



DEGREE PROJECT IN ENGINEERING CHEMISTRY,  
SECOND CYCLE, 30 CREDITS  
STOCKHOLM, SWEDEN 2018

*Gottland!*

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*2018-02-16*

# **Monitoring Kraft Recovery Boiler Fouling by Multivariate Data Analysis**

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*Modellering av avsettningsar  
i sålspann med multivariat  
dataanalys*

## **Abstract**

This work deals with fouling in the recovery boiler at Montes del Plata, Uruguay. Multivariate data analysis has been used to analyze the large amount of data that was available in order to investigate how different parameters affect the fouling problems. Principal Component Analysis (PCA) and Partial Least Square Projection (PLS) have in this work been used. PCA has been used to compare average values between time periods with high and low fouling problems while PLS has been used to study the correlation structures between the variables and consequently give an indication of which parameters that might be changed to improve the availability of the boiler. The results show that this recovery boiler tends to have problems with fouling that might depend on the distribution of air, the black liquor pressure or the dry solid content of the black liquor. The results also show that multivariate data analysis is a powerful tool for analyzing these types of fouling problems.

**Keywords: Recovery Boiler, Fouling, Multivariate Data Analysis, Principal Component Analysis (PCA), Partial Least Square Projection (PLS)**

## **Sammanfattning**

Detta arbete handlar om inkruster i sodapannan på Montes del Plata, Uruguay. Multivariat dataanalys har använts för att analysera den stora datamängd som fanns tillgänglig för att undersöka hur olika parametrar påverkar inkrusterproblemen. Principal Component Analysis (PCA) och Partial Least Square Projection (PLS) har i detta jobb använts. PCA har använts för att jämföra medelvärden mellan tidsperioder med höga och låga inkrusterproblem medan PLS har använts för att studera korrelationen mellan variablerna och därmed ge en indikation på vilka parametrar som kan tänkas att ändras för att förbättra tillgängligheten på sodapannan. Resultaten visar att sodapannan tenderar att ha problem med inkruster som kan bero på fördelningen av luft, på svartlutens tryck eller på torrhalten i svartluten. Resultaten visar också att multivariat dataanalys är ett användbart verktyg för att analysera dessa typer av inkrusterproblem.

**Nyckelord: Sodapanna, Inkruster, Multivariat Dataanalys, Principal Component Analysis (PCA), Partial Least Square Projection (PLS)**

## Executive Summary

The recovery of the cooking chemicals at a Kraft mill is an advanced technique and the process has been developed for many years. One of the units at a mill that are involved in the recovery of the chemicals is the recovery boiler. The recovery boiler has two main aims during the process. The first aim is to convert all sodium and sulfur into sodium carbonate ( $\text{Na}_2\text{CO}_3$ ) and sodium sulfide ( $\text{Na}_2\text{S}$ ) by burning the black liquor. The second aim is to extract the heat in the organic material to produce a high pressure steam. Flue gases are released during burning of the black liquor and the heat from the flue gases is transferred to the feed water inside the boiler by heat exchange surfaces. The flue gases contain particles and due to that, deposits or fouling will be formed under certain circumstances on the heat exchange surfaces which lowers the heat transfer efficiency.

Occasionally, the heat transfer efficiency will be so low that it is not beneficial to run the boiler due to that a low amount of high pressure steam is produced. The boiler will in that case be shut down for cleaning. If the mill has problems with fouling, many unscheduled shut downs will occur. Unscheduled shut downs are costly and therefore, the fouling in the recovery boiler is a serious problem for the mills. Multivariate data analysis has been used to analyze the process data to investigate how different parameters affect fouling (1). However, the technology is not that common yet and Stora Enso has not used the technology before for these types of problems.

Montes del Plata, one of Stora Enso's mills has had issues with fouling in the recovery boiler like many other mills. The scope of this thesis work was to perform a multivariate data analysis of the recovery boiler at Montes del Plata to investigate how different parameters affect fouling. An additional scope was to investigate if multivariate data analysis is a tool to use for study this types of problems. Two different types of multivariate statistical techniques have been used in this work, Principal Component Analysis (PCA) and Partial Least Square Projection (PLS).

Two different time periods have been used in this work. The first models were built with data from January 5, 2017 to March 12, 2017. PCA models have first been analyzed and average values for high and low fouling periods have been calculated. No clear differences between the average values could be seen. The correlation structures between the parameters have also been investigated and the results indicate that the fouling might be due to unfavorable distribution of the air.

Additional models were built with data from April 4, 2017 to June 25, 2017. PCA models have been analyzed and the average values between high and low fouling have been compared. No clear differences between the average values could be seen in these models either. The correlation structures between the parameters have also been investigated and the results indicate that it might be low black liquor dry solids or low black liquor pressure that generate fouling.

From the work it can be concluded that multivariate data analysis seems to be a powerful and useful tool that can be used to analyze large amounts of process data. Parameters that show correlation with fouling in the results are the distribution of the air, the black liquor dry solids and the black liquor pressure. Additional investigations would preferably be done with these

parameters. The results show no clear correlation between the fouling problems and the sulfidity.

## Acknowledgements

- This thesis work has been conducted at the Pulp Competence Centre (PCC), Stora Enso Research Centre Karlstad (RCK). I would like to start to thank Stora Enso for the opportunity to do my thesis work at the company. It has been a great honor to do the work at one of the world's leading pulp and paper companies!
- I would also like to express my gratitude to my supervisors Maria Björk (Stora Enso Biomaterials, Karlstad) and Rickard Wadsborn (Stora Enso Biomaterials, Stockholm). Thanks for the support and guidance through the work. Your competences in the area have inspired me. I would also like to thank Mikael Lindström (KTH Royal Institute of Technology) for being my examiner and always supported me when needed.
- I am also grateful to Skoghall mill and to Montes del Plata for the study trips. Thanks to PCC for supporting my trip to Montes del Plata, Uruguay. The study trips have result in valuable discussions and experiences.
- A special thanks also to Raija Bådenlid (Stora Enso Technology Development, Karlstad), Honghi Tran (University of Toronto), Andres Garcia (Montes del Plata), Paula Silveyra (Montes del Plata), Ignacio Caetano (Montes del Plata), German Albin (Montes del Plata) and Gaston Posas (Montes del Plata) for their help, support and discussions during the project.
- My gratitude also goes out to everyone at PCC and RCK for making the work environment enjoyable.
- Thanks also to everyone that in one or another way has contributed to this work.

*Karlstad, February 2018*

*Alexandra Edberg*

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# **1 Introduction**

## **1.1 Background**

Montes del Plata has had some issues with fouling in the recovery boiler like many other mills. Fouling on the heat transfer surfaces is a problem that results in an inefficient way to use the heat and generates a lower steam production. During time, the fouling in the boiler will be so high that the boiler has to be shut down which is costly for the mill. It is therefore important to investigate the fouling problems in order to be able to decrease the problems and to improve the efficiency of the recovery boiler.

Multivariate data analysis is a tool that can be used to study large amounts of data and is used for these types of problems. Principal Component Analysis (PCA) can be used to compare values between periods with high and low fouling while Partial Least Square Projection (PLS) can be used to study the correlation structures between the variables.

This master thesis was performed at Stora Enso Research Center, Pulp Competence Centre (PCC) in Karlstad.

## **1.2 Problem formulation**

The aim of this work was to use multivariate data analysis to analyze the fouling problems. More specific, to find parameters that have a high impact on fouling and to study if the sulfidity might be one reason to the fouling. Furthermore, to investigate if multivariate data analysis is a powerful tool for these types of problems and if the company can use the tool in the future for these types of problems.

## **1.3 Delimitations and assumptions**

The delimitations and assumptions that have been done in the work are listed below.

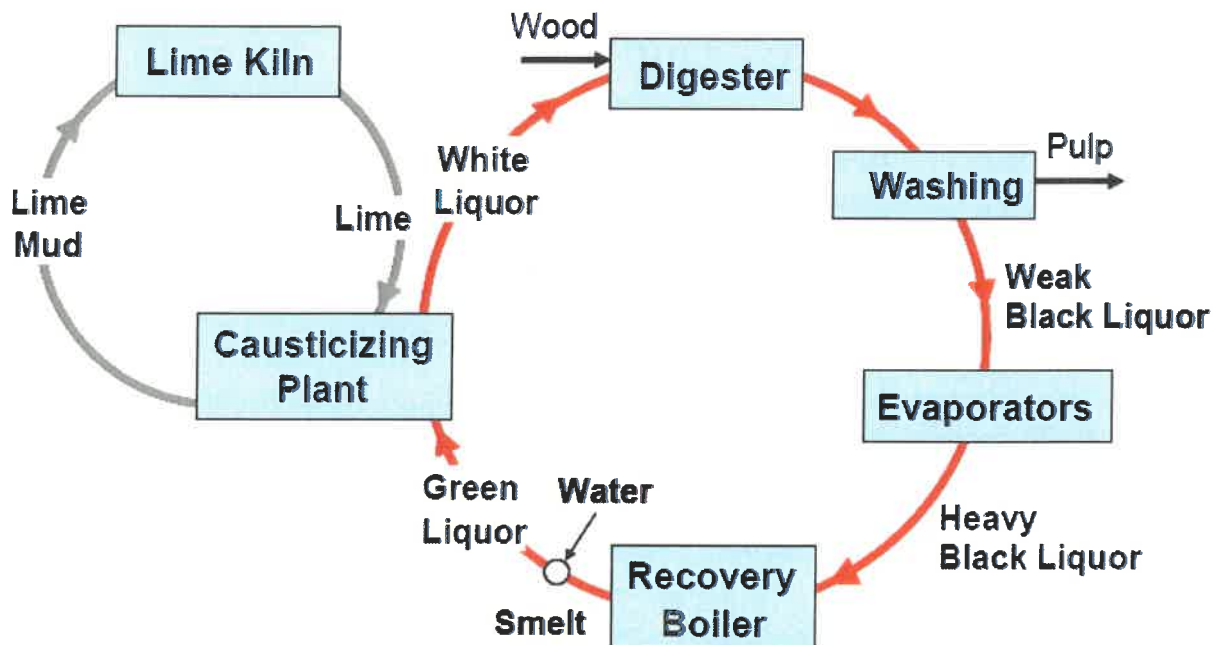
- To do an analysis similar to this one, data during several years would preferably be included. However, the mill has just started up and there have been problems with the collection of data. Only data during shorter time has therefore been used.
- The soot blowing efficiency affect the fouling problems. If the rate of the fouling is higher than the removing of the fouling by soot blowing, fouling will increase with time. However, it is assumed that the soot blowing in the recovery boiler works beneficially in this work. There exist probably several ways to improve the soot blowing efficiency but that has not been considered in this work.
- The steam production has not been included in the analysis due to unstable process data.
- Some parameters that might affect fouling are measured infrequently or are not measured at all. Only the parameters that might affect fouling that are measured frequently have been included in this analysis.
- The liquor guns will hopefully be in the same position during process. However, the liquor guns are sometimes removed for cleaning and some changes in positions might

occur when returning those. In this work, it is assumed that the liquor guns are located at the same position all the time.

- After a stop, it might take up to 4 weeks for the measuring devices to stabilize again. This has not been considered in this work. Only measurements two days before and after a stop have been excluded.
- The mill has had some start-up problems and the production has been unstable during the first time to some extent. Time periods with stable production would be desirable but due to lack of stable time periods, unstable periods had to be used.
- There is a time delay in the process. In this work, no time delay has been considered.

## 2 Theory

There exist several different pulping methods today but the dominating pulping method is the Kraft pulping and around 130 million tons Kraft pulp are produced globally every year. The method uses NaOH and Na<sub>2</sub>S as cooking chemicals to pulp the wood (2) (3). *Figure 1* shows an overview over the Kraