heavily influence the cost of neutralisation of hydrochloric acid at Lubrizol. The cost of neutralisation was established in 2015, but recalculated during the fall of 2016, increasing the estimated cost for neutralisation by almost 10%. Such a large difference within two years could mean that the margins of cost savings for hydrochloric acid at Lubrizol might be lower or higher than estimated and fluctuate significantly in the future. Although the cost of neutralisation has not changed since the fall of 2016 and, according to expert opinion at Lubrizol, is expected not to change significantly in the near future.

The cost of transportation of hydrochloric acid was established several years ago. The current and future cost of transportation may be different. But this does not significantly affect the feasibility of a process to remove calcium carbonate at a paper mill.

The model sludge used for cost calculations is proposed by the CCPB. Although the accuracy of the composition of this sludge falls within the range of variation between deinking sludge from different sources, it's this variation which impacts the final cost of neutralisation quite significantly. The most important attribute for both Lubrizol and a paper mill is the calcium carbonate content, and changes in this content influence the required amount of sludge or acid significantly.

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8.0. Further Research

To conclude this project, a multitude of new questions and issues which were insufficiently explored have arisen. Although this exploratory research provides an overall negative prospect on the use of hydrochloric acid to remove calcium carbonate from paper waste sludge, it is ultimately the stakeholders' decision to progress with this research. Therefore, any uncertainties and unspecified issues are addressed in this section. First is the mapping and availability of all logistically available deinking sludge. At the time of writing, the exact locations of all available deinking sludge suitable for this process and properties are not included. The assumption has been made that sufficient deinking sludge is readily and locally available for treatment with hydrochloric acid produced by Lubrizol.

The effects of acid hydrolysis on the fibre length distribution by hydrochloric acid at this specific concentration are unknown. By exposing sludge to (a surplus of) acid for fixed periods of time, the degradation of the overall average fibre length could be mapped. This periodical measurement could be undertaken to examine bacterial degradation of fibres as well. Further research can be done in the area of degradation of fibres regarding bacteria. Optimal storage and process conditions could be achieved by researching the effects of bacteria on different varieties and compositions of deinking sludge, both treated and untreated. But all in all, it has to be stated that even if fibres from treated deinking sludge can be reused for papermaking, the value of these fibres will not cover the expenses generated by the proposed designs.

Lastly, the emission of CO₂ would include additional costs to any who introduces this demineralisation process. Permits and SHE-aspects have to be thoroughly investigated and must be specified for each scenario and location. Environmental charges are included within the framework of Sinnot & Towler. But it is unknown whether these cost estimations are realistic.

Overall, although the technical elements of the demineralisation process of deinking sludge are feasible, the financial feasibility lacks. At current costing of incineration of processed deinking sludge, each proposed scenario would be unaffordable, even with the inclusion of current additional neutralisation cost hydrochloric acid. Optimisation of the demineralisation process could provide a significant reduction in overall capital cost, with even the slightest of chance of attaining a feasible process. But even with the inclusion of reusing processed sludge, the demineralisation process still seems unfeasible.

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10.0. Appendices

The first section of the appendix entails the first set of experiments performed at Lubrizol. The full set of experiments were aimed at determining technical feasibility of the neutralisation reaction, analysis of deinking sludge samples, and the optimisation of the reaction time. The appendix continues with an overview of the creation of the base design. This chapter is supplemented with process and instrumentation diagrams, as well as process flow diagrams created in Aspen Plus.

Finally, a step-by-step description of the framework of Sinnott and Towler used in this research is provided, as well as an overview of the results of financial feasibility study.

10.1. Experiments Lubrizol Advanced Materials & Resins

The following section will provide a short overview of the test results concerning the neutralisation of calcium carbonate in deinking sludge with hydrochloric acid attained at Lubrizol Delfzijl. Every experiment is performed at Lubrizol Advanced Materials Resin B.V. Delfzijl and supervised by the respective lab administrator at this location.

The aim of these experiments is to eventually partially resolve the research questions mentioned in chapter 3.0, considering the process conditions. The aim is thus to depict the parameters under which the proposed neutralisation reaction would be most feasible, both practical and economical.

Conclusions on the results of these experiments can be summarized by:

- Preferably a conversion rate of 90% of calcium carbonate should be attained in order to attain neutral endproduct and monitoring the reaction through measuring the pH. Only a small surplus of HCl results into a very acidic suspension. This will make it quite arduous to determine whether the reaction has been completed and an acidic endproduct is not favoured by stakeholders. The cause of these difficulties is due to varying concentration of calcium carbonate at small amounts of deinking sludge. It also makes monitoring the neutralisation reaction rate next to impossible if during some experiments, a surplus of acid is present in the suspension.
- Monitoring the reaction is done through measuring the pH of the suspension at constant intervals. The pH provides an indication on the overall concentration of HCl in the suspension at any given time.
- Ambient temperature and pressure can be applied. These parameters have influence on overall reaction time but practicality seems to be an issue. This makes altering these process conditions undesirable.
- The largest practical issue found during experiments was the production of CO₂. The bubbling phase influences the accuracy of monitoring the reaction. The build-up of CO₂ foam potentially encloses reactants, resulting in inconsistent reaction times.

10.1.1. Overview sludge samples

Two samples of deinking sludge were attained from various paper recycling mills. Another sludge sample was retrieved from a different paper mill, specifically the water clarification process or DAF unit. This sample was included to indicate the possibility of using a demineralisation process not only for deinking sludge, but for other sludge waste streams within the paper recycling industry as well. An overview of basic properties of each sample is provided below. The data was supplied by either datasheets provided by each paper mill or through experimentation of the sludge samples.

Table 19 Overview properties deinking sludge samples (A and B), and a sample collected from a DAF unit (C). Each sample is stored at 4-7°C in an airtight container.

A	
Dry content A	53.3 wt%.
Moisture content	46.7 wt%.
Titration CaCO ₃	26.7 wt%.
CaCO ₃ % DC	50.1 wt%.
Av. Bulk Density	0.54 g/ml
Initial pH	7.7
Appearance	Flakes
Colour	Light grey

B	
Dry content	58.0 wt%.
Moisture content	42.0 wt%.
Titration CaCO ₃	21.0 wt%.
CaCO ₃ % DC	36.3 wt%.
Av. Bulk Density	0.26 g/ml
Initial pH	8.9
Appearance	Flakes
Colour	Dark grey

C	
Dry content	9.4wt%.
Moisture content	90.6 wt%.
Titration CaCO ₃	2.7 wt%.
CaCO ₃ % DC	28.5 wt%.
Av. Bulk Density	1.03 g/ml
Initial pH	~6.5
Appearance	Viscous
Colour	Dark grey

10.1.2. Practical issues

The neutralisation reaction is almost an instantaneous reaction, meaning >99% of hydrochloric acid has disappeared after a few seconds. The sudden production of CO₂ results in a rapid expansion of the suspension in terms of volume. The resulting foam creates enclosed pockets in which reactants and fibres can be trapped. This phenomenon itself causes difficulty in determining the exact pH of the total suspension due to this bubbling phase as well as suspicion of affecting the overall reaction rate. Observed was an almost immediate increase of 200-400% in total volume after adding hydrochloric acid to the suspension of sludge. Most CO₂ disappears immediately after adding the HCl acid, as the total volumes of produced gas from mere 100 grams of dry content sludge across samples are estimated to be between six to eleven litres at a conversion of 100%.

Table 20 Average produced CO₂ in litres in relation to 100G of sludge sample (dry content).

	MASS DC (G)	MASS CaCO ₃ (G)	MOL CO ₂	MASS CO ₂ XA=100% (G)	VOLUME CO ₂ (L)
A	100	50.08	0.50	22.02	11.1
B	100	36.25	0.36	15.94	8.1
C	100	28.53	0.29	12.54	6.3

Furthermore, around a pH of 4-5, the concentration of HCl becomes too low to impact the overall reaction rate significantly. CO₂ is suspected to take over as the rate determining entity, in terms of shifting pH. This issue was suggested by (Maat & Rexwinkel, 2012) and was confirmed by monitoring the pH whilst blowing air through the suspension after this point in pH has been reached. The pH rapidly increased to neutral values after initiating air flow. Remarkable is that the solubility of CO₂ in water supposedly should be lower at higher temperatures. Whereas the found results display a lower final value for the pH during testing. An explanation for this phenomenon has yet to be found.

In terms of improving the reaction time in a larger scale process, several solutions are possible regarding a reduction in the influence of CO₂ on the overall reaction rate. These will be discussed in section 5.2.

10.2. Base Design & Simulation

Aspen Plus information:

- Almost all components are expressed as conventional components.
- Calcium carbonate is expressed as a solid component, as well as other filler components of deinking sludge.
- Non-conventional solids to express cellulose, with added particle size distribution found at ESKA Hoogezand. Listed in CISOLID stream. Not involved in any reaction or phase equilibrium.
- ELECTNRTL database for ease of reaction and subcomponents.
- Reaction time is therefore based on experimentation performed at Lubrizol.
- Non-reacting substances such as filler components, cellulose, and argon are included for mass balancing. No recycling streams are included in the proposed designs.
- Solid handling not included.
- No user components were added.
- Reactions are included in mix unit operations instead of reactors. Unnecessary inclusion of reactors, as reaction rate found during experiments is far off representable of the reaction provided in Aspen due to inconsistency in the reactions at Lubrizol. An average reaction time is found at Lubrizol, which will be included in the design of a reactor after process simulation.
- CO₂ vent is translated into a component splitter.
- Non-conventional solids cannot be filtered due to missing data.

10.2.1. Material and Energy Balances

The significance of a material balance is that it will determine the quantities of raw materials required and products produced. Balances over individual process units set the process stream flows and compositions, and provide the basic equations for sizing equipment (Sinnott & Towler, Chemical Engineering Design, 2009). It is also to confirm the law of conservation of mass.

Table 21 Mass balance base design 1 ton/hr HCl 8wt%, translated from Aspen Plus 8.

	Units	INGOING FLOW			OUTGOING FLOW	
		SLUDGE	WATER	HCL	VENT2	NEUTRAL3
FROM					VENT	P4
TO		R1	P1	P3		
SUBSTREAM: ALL						
MASS FLOW	KG/HR	709.6	7805.5	1000.0	47.9	9467.3
MASS ENTHALPY	GCAL/HR	-1.57	-29.64	-3.58	-0.10	-34.68
MASS FLOW RATE						
H2O	KG/HR	283.8	7805.5	880.5	0.0	9029.0
TIO	KG/HR	29.8	0.0	0.0	0.0	29.8
AL2SI-01	KG/HR	29.8	0.0	0.0	0.0	29.8
CACO3	KG/HR	0	0	0	0	0
HCL	KG/HR	0	0	2.2E-04	0	4.1E-11
CA++	KG/HR	8.9E-04	0	0	0	44.2
H3O+	KG/HR	0	0	41.7	0	4.5E-05
CO₂	KG/HR	0	0	0	47.9	0.1
CACL2(S)	KG/HR	0	0	0	0	0
CACO3(S)	KG/HR	110.7	0	0	0	0.2
HCO3-	KG/HR	0	0	0	0	0.8
CL-	KG/HR	0	0	77.8	0	77.8
CO3--	KG/HR	1.3E-03	0	0	0	7.9E-04
CELL	KG/HR	255.5	0	0	0	255.5
VOLUME FLOW RATE	CUM/HR	0.51	7.82	0.96	26.44	9.25

Table 22 Mass balance neutralisation phase base design, translated from Aspen Plus 8.

FROM		P3	P2	R2
TO		R2	R2	VENT
SUBSTREAM: ALL				
MASS FLOW	KG/HR	1000.0	8515.2	9515.2
MASS ENTHALPY	GCAL/HR	-3.6	-31.2	-34.8
MASS FLOW RATE				
H2O	KG/HR	880.5	8089.4	9029.0
TIO	KG/HR	0.0	29.8	29.8
AL2SI-01	KG/HR	0.0	29.8	29.8
CACO3	KG/HR	0.0	0.0	0.0
HCL	KG/HR	2.18E-04	0.0	1.04E-08
CA++	KG/HR	0.0	0.0	44.3
H3O+	KG/HR	41.7	0.0	0.0
CO ₂	KG/HR	0.0	0.0	47.9
CACL2(S)	KG/HR	0.0	0.0	0.0
CACO3(S)	KG/HR	0.0	110.6	0.0
HCO3-	KG/HR	0.0	0.0	1.1
CL-	KG/HR	77.8	0.0	77.8
CO3--	KG/HR	0	0.04	4.40E-06
CELL	KG/HR	0	255.5	255.5
VOLUME FLOW RATE	CUM/HR	0.96	8.33	9.32

10.2.2. Equipment selection and sizing

Using standard equipment would allow for easy integration into the rest of the plant. For standardized equipment, national codes and standards are commonly used. The process stream flow averages are increased by 10% for equipment, instrumentation and piping design to allow a sufficient margin of error. The estimated sizes for the main pieces of equipment following the mass balances from the base design file are displayed in next table.

Table 23 Overview sizing main process equipment 1-20 metric ton per hour of hydrochloric acid 8wt%.

MAIN PROCESS EQUIPMENT

1TON/HR	Description	S unit	S	Residence time	Estimated S	S+Margin of error
P1	Pump, process water	m3/h	7.8	NA	7.8	8.6
R1	Suspension vessel, mix	m3	8.3	1800	4.2	4.6
P2	Pump suspension 95%	m3/h	8.3	NA	8.3	9.2
P3	Pump HCl, corrosion resistant	m3/h	1.0	NA	1.0	1.1
R2	Neutralisation phase	m3	9.3	3600	9.3	10.2
P4	Pump, neutralised suspension	m3/h	9.3	NA	9.3	10.2
10TON/HR	Description	S unit	S	Residence time	Estimated S	S+Margin of error
P1	Pump, process water	m3/h	78.2	NA	78.2	86.0
R1	Suspension vessel, mix	m3	83.3	1800	41.7	45.8
P2	Pump suspension 95%	m3/h	83.3	NA	83.3	91.6
P3	Pump HCl, corrosion resistant	m3/h	9.6	NA	9.6	10.6
R2	Neutralisation phase	m3	93.2	3600	93.2	102.5
P4	Pump, neutralised suspension	m3/h	92.5	NA	92.5	101.8
20TON/HR	Description	S unit	S	Residence time	Estimated S	S+Margin of error
P1	Pump, process water	m3/h	156.4	NA	156.4	172.0
R1	Suspension vessel, mix	m3	166.6	1800	83.3	91.6
P2	Pump suspension 95%	m3/h	166.6	NA	166.6	183.3
P3	Pump HCl, corrosion resistant	m3/h	19.3	NA	19.3	21.2
R2	Neutralisation phase	m3	186.3	3600	186.3	205.0
P4	Pump, neutralised suspension	m3/h	185.1	NA	185.1	203.6

10.3. P&IDs

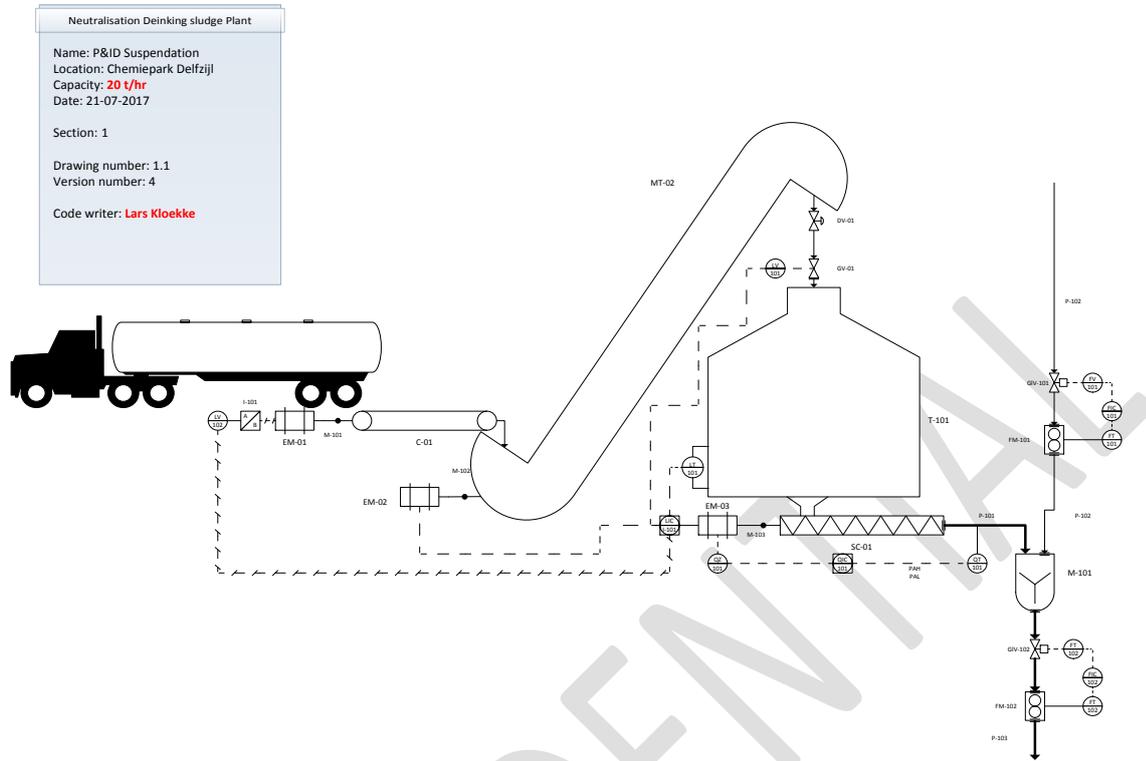


Figure 12 P&ID Suspension phase, created in MS Visio.

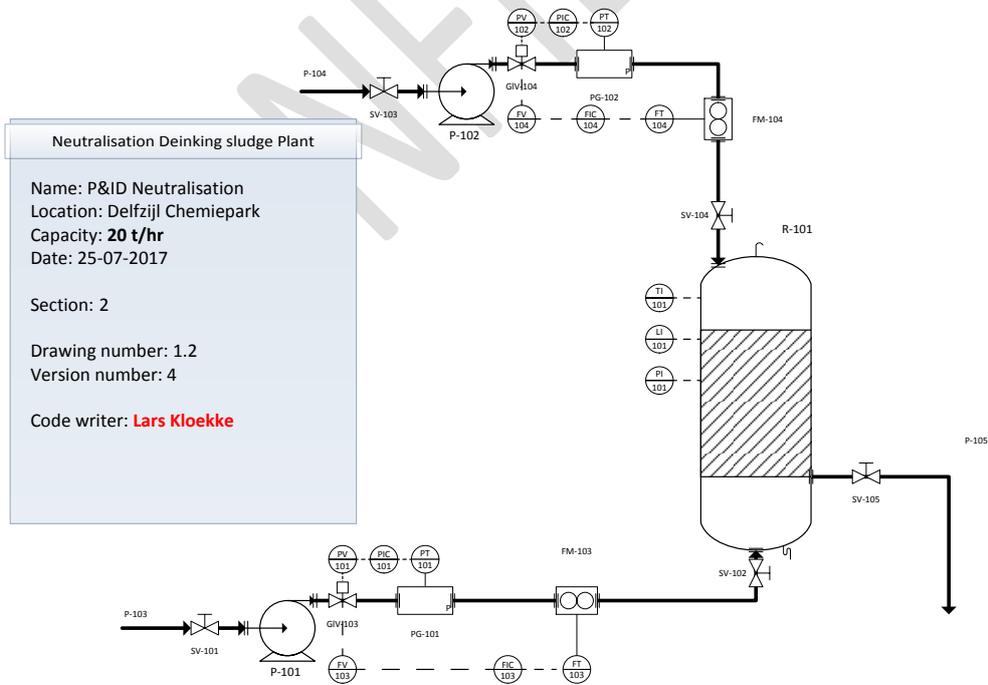


Figure 13 P&ID Neutralisation phase, created in MS Visio.

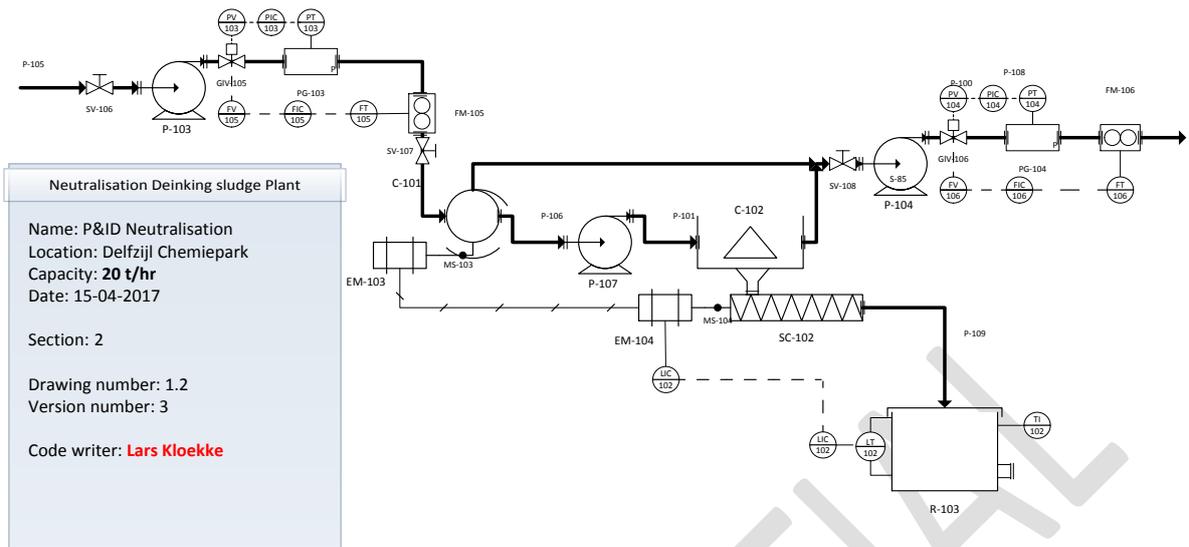


Figure 14 P&ID Dewatering phase, created in MS Visio.

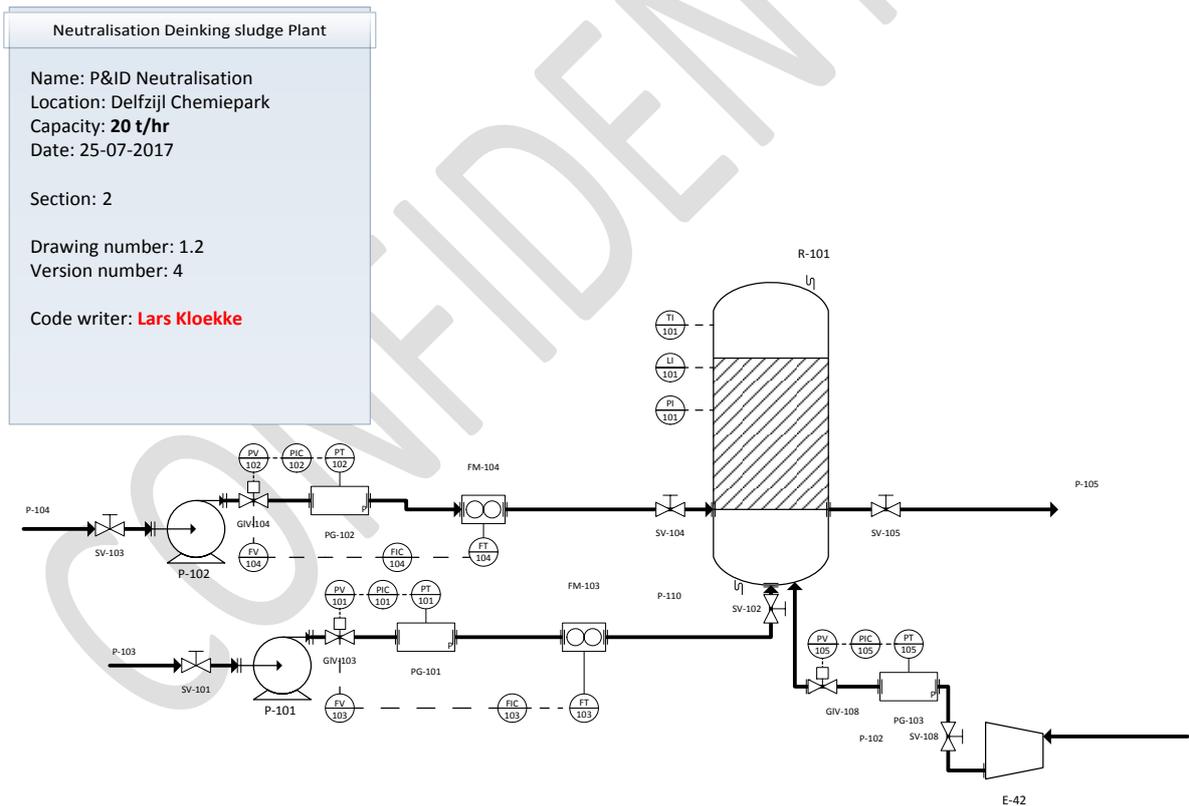
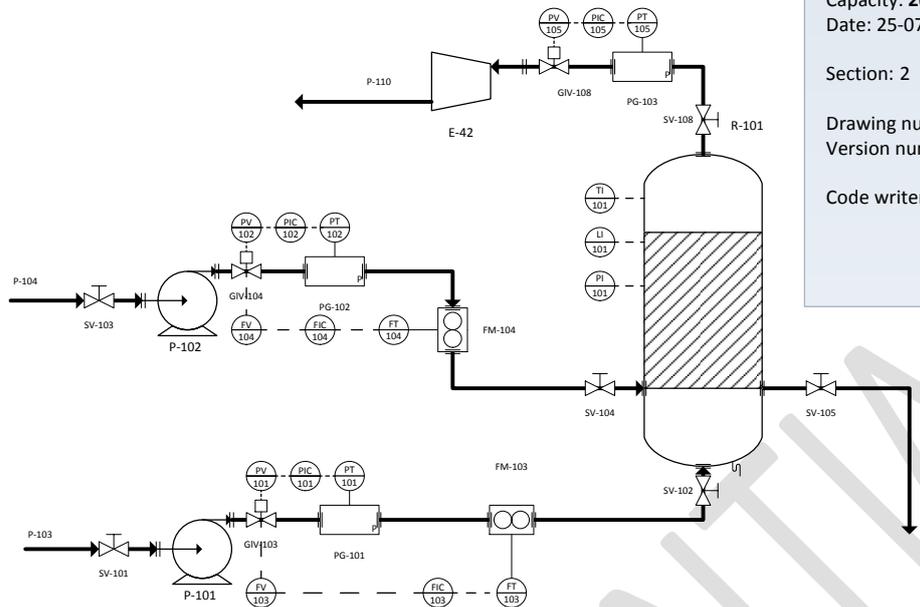


Figure 15 P&ID Neutralisation Air flow, created in MS Visio.



Neutralisation Deinking sludge Plant

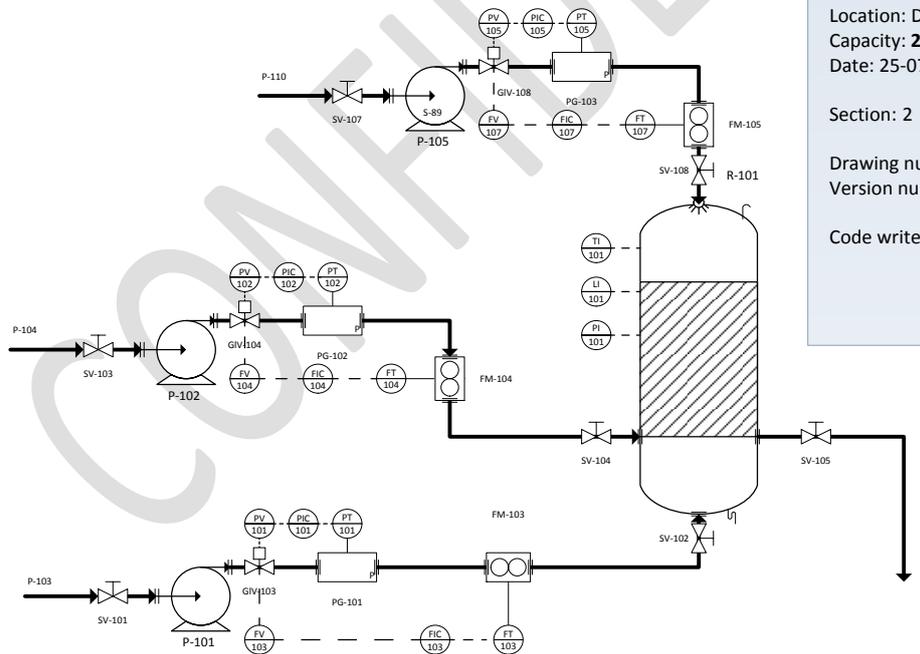
Name: P&ID Neutralisation
 Location: Delfzijl Chemiepark
 Capacity: **20 t/hr**
 Date: 25-07-2017

Section: 2

Drawing number: 1.2
 Version number: 4

Code writer: **Lars Kloekke**

Figure 16 P&ID Neutralisation Vacuum, created in MS Visio.



Neutralisation Deinking sludge Plant

Name: P&ID Neutralisation
 Location: Delfzijl Chemiepark
 Capacity: **20 t/hr**
 Date: 25-07-2017

Section: 2

Drawing number: 1.2
 Version number: 4

Code writer: **Lars Kloekke**

Figure 17 P&ID Neutralisation Water Spray, created in MS Visio.

10.4. Overview Simulations Aspen Plus

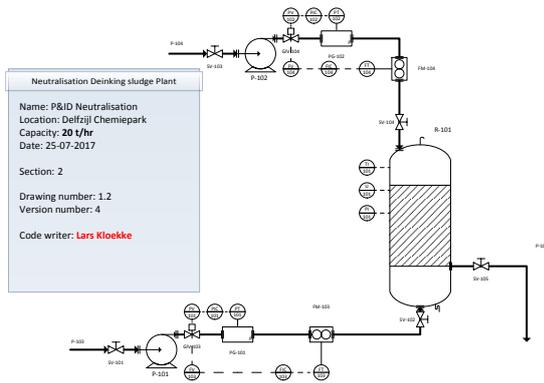


Figure 18 P&ID Neutralisation phase, created in MS Visio.

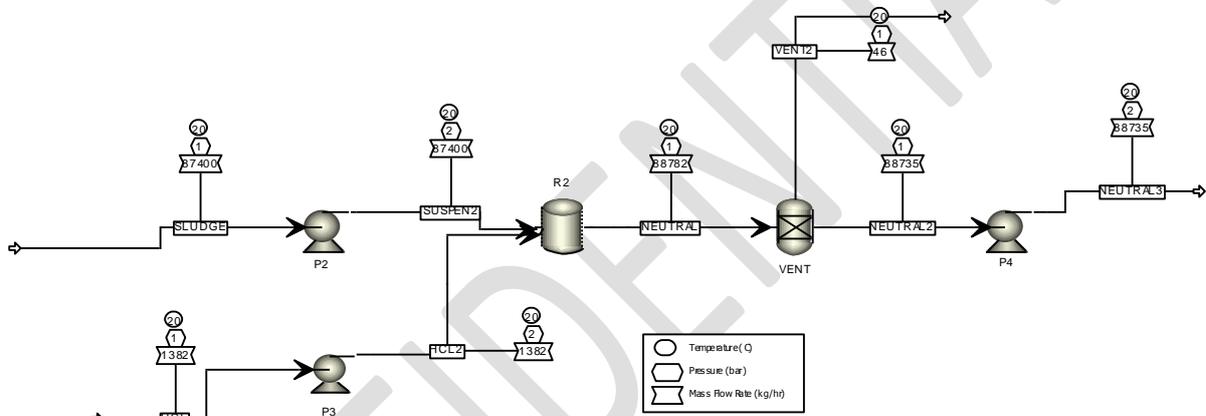


Figure 19 Process Flow Diagram Paper mill Variant I, generated in Aspen Plus 8.

Table 24 Overview mass balance Variant I, generated in Aspen Plus 8.

	HCL	HCL2	NEUTRAL	NEUTRAL2	NEUTRAL3	SLUDGE	SUSPEN2	VENT2
TEMPERATURE C	20	20.1	20.2	20.2	20.2	20	20	20.2
PRESSURE BAR	1	2	1	1	2	1	2	1
MASS VFRAC	0	0	0	0	0	0	0	1
MASS SFRAC	0	0	0.02	0.021	0.021	0.023	0.023	0
*** ALL PHASES ***								
MASS FLOW KG/HR	1381.7	1381.7	88781.7	88735.22	88735.22	87400	87400	46.475
VOLUME FLOW CUM/HR	1.33	1.33	88.068	88.028	88.024	86.745	86.741	25.622
ENTHALPY GCAL/HR	-4.947	-4.947	-330.445	-330.342	-330.339	-325.501	-325.498	-0.099
DENSITY KG/CUM	1038.75	1038.778	1008.102	1008.037	1008.08	1007.556	1007.599	1.814
MASS FLOW KG/HR								
H2O	1216.548	1216.548	86687.15	86691.39	86691.39	85396.96	85396.96	0
TIO	0	0	0	0	0	0	0	0
AL2SI-01	0	0	0	0	0	0	0	0
CACO3	0	0	0	0	0	0	0	0
HCL	0	0	0	0	0	0	0	0
CA++	0	0	79.179	69.755	69.755	0.269	0.269	0
H3O+	57.67	57.67	0.001	0.001	0.001	0	0	0
CO2	0	0	46.476	10.351	10.352	0	0	46.475
CACL2(S)	0	0	0	0	0	0	0	0
CACO3(S)	0	0	239.297	262.832	262.833	436.364	436.364	0
HCO3-	0	0	56.106	27.407	27.406	0	0	0
CL-	107.482	107.482	107.482	107.482	107.482	0	0	0
CO3--	0	0	0.008	0.008	0.008	0.403	0.403	0
CELL	0	0	1566	1566	1566	1566	1566	0

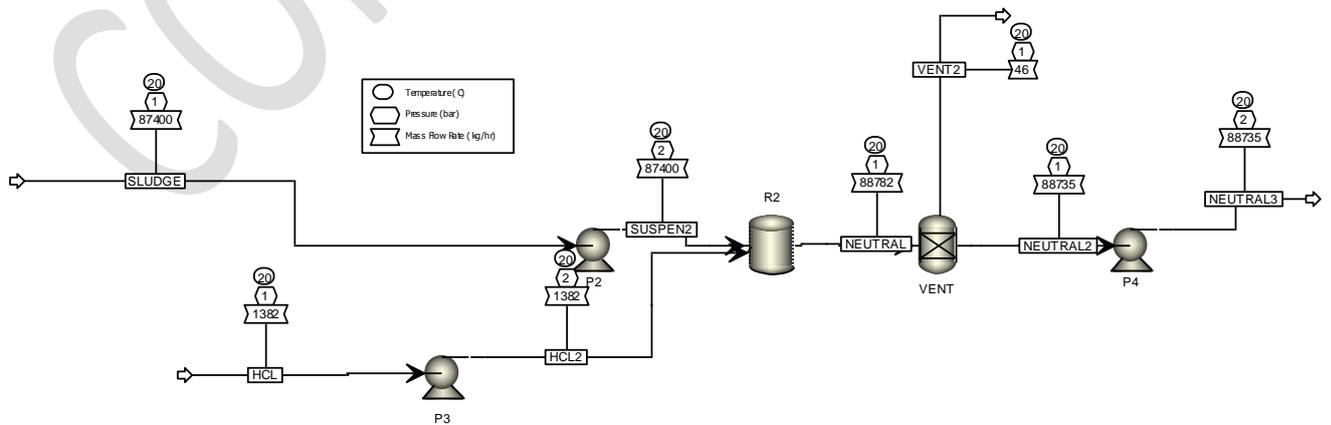


Figure 20 Process Flow Diagram Variant II, generated in Aspen Plus 8.

Table 25 Overview mass balance variant II, generated in Aspen Plus 8.

	HCL	HCL2	NEUTRAL	NEUTRAL2	NEUTRAL3	SLUDGE	SUSPEN2	VENT2
TEMPERATURE C	20	20.1	20.2	20.2	20.2	20	20	20.2
PRESSURE BAR	1	2	1	1	2	1	2	1
MASS VFRAC	0	0	0	0	0	0	0	1
MASS SFRAC	0	0	0.02	0.021	0.021	0.023	0.023	0
*** ALL PHASES ***								
MASS FLOW KG/HR	1381.7	1381.7	88781.7	88735.22	88735.22	87400	87400	46.475
VOLUME FLOW CUM/HR	1.33	1.33	88.068	88.028	88.024	86.745	86.741	25.622
ENTHALPY GCAL/HR	-4.947	-4.947	-330.445	-330.342	-330.339	-325.501	-325.498	-0.099
DENSITY KG/CUM	1038.75	1038.778	1008.102	1008.037	1008.08	1007.556	1007.599	1.814
MASS FLOW KG/HR								
H2O	1216.548	1216.548	86687.15	86691.39	86691.39	85396.96	85396.96	0
TIO	0	0	0	0	0	0	0	0
AL2SI-01	0	0	0	0	0	0	0	0
CACO3	0	0	0	0	0	0	0	0
HCL	0	0	0	0	0	0	0	0
CA++	0	0	79.179	69.755	69.755	0.269	0.269	0
H3O+	57.67	57.67	0.001	0.001	0.001	0	0	0
CO₂	0	0	46.476	10.351	10.352	0	0	46.475
CACL2(S)	0	0	0	0	0	0	0	0
CACO3(S)	0	0	239.297	262.832	262.833	436.364	436.364	0
HCO3-	0	0	56.106	27.407	27.406	0	0	0
CL-	107.482	107.482	107.482	107.482	107.482	0	0	0
CO3--	0	0	0.008	0.008	0.008	0.403	0.403	0
CELL	0	0	1566	1566	1566	1566	1566	0

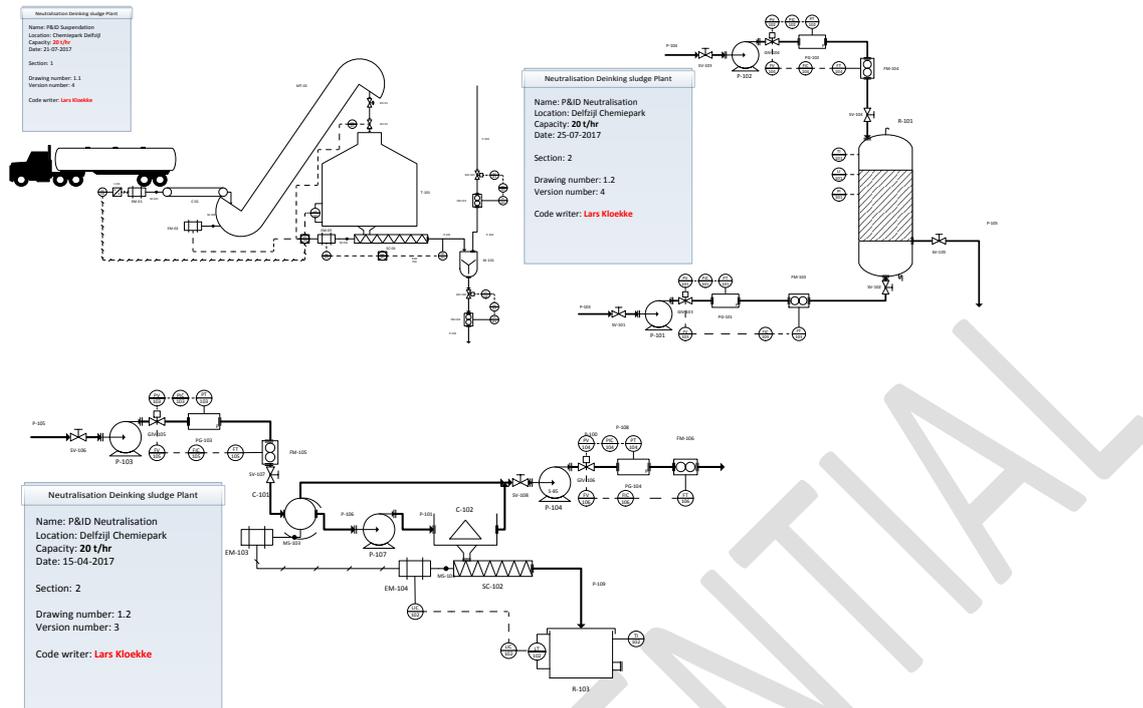


Figure 21 P&ID overview Base Design, created in MS Visio.

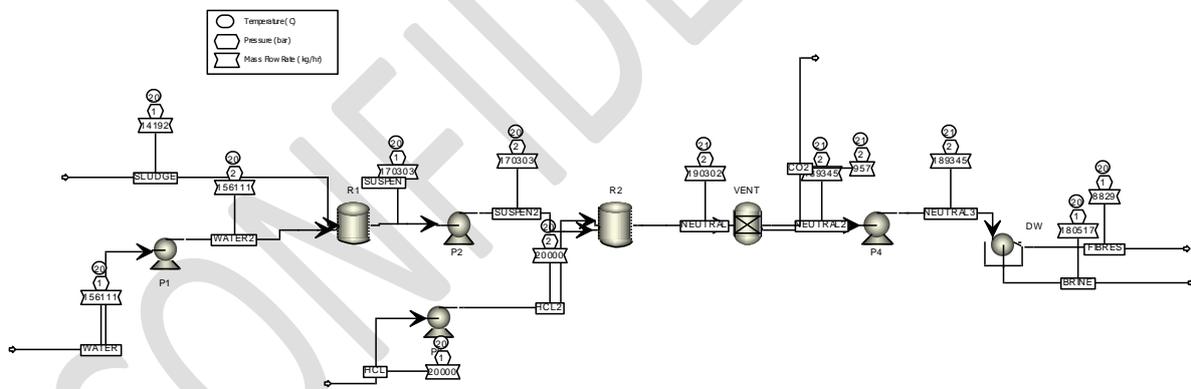
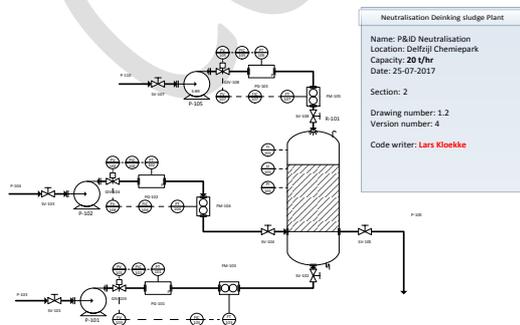


Figure 22 Process Flow Diagram Base Design, 20 ton/hr HCl 8wt%, generated in Aspen Plus 8.

Table 26 Mass balance Base design, 20 ton/hr. HCl 8wt% , generated in Aspen Plus 8.

	BRINE	CO2	FIBRES	HCL	HCL2	NEUTRAL	NEUTRAL2	NEUTRAL3	SLUDGE	SUSPENSION	SUSPENSION2	WATER	WATER2
TEMPERATURE C	20	20.7	20	20	20	20.7	20.7	20.7	20	20	20	20	20
PRESSURE BAR	1	2	1	1	2	2	2	2	1	1	2	1	2
MASS VFRAC	0	1	0	0	0	0	0	0	0	0	0	0	0
MASS SFRAC	0	0	0.714	0	0	0.033	0.033	0.033	0.6	0.05	0.05	0	0
*** ALL PHASES ***													
MASS FLOW KG/HR	180516.8	957.29	8828.525	20000	20000	190302.6	189345.3	189345.3	14191.9	17030.26	17030.26	15611.07	15611.07
VOLUME FLOW CUM/HR	178.801	262.999	3.701	19.254	19.253	183.762	182.521	182.521	7.704	164.075	164.068	156.372	156.365
ENTHALPY GCAL/HR	680.778	-2.047	13.011	71.605	71.604	695.742	693.657	693.657	31.419	624.143	624.138	592.728	592.723
DENSITY KG/CUM	1009.597	3.64	2385.639	1038.75	1038.787	1035.592	1037.391	1037.391	1842.233	1037.954	1037.998	998.333	998.374
MASS FLOW KG/HR													
CELLU-01	0	0	5109.084	0	0	5109.084	5109.084	5109.084	5109.084	5109.084	5109.084	0	0
H2O	178091.9	0	2488.551	17609.44	17609.44	180579.1	180580.4	180580.4	5676.76	16178.6	16178.75	15611.07	15611.07
TIO	0	0	596.06	0	0	596.06	596.06	596.06	596.06	596.06	596.06	0	0
AL2SI-01	0	0	596.06	0	0	596.06	596.06	596.06	596.06	596.06	596.06	0	0
CACO3	0	0	0	0	0	0	0	0	0	0	0	0	0
HCL	0	0	0	0.004	0.004	0	0	0	0	0	0	0	0
CA++	872.358	0	12.19	0	0	886.504	884.548	884.548	0.018	0.51	0.51	0	0
H3O+	0.001	0	0	834.768	834.768	0.211	0.001	0.001	0	0	0	0	0
CO2	2.611	957.29	0.036	0	0	957.29	2.647	2.647	0	0	0	0	0
CACL2(S)	0	0	0	0	0	0	0	0	0	0	0	0	0
CACO3(S)	0	0	4.885	0	0	0	4.886	4.886	2213.892	2212.663	2212.663	0	0
HCO3-	15.592	0	0.219	0	0	22.474	15.81	15.81	0	0	0	0	0
CL-	1534.353	0	21.44	1555.789	1555.789	1555.793	1555.793	1555.793	0	0	0	0	0
CO3--	0.016	0	0	0	0	0	0.016	0.016	0.027	0.764	0.764	0	0



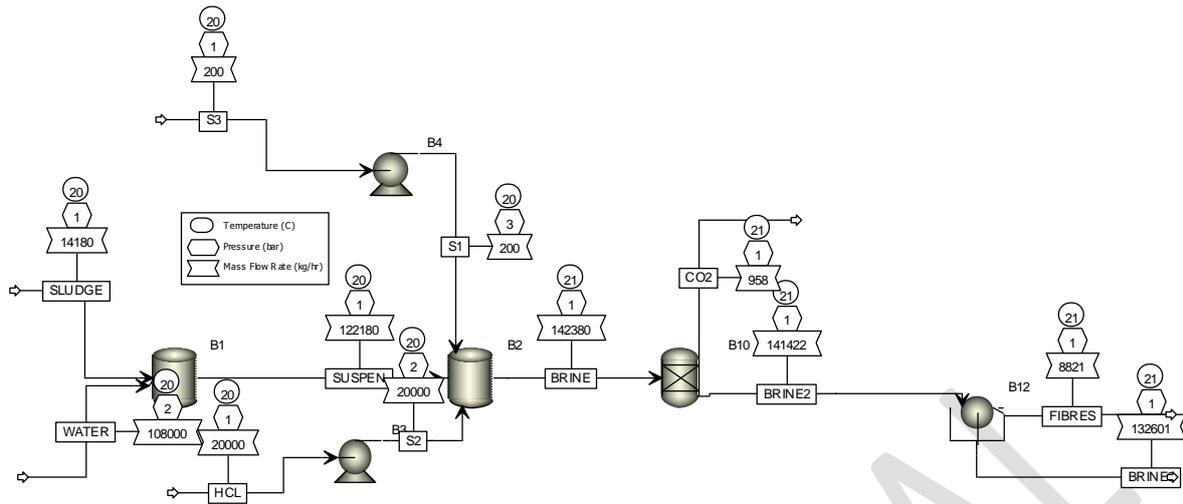


Figure 24 Process Flow Diagram water spray, 20 ton/hr HCl 8wt%, generated in Aspen Plus 8.

Table 27 Mass balance Water spray design generated in Aspen Plus 8.

	BRINE	BRINE2	BRINE3	CO2	FIBRES	HCL	S1	S2	S3	SLUDGE	SUSPEN	WATER
TEMPERATUR E C	21	21	21	21	21	20	20.1	20	20	20	20	20
PRESSURE BAR	1	1	1	1	1	1	3	2	1	1	1	2
VAPOR FRAC	0	0	0	1	0	0	0	0	0	0	0	0
SOLID FRAC	0.006	0.006	0	0	0.237	0	0	0	0	0.172	0.01	0
MOL FLOW KMOL/HR	7495.18 3	7473.42 2	7291.66 5	21.771	181.757	1065.23 8	11.10 2	1065.23 8	11.10 2	380.059	6374.97 9	5994.91 1
MASS FLOW KG/HR	142380	141421. 9	132600. 6	958.14 9	8821.24 5	20000	200	20000	200	14180	122180	108000
VOLUME FLOW CUM/HR	135.781	134.535	130.847	529.64 8	3.688	19.254	0.2	19.253	0.2	7.697	115.878	108.176
ENTHALPY GCAL/HR	-	-	-	-2.049	-12.975	-71.605	-0.759	-71.604	-0.759	-31.393	-441.45	-
MASS FLOW KG/HR	513.813	511.726	498.751									410.057
H2O	132664	132665. 3	130190. 7	0	2474.55 1	17609.4 4	200	17609.4 4	200	5672	113672	108000
HCL	0	0	0	0	0	0	0	0	0	0	0	0
CACO3	0	0	0	0	0	0	0	0	0	0	0	0
CA++	885.761	883.771	867.286	0	16.485	0	0	0	0	0.018	0.358	0
H3O+	0.193	0.001	0.001	0	0	834.771	0	834.771	0	0	0	0
CO2	958.149	2.638	2.589	958.14 9	0.049	0	0	0	0	0	0	0
CACL2(S)	0	0	0	0	0	0	0	0	0	0	0	0
CACO3(S)	0	4.969	0	0	4.969	0	0	0	0	2212.03 5	2211.18 5	0
HCO3-	20.151	13.451	13.2	0	0.251	0	0	0	0	0	0	0
CL-	1555.79 3	1555.79 3	1526.77 3	0	29.02	1555.79 3	0	1555.79 3	0	0	0	0
CO3--	0	0.013	0.012	0	0	0	0	0	0	0.027	0.537	0
CELLULOS	5104.8	5104.8	0	0	5104.8	0	0	0	0	5104.8	5104.8	0
TIO	595.56	595.56	0	0	595.56	0	0	0	0	595.56	595.56	0
AL2SI-01	595.56	595.56	0	0	595.56	0	0	0	0	595.56	595.56	0
MOL FLOW KMOL/HR												
H2O	7363.97 3	7364.04 3	7226.68 4	0	137.358	977.472	11.10 2	977.472	11.10 2	314.844	6309.75 5	5994.91 1
HCL	0	0	0	0	0	0	0	0	0	0	0	0
CACO3	0	0	0	0	0	0	0	0	0	0	0	0
CA++	22.102	22.052	21.641	0	0.411	0	0	0	0	0	0.009	0
H3O+	0.01	0	0	0	0	43.883	0	43.883	0	0	0	0
CO2	21.771	0.06	0.059	21.771	0.001	0	0	0	0	0	0	0
CACL2(S)	0	0	0	0	0	0	0	0	0	0	0	0
CACO3(S)	0	0.05	0	0	0.05	0	0	0	0	22.101	22.093	0
HCO3-	0.33	0.22	0.216	0	0.004	0	0	0	0	0	0	0
CL-	43.883	43.883	43.064	0	0.819	43.883	0	43.883	0	0	0	0
CO3--	0	0	0	0	0	0	0	0	0	0	0.009	0
CELLULOS	31.483	31.483	0	0	31.483	0	0	0	0	31.483	31.483	0
TIO	9.323	9.323	0	0	9.323	0	0	0	0	9.323	9.323	0
AL2SI-01	2.307	2.307	0	0	2.307	0	0	0	0	2.307	2.307	0

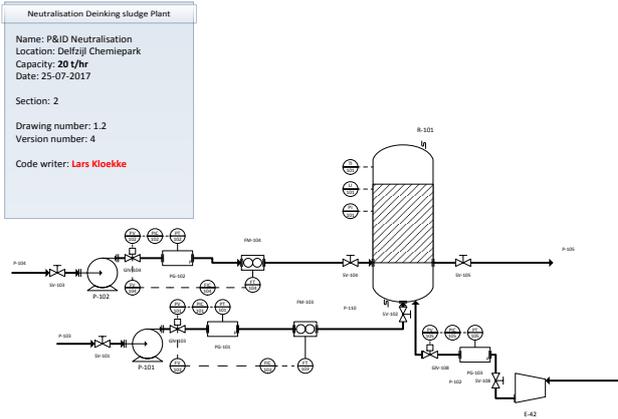


Figure 25 P&ID Air flow design, created in MS Visio.

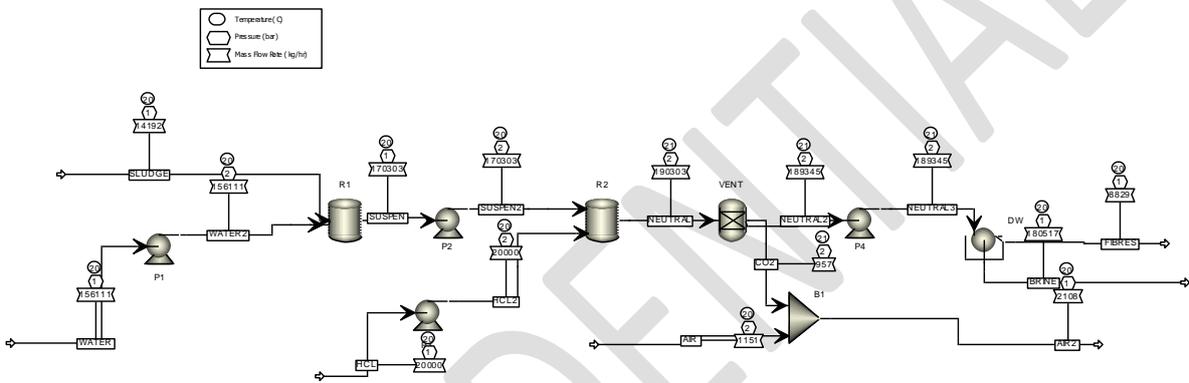


Figure 26 Process Flow Diagram Air flow, 20 ton/hr HCl 8wt%.

Table 28 Mass balance Air flow design, 20 ton/hr HCl 8wt%.

	AIR	AIR2	BRINE	CO2	FIBRES	HCL	HCL2	NEUTRAL	NEUTRAL2	NEUTRAL3	SLUDGE	SUSPENSION	SUSPENSION2	WATER	WATER2
TEMPERATURE C	20	19.7	20	20.7	20	20	20	20.7	20.7	20.7	20	20	20	20	20
PRESSURE BAR	2	1	1	2	1	1	2	2	2	2	1	1	2	1	2
MASS VFRAC	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0
MASS SFRAC	0	0	0	0	0.714	0	0	0.033	0.033	0.033	0.6	0.05	0.05	0	0
*** ALL PHASES ***															
MASS FLOW KG/HR	1150.974	2108.264	1805.16.8	957.29	8828.525	2000.0	2000.0	1903.02.6	18934.5.3	18934.5.3	1419.1.9	1703.02.6	1703.02.6	1561.10.7	1561.10.7
VOLUME FLOW CUM/HR	484	1494.859	178.801	262.999	3.701	19.25.4	19.25.3	183.7.62	182.52.1	182.52.1	7.704	164.0.75	164.0.68	156.3.72	156.3.65
ENTHALPY GCAL/HR	0.002	2.048	680.778	2.047	13.011	71.605	71.604	695.742	693.657	693.657	31.419	624.143	624.138	592.728	592.723
DENSITY KG/CUM	2.378	1.41	1009.597	3.64	2385.639	1038.75	1038.787	1035.592	1037.391	1037.391	1842.233	1037.954	1037.998	998.33	998.374
MASS FLOW KG/HR															
CELLULOSE	0	0	0	0	5109.084	0	0	5109.084	5109.084	5109.084	5109.084	5109.084	5109.084	0	0
H2O	0	0	1780.91.9	0	2488.551	1760.9.44	1760.9.44	1805.79.1	18058.0.4	18058.0.4	5676.76	1617.87.5	1617.87.5	1561.10.7	1561.10.7
TIO	0	0	0	0	596.06	0	0	596.06	596.06	596.06	596.06	596.06	596.06	0	0
AL2SI-01	0	0	0	0	596.06	0	0	596.06	596.06	596.06	596.06	596.06	596.06	0	0
CACO3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HCL	0	0	0	0	0	0.004	0.004	0	0	0	0	0	0	0	0
CA++	0	0	872.358	0	12.19	0	0	886.504	884.548	884.548	0.018	0.51	0.51	0	0
H3O+	0	0	0.001	0	0	834.768	834.768	0.211	0.001	0.001	0	0	0	0	0
CO2	0	957.29	2.611	957.29	0.036	0	0	957.29	2.647	2.647	0	0	0	0	0
CACL2(S)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CACO3(S)	0	0	0	0	4.885	0	0	0	4.886	4.886	2213.892	2212.663	2212.663	0	0
HCO3-	0	0	15.592	0	0.219	0	0	22.474	15.81	15.81	0	0	0	0	0
CL-	0	0	1534.353	0	21.44	1555.789	1555.789	1555.793	1555.793	1555.793	0	0	0	0	0
CO3--	0	0	0.016	0	0	0	0	0	0.016	0.016	0.027	0.764	0.764	0	0
AIR	1150.974	1150.974	0	0	0	0	0	0	0	0	0	0	0	0	0

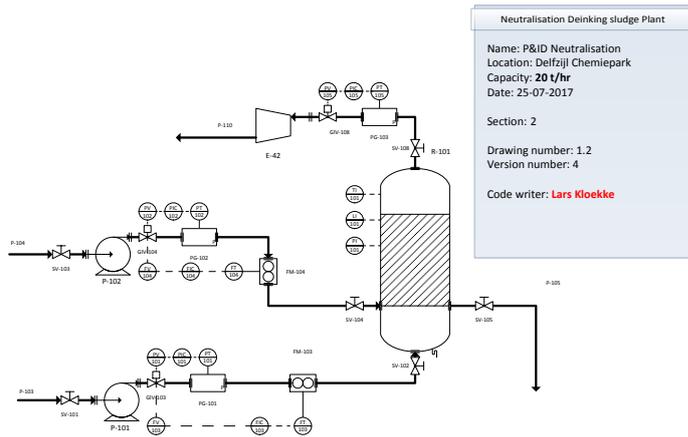


Figure 27 P&ID Vacuum design.

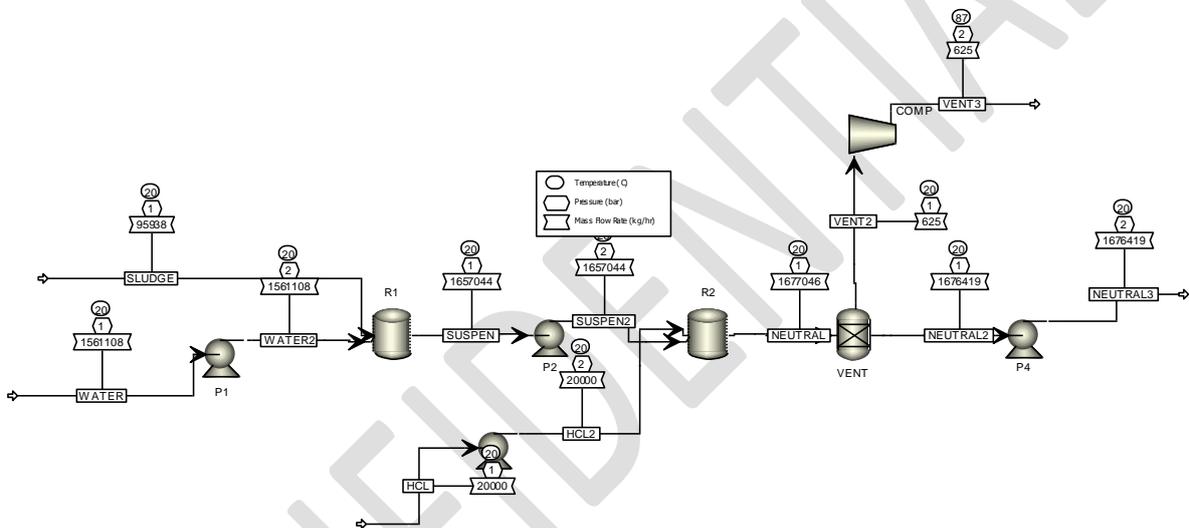


Figure 28 Process Flow Diagram Vacuum design, 20 ton/hr HCl 8wt%..

Table 29 Mass balance Vacuum design, 20 ton/hr HCl 8wt%..

	HCL	HCL2	NEUTR AL	NEUTR AL2	NEUTR AL3	SLUDG E	SUSPE N	SUSPE N2	VENT 2	VENT 3	WATE R	WATE R2
TEMPERATURE C	20	20	20.2	20.2	20.2	20	20	20	20.2	86.8	20	20
PRESSURE BAR	1	2	0.99	0.99	2	1	1	2	0.99	1.99	1	2
MASS VFRAC	0	0	0	0	0	0	0	0	1	1	0	0
MASS SFRAC	0	0	0.022	0.022	0.022	0.408	0.024	0.024	0	0	0	0
*** ALL PHASES ***												
MASS FLOW KG/HR	20000	20000	1.68E+06	1.68E+06	1.68E+06	95938	1.66E+06	1.66E+06	625.444	625.444	1.56E+06	1.56E+06
VOLUME FLOW CUM/HR	19.254	19.253	1654.718	1654.215	1654.142	71.931	1635.645	1635.573	348.285	212.526	1563.717	1563.647
ENTHALPY GCAL/HR	-71.605	-71.604	6312.99	-6311.6	6311.55	314.18	6241.43	6241.38	1.337	1.329	5927.28	5927.24
DENSITY KG/CUM	1038.75	1038.787	1013.492	1013.422	1013.467	1333.759	1013.083	1013.128	1.796	2.943	998.33	998.375
MASS FLOW KG/HR												
H2O	17609.44	17609.44	1.64E+06	1.64E+06	1.64E+06	56767.5	1.62E+06	1.62E+06	0	0	1.56E+06	1.56E+06
TIO	0	0	5960.587	5960.587	5960.587	5960.587	5960.587	5960.587	0	0	0	0
AL2SI-01	0	0	5960.587	5960.587	5960.587	5960.587	5960.587	5960.587	0	0	0	0
CACO3	0	0	0	0	0	0	0	0	0	0	0	0
HCL	0.004	0.004	0	0	0	0	0	0	0	0	0	0
CA++	0	0	1189.194	1042.59	1042.489	0.179	5.099	5.099	0	0	0	0
H3O+	834.768	834.768	0.018	0.009	0.009	0	0	0	0	0	0	0
CO2	0	0	625.458	161.132	161.144	0	0	0	625.444	625.444	0	0
CACL2(S)	0	0	0	0	0	0	0	0	0	0	0	0
CACO3(S)	0	0	19169.46	19535.81	19535.84	22138.88	22126.59	22126.59	0	0	0	0
HCO3-	0	0	943.237	496.501	496.467	0	0	0	0	0	0	0
CL-	1555.789	1555.789	1555.793	1555.793	1555.793	0	0	0	0	0	0	0
CO3--	0	0	0.157	0.165	0.165	0.268	7.636	7.636	0	0	0	0
CELL	0	0	5110	5110	5110	5110	5110	5110	0	0	0	0

10.5. Assumptions Economic Model

Several assumptions are made throughout the economic model. Starting with the assumptions regarding the feedstock and product prices, and content;

1. Currently, paper mills on average have to pay €25,- per metric ton of deinking sludge for its removal (transport) and elimination through incineration. For ease of calculation, in the case of a third party, in respect to a paper mill, handling the demineralisation process with HCl acid, it is assumed that the same amount of cost applies for the paper mill. An average amount of €25,- per metric ton is to be paid for transport and removal of this waste stream. Any eventual profit or diminishing cost can eventually be spread across all involved parties, allowing the paper a financial compensation if possible, in respect to the current method of incineration.
2. Only four different samples including a 'model' sludge sample were included in testing and further calculations. Although a clear and definite distribution between each sample were found in regards to content, it could be possible that other paper mills could supply deinking sludge which very different when compared to the tested samples. In regards to which factors of deinking sludge are of any significance, this is expressed in the discussion section of this report.
3. The third assumption is that it would be possible to convert the feedstock sludge stream to the final product stream and eventually produce sludge with the same relative dry content. This means that both calcium carbonate and a portion of water are removed from the deinking sludge stream in respect to the final product stream.
4. The objective of the demineralisation process is to remove calcium carbonate filler from deinking sludge using hydrochloric acid. The final product is a sludge containing mostly fibres and fines, other mineral fillers, calcium chloride salts and remaining contaminants. The assumption is made that this product can be sold for the same price per metric ton as the feedstock deinking sludge. This allows for a margin of 30-50%, in regards to conversion of feedstock to product, as this quantity is expected to be removed from the sludge stream, depending on calcium carbonate content of the feedstock.
5. Another assumption regarding to feedstock is the concentration of hydrochloric acid produced by Lubrizol. The concentration of hydrochloric acid has been found to not be consistently between eight and nine percent regarding weight. Lower percentages of HCl acid were found by the researcher, as low as 6.9 wt%. For calculation regarding the economic model, a range of three percentages were used to calculate acid requirements for the demineralisation process from best to worst case scenario in regards to Lubrizol. These percentages were set at seven, eight, and nine weight percent respectively.
6. Three day storage capability for both feedstock and product.
7. The framework as described by Sinnott and Towler provides only option in the case of corrosion resistant reactors; glass lined. The issue with this option is that the design variable is the size of the reactor. The upper and lower limits on this variable are 25 and 0.5 cubic metres respectively. For a required reactor size lower than 0.5, this does not impact the final estimation of the required investment costs for each scenario coping with this phenomenon. It is only when a (much) larger reactor is required. For the conversion of ten or twenty metric tons of hydrochloric acid, up to eight of these reactors are required. Therefore, for modelling

purposes, multiple reactors are included. Later stages in the design can opt for changes in the number of reactors.

10.6. Complementary Process Design

Three basic scenarios are possible regarding the location of the demineralisation process:

- 1) At Lubrizol Delfzijl.
- 2) At individual participating paper mill either generating sludge or using the final products.
- 3) On a central location most suitable for treatment of waste materials.

Furthermore, there are several scenarios possible in terms of production capacity, process design, and product disposal. For production capacity, it largely depends on the location of the proposed process. To translate the location, a rough estimate of the production capacity is used:

- 1) Production capacity: 20 metric ton/h HCl 8%.
- 2) Production capacity: 0.1 metric ton/h HCl 8%.
- 3) Production capacity: 1 metric ton/h HCl 8%.

The deinking sludge in question is divided into three compositions. Two of which are directly comparable to the samples provided by the paper industry. The third is based on a 'model' sludge proposed by the CCPB as a representative sludge. This all in regard to dry content, filler content, and calcium carbonate content.

Furthermore, there are several possible design solutions regarding the practical issues depicted regarding removal of CO₂ from the suspension, the dewatering of fibres, and achieving a neutral endproduct.

For counteracting foam production there are three methods:

- Apply a negative pressure with expansion vessel.
- Direct air flow
- Continuous top down water spray

In the case of dewatering fibres after neutralisation, there are three main design options. A combination of methods would also be applicable.

- Flocculants
- Vacuum filtration for dewatering
- Centrifugal separation for dewatering

Lastly there are two options for decreasing the overall reaction time. A high conversion of hydrochloric acid has been observed in the first few minutes of the reaction, as the pH increases rapidly from around 0 pH to 4 in mere minutes. This increase indicates a conversion of HCl of more than 99%. As the reaction time is based on pH, the pH level of the suspension can be increased manually by adding a strong alkaline. Another option would be to transfer the suspension after a certain period of time when the pH has reached a threshold of for example pH 4 into a larger storage

vessel, where the reaction can continue. These processes can be considered refinement processes of the process stream to conform to the demands of the stakeholders; a pH neutral endproduct.

10.6.1. Testing possible scenarios

In order to depict whether the removal of calcium carbonate from deinking sludge would be practically feasible, a multitude of potential process designs can be developed. A base design would remain identical throughout different scenarios, each scenario testing and validating suggestions provided by both the researcher and stakeholders. The differences between the scenarios posted are mainly concerning carbon dioxide removal and the dewatering of the treated fibres.

The most optimal process design for each proposed production capacity is determined throughout establishing an economic analysis. The primary criterion for design selection is the economic performance. The economic performance is determined through analysing the capital and operating costs. In the case of close variation, the safest design will be chosen. By estimating the required investment costs, as well as determining the average required variable costs, a net return on investment (ROI) can be calculated. The ROI portrays the efficiency of a certain investment within a reasonable margin of error. The ROI is used for its simplicity and versatility its use is therefore widespread as a gauge of an investment's profitability. Finally, highest ROI indicates the best possible investment given the constraints set by the researcher and stakeholders of the project. The next section will provide an overview of the ROI of the depicted scenarios.

Yield of paper fibres from sludge potentially lower due to insufficient fibre length. At mesh smaller than 200, fibres would probably not be recovered and removed alongside the brine stream after the dewatering process. The effects of exposing fibre to both fibres and bacteria would lessen the yield of potentially reusable fibres.

As described above, two dewatering mechanisms are possible to implement. To avoid calculations of every possible scenario twice, the choice has been made to identify one optimal dewatering mechanism beforehand, and maintaining this throughout every scenario. The choice was finally made to include all dewatering methods within each design, as literature and stakeholders have indicated the essential use of using both dewatering methods in combination with flocculants as this is standard practice to attain a desirable dry content higher than 50% (Göttsching & Pakarinen, Recycled Fiber and Deinking, 2000).

10.6.2. Economic Model Results

Table 35 displays the minimal required process equipment for processing one metric ton of hydrochloric acid per hour. Additional process designs include increased production capacities at ten and twenty tons per hour, which basically include more reactors, as well as additional process equipment for optimisation initiatives. Factor 'S' corresponds to a certain variable which was based on the designed mass flow rate (+10%) and reaction time, if applicable. For each piece of equipment, limits were set at which the framework would still hold a certain degree of accuracy. Ultimately, the designs based on processing one and ten metric tons of HCl acid were not included in the results of this report, as these designs were less viable and less practical.

The purchasing costs were calculated using the following formula:

$$C_e = a + b S^n$$

By multiplying the purchasing cost with the Lang factor, an initial estimation of the ISBL can be made. The results are as displayed below in M\$ rounded to one decimal.

Table 30 Overview ISBL estimation based on framework of Lang.

Scenario	Base	Air flow	Vacuum	Flocculants	Water spray
WWC	M\$ 17.7	M\$ 14.1	M\$ 14.5	M\$ 13.4	M\$ 13.5
WC	M\$ 16.3	M\$ 12.6	M\$ 13.6	M\$ 12.5	M\$ 12.6
Average	M\$ 16.6	M\$ 12.6	M\$ 13.6	M\$ 12.5	M\$ 12.6
BC	M\$ 13.1	M\$ 10.2	M\$ 11.3	M\$ 10.2	M\$ 10.2
BBC	M\$ 12.1	M\$ 9.4	M\$ 10.4	M\$ 9.4	M\$ 9.4

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Table 31 Overview framework Sinnot & Towler for calculating ISBL/OSBL

Typical factors for estimation of project fixed capital cost		
Equipment erection	fer	0.5
Piping	fp	0.6
Instrumental and control	fi	0.3
Electrical	fel	0.2
Civil	fc	0.3
Structures and buildings	fs	0.2
Lagging and paint	fl	0.1
Off-sites	OS	0.4
Design and Engineering	D&E	0.25
Contingency	X	0.1
Material cost factor SS 316	fm	1.3

According to Sinnot & Towler, the purchasing cost can be multiplied with the factors above to calculate the project fixed capital cost according to formula:

$$C = \sum_{i=1}^{i=M} C_{e,i,CS} [(1 + f_p)f_m + (f_{er} + f_{el} + f_i + f_c + f_s + f_l)]$$

Where:

$C_{e,i,CS}$ = purchasing cost of equipment i in carbon steel.
 M = number of pieces of equipment.

Table 32 ISBL of each design and scenario according to the framework of Sinnot and Towler for 20 metric ton per hour HCl solution.

Scenario	Base	Air flow	Vacuum	Flocculants	Water spray
WWC	M\$ 17.9	M\$ 14.3	M\$ 14.7	M\$ 13.6	M\$ 13.6
WC	M\$ 16.5	M\$ 12.8	M\$ 13.8	M\$ 12.7	M\$ 12.8
Average	M\$ 16.8	M\$ 12.8	M\$ 13.8	M\$ 12.7	M\$ 12.8
BC	M\$ 13.3	M\$ 10.4	M\$ 11.4	M\$ 10.3	M\$ 10.4
BBC	M\$ 12.3	M\$ 9.5	M\$ 10.6	M\$ 9.5	M\$ 9.5

The average difference found was 13.4%, which falls within the error range of $\pm 25\%$. By including off-site costs, design and engineering cost and incorporate a contingency, the following figures arise.

Table 33 Overview ISB + OSBL of each design in each scenario according to framework Sinnot and Towler.

ISBL+OSBL					
Scenario	Base	Air flow	Vacuum	Flocculants	Water spray
WWC	M\$ 33.9	M\$ 27.0	M\$ 27.7	M\$ 25.7	M\$ 25.8
WC	M\$ 31.2	M\$ 24.1	M\$ 26.1	M\$ 24.0	M\$ 24.2
Average	M\$ 31.8	M\$ 24.1	M\$ 26.1	M\$ 24.0	M\$ 24.1
BC	M\$ 25.1	M\$ 19.6	M\$ 21.6	M\$ 19.5	M\$ 19.6
BBC	M\$ 23.2	M\$ 18.0	M\$ 20.0	M\$ 17.9	M\$ 18.0

Figures drawn within the framework of Sinnot & Towler need to be adjusted to current values. The index chosen to adjust these figures is the CEPCI index as recommended by Sinnot & Towler.

Table 34 Adjusted capital investment for each design and scenario according to CEPCI index.

CEPCI index					
Scenario	Base	Air flow	Vacuum	Flocculants	Water spray
WWC	M\$ 37.2	M\$ 29.5	M\$ 30.4	M\$ 28.2	M\$ 28.3
WC	M\$ 34.2	M\$ 26.4	M\$ 28.6	M\$ 26.3	M\$ 26.5
Average	M\$ 34.8	M\$ 26.4	M\$ 28.6	M\$ 26.3	M\$ 26.4
BC	M\$ 27.5	M\$ 21.5	M\$ 23.6	M\$ 21.4	M\$ 21.5
BBC	M\$ 25.4	M\$ 19.7	M\$ 21.9	M\$ 19.6	M\$ 19.8

The framework of Sinnot & Towler is based on US Gulf Coast parameters. By multiplying the ISBL+ OSBL to a 'location factor' as described by Sinnot & Towler, which is 1.19 for the Netherlands, the correct figures can be drawn.

Table 35 Adjusted initial capital investment based on location factor of the Netherland (=1.19) according to Sinnot and Towler.

Adjusted to location (=1.19 for the Netherlands)					
Scenario	Base	Air flow	Vacuum	Flocculants	Water spray
WWC	M\$ 44.2	M\$ 35.2	M\$ 36.1	M\$ 33.5	M\$ 33.7
WC	M\$ 40.7	M\$ 31.4	M\$ 34.0	M\$ 31.3	M\$ 31.5
Average	M\$ 41.4	M\$ 31.4	M\$ 34.1	M\$ 31.3	M\$ 31.4
BC	M\$ 32.7	M\$ 25.5	M\$ 28.1	M\$ 25.4	M\$ 25.5
BBC	M\$ 30.2	M\$ 23.5	M\$ 26.1	M\$ 23.4	M\$ 23.5

Finally, the conversion to the currency used in the Netherlands.

Table 36 Adjusted initial capital investments for each design and scenario to Euros.

Projected fixed capital cost in euros		€/ \$ as of 29-09 0.85			
Scenario	Base	Air flow	Spray	Vacuum	
WWC	M€ 37.4	M€ 29.8	M€ 28.5	M€ 30.6	
WC	M€ 34.4	M€ 26.6	M€ 26.7	M€ 28.8	
Average	M€ 35.1	M€ 26.6	M€ 26.6	M€ 28.8	
BC	M€ 27.7	M€ 21.6	M€ 21.6	M€ 23.8	
BBC	M€ 25.6	M€ 19.9	M€ 19.9	M€ 22.1	

Table 37 Overview fixed and variable capital costs of each design and scenario based on the framework of Sinnot and Towler.

Projected Variable Cost						
Scenario	Base	Air flow	Vacuum	Flocculants	Water spray	
WWC	k€ 2,008	k€ 2,039	k€ 1,968	k€ 1,973	k€ 1,976	
WC	k€ 1,786	k€ 1,760	k€ 1,751	k€ 1,753	k€ 1,757	
Average	k€ 1,765	k€ 1,739	k€ 1,730	k€ 1,732	k€ 1,736	
BC	k€ 1,170	k€ 1,150	k€ 1,143	k€ 1,145	k€ 1,148	
BBC	k€ 1,024	k€ 1,008	k€ 1,001	k€ 1,002	k€ 1,006	
Projected Fixed cost						
Scenario	Base	Air flow	Vacuum	Flocculants	Water spray	
WWC	k€ 3,967	k€ 3,358	k€ 3,423	k€ 3,246	k€ 3,258	
WC	k€ 3,728	k€ 3,105	k€ 3,282	k€ 3,096	k€ 3,110	
Average	k€ 3,780	k€ 3,106	k€ 3,283	k€ 3,100	k€ 3,106	
BC	k€ 3,191	k€ 2,709	k€ 2,884	k€ 2,702	k€ 2,710	
BBC	k€ 3,026	k€ 2,569	k€ 2,745	k€ 2,563	k€ 2,573	

Table 38 Overview initial capital investment required for Variant I & II according to the framework of Sinnot and Towler.

	ISBL Lang factor	ISBL Sinnot & Towler	ISBL+ OSBL	CEPCI	Location factor	ISBL/OSBL Euro
Variant I	k\$ 604	k\$ 612	k\$ 1,157	k\$ 1,267	k\$ 1,508	k€ 1,282
Variant II	k\$ 673	k\$ 682	k\$ 1,289	k\$ 1,412	k\$ 1,680	k€ 1,428

Table 39 Estimated variable cost of Variant I & II according to the framework of Sinnot and Towler.

Scenario	Distance	Variable Cost
Variant I	50km	k€ 35
	100km	k€ 36
	150km	k€ 39
Variant II	50km	k€ 112
	100km	k€ 118
	150km	k€ 131

Table 40 Estimated fixed capital cost of Variant I & II according to the framework of Sinnot and Towler.

Scenario	Fixed cost
Variant I	k€ 713
Variant II	k€ 728

10.7. Health & Safety

Hydrochloric acid

The most significant threat posed by hydrochloric acid is exposure and oxidation to the environment. Therefore, using the appropriate material of construct is essential. Spill prevention must be absolutely assured and the possibility of human contact must be minimal. Especially contact with vapour should be avoided. The use of personal protective equipment is essential. Personnel must always handle according to safety regulations and hygiene standards.

A fire must be extinguished by using a water spray, alcohol-resistant foam, dry chemical or inert gas. A ventilation system could an adequate investment, allowing the control of hydrochloric acid concentrations in air, would it not be that hydrochloric acid will fume at concentrations higher than 25wt% (Online, 2017). Exposure to HCl vapour can lead to suffocation, as it destructive to the mucous membranes. It creates a burning sensation, followed by coughing, spasms, chest pains, headache and a choking sensation. Medical attention has to be sought immediately. If breathing stops, artificial breathing has to be started. If HCl acid comes into contact with skin, rinse immediately with water for at least 15 minutes, and remove any contaminated clothing. Flush eyes with water after contact with HCl acid. After ingestion of HCl acid, do not vomit and seek medical attention.

Rubber-lined steel storage or fibreglass-reinforced plastic storage tanks are commonly used for hydrochloric acid (OxyChem, 2017). A concrete containment dike coated with acid resistant coating is required to confine any spilled liquid. Additional instrumentation to measure inventory is required to notify of spilling or overflow conditions. Tank manufacturers are to be consulted for recommendation on vents, pressure relief system, temperature resistance, nozzles, inlet lines etc. Lined steel piping systems are commonly used for the transport of HCl acid. The lining of these pipes can differ based on requirements such as strength or temperature resistance.

Carbon dioxide

When coming into contact with high concentrations of carbon dioxide in air, it can cause headache, loss of spatial perception, confusion, loss of consciousness and suffocation.

A good ventilation system is an excellent investment in order to prevent the release and build-up of carbon dioxide gas. Respiratory equipment must be available at all times for near personnel.

Safety and Loss Prevention

Identification and Assessment of Hazards

Control systems within the process keep process variables within the steady-state condition (Towler & Sinnott, 2013).

- Temperature gauges
 - o Excessive temperatures lead to structural failure of equipment and ultimately loss of containment.
- Pressure Gauges
 - o In case a pressure exceeds the system design pressure, or overpressure, because this leads to failure of equipment and ultimately to loss of containment. Lowered pressure, or vacuum, is also unwanted since this will give large stresses on the walls of equipment that can lead to bucking.
- Steam pressure gauges
- Level Indicators
- Flow indicators
- Vapour detection system
 - o Hydrochloric acid vapour and carbon dioxide gas.

If any of the detection systems above detect that a process variable falls out of the safe operating range, an alarm should be triggered in the plant control room. The alarm should warn operators of possible deviations from the safe operating range, so that the operators can intervene accordingly. What should be kept in mind is that not too many complicated alarms should be placed in the plant control room since this can overwhelm operators and thus increase the likelihood of human error. Alarms should be clearly indicated and operators must know what to do for every type of alarm. Furthermore, alarms should also not be triggered by normal process variability and should also allow the operator with enough time to react to the alarm. In the case that the operator is unable to bring back the process within the safe operating range, an automatic shutdown must occur in order to prevent any hazardous conditions. When shutdown does occur, the suspension must be placed in a holding vessel. The holding vessel used in this scenario is tank T1. Additionally, any sources of heat are shut down, every piece of equipment is depressurized and the plant is purged with inert material. What has to be kept in mind is that no unsafe conditions are created during the shutdown. In various mixing equipment, heat of mixing still releases after shutdown. This excess heat must be transferred away in order to attain stable temperatures.

Control of the Hazards

- Ventilation system in combination with vent scrubbers (Towler & Sinnott, 2013)
- Automatic Shut Down System
 - o If the system threatens to fall outside the safe operating limit, the entire process, or portions, can be shut down.
- Duplication of key equipment
 - o If the primary equipment fails, secondary equipment can take over. The correct placement of valves can increase the ease of transition from the primary to the secondary equipment.
- Fire fighting equipment
 - o In case of a fire, fire fighting equipment must be available for the personnel trained to use this equipment.
- Sprinkler system in case of fire or the threat of fire.
- Blast walls in case of an explosion.
- Loss of Containment prevention
 - o Secondary containment to prevent any runoff, which is especially effective for pump and welded portions of equipment. However, if chemicals which are flammable can easily ignite.
 - o Contained drainage and sewer systems can collect any runoff and potentially apply waste treatment if necessary.
 - o Concrete foundations to protect the soil and groundwater underneath the facility.
- Well-trained operators
 - o Although the possibility of human error is always existent, it can be reduced significantly when personnel is trained properly. The likelihood of human error increases when operating procedures are not clearly documented. The presence of a safety checklist is always a good technique to reduce the amounts of human error.

Control of the Process

Temperature

Temperature gauges which can indicate when the system falls out the safe operating range can raise an alarm, leading to the shutdown of reactor feeds through interlocks (Towler & Sinnott, 2013). Heating equipment can also be shut down remotely and/or automatically when the temperature falls out of range.

Emergency cooling systems can be an excellent addition in order to prevent an excessive rise in temperature. This becomes of more importance when dealing with heat of mixing. Another method of reducing the risk of overheating is the implementation of quench systems. Quench systems flood the equipment with cool, inert material.

Another method of reducing the risk of overheating is the substitution of fired and electric heat with a steam or other vapour heating system. This is because of the temperature not being able to exceed the saturation temperature at the supply pressure of the vapour.

Pressure

Pressure indicators can be connected to Pressure Relief Devices to prevent equipment from exceeding maximum pressure (Towler & Sinnott, 2013). Currently, three types of relief devices can be used of which one is connected to pressure indicators;

- Directly actuated valves, which are either weight or spring loaded valves that open at pre-determined pressures.
- Indirectly actuated valves, which are either pneumatically or electrically opened valves
- Bursting discs, which are disc of a material which bursts at a specific pressure.

What is possible, and advisable, are the use of a combination of at least two types of valves. The addition of one extra valve outweighs the costs of replacing a piece of equipment. This becomes more important when pressures are higher within the system. Usually the maximum allowable pressure is about 10% above the normal operating pressure.

Limitations of the loss, damage, and injury caused

A loss of containment is when fluid is leaking from the process equipment to the environment (Towler & Sinnott, 2013). A small scale loss can also be very dangerous as some vapours can ignite. These vapours have the possibility to burn an invisible flame, of which personnel as to taken into account. Personnel of the plant have to be extensively trained in safety regulations. For example, personnel must trust on their sense of heat when encountering valves and welded joints because the possibility of invisible flames.

10.8. Utility needs and costs

This section will describe the estimated needs and costs of all the utilities included within the base design of the demineralisation process.

Process Description P1 P1 is a liquid-only centrifugal pump utility increasing the pressure of the feed stream P-102. The pressure of this stream must be increased in order to overcome the pressure loss in the mixing unit R1.		Pressure Ingoing stream: 1.0 bar Outgoing stream: 2.0 bar Pressure increase: 1.0 bar
Required Power Fluid power: 4.3 kW Brake power: 5.9 kW Power consumption: 5.9 kW Volumetric flow rate: 156 m ³ /hr. Efficiency: 0.75	Operating Costs Power consumption: 5.9 kW Electricity price: € 0.066 per kWh Operating costs = (5.9/0.75) · 0.066 = € 0.52 per hour	Temperature Ingoing stream: 20.0°C Outgoing stream: 20.0°C Temperature increase 0.0°C

Process Description P2 P2 is a liquid-solid centrifugal pump utility increasing the pressure of stream P-103. The pressure of this stream must be increased in order to overcome the pressure loss in the upcoming neutralization reactors R101.		Pressure Ingoing stream: 1.0 bar Outgoing stream: 2.0 bar Pressure increase: 1.0 bar
Required Power Fluid power: 4.6 kW Brake power: 6.1 kW Power consumption: 6.1 kW Volumetric flow rate: 164 m ³ /hr. Efficiency: 0.75	Operating Costs Power consumption: 6.1 kW Electricity price: €0.066 per kWh Operating costs = $(6.1/0.75) \cdot 0.066 = €0.54$ per hour	Temperature Ingoing stream: 20.0°C Outgoing stream: 20.0°C Temperature increase 0.0°C

Process Description P3 P3 is a liquid-only centrifugal pump utility increasing the pressure of the feed hydrochloric acid from silo TK5F. The pressure of this stream must be increased in order to overcome the pressure loss in neutralization reactor R101.		Pressure Ingoing stream: 1.0 bar Outgoing stream: 2.0 bar Pressure increase: 1.0 bar
Required Power Fluid power: 0.5 kW Brake power: 1.0 kW Power consumption: 1.0 kW Volumetric flow rate: 19.3 m ³ /hr. Efficiency: 0.51	Operating Costs Power consumption: 1.0 kW Electricity price: €0.066 per kWh Operating costs = $(1.0/0.51) \cdot 0.066 = €0.13$ per hour	Temperature Ingoing stream: 20.0°C Outgoing stream: 20.0°C Temperature increase 0.0°C

Process Description P4 P4 is a liquid-solid centrifugal pump utility increasing the pressure of stream P-105. The pressure of this stream must be increased in order to overcome the pressure loss in dewatering processes.		Pressure Ingoing stream: 1.0 bar Outgoing stream: 2.0 bar Pressure increase: 1.0 bar
Required Power Fluid power: 5.1 kW Brake power: 6.8 kW Power consumption: 6.8 kW Volumetric flow rate: 183 m ³ /hr. Efficiency: 0.75	Operating Costs Power consumption: 6.8 kW Electricity price: €0.066 per kWh Operating costs = $(6.8/0.75) \cdot 0.066 = €0.60$ per hour	Temperature Ingoing stream: 20.7°C Outgoing stream: 20.7°C Temperature increase 0.0°C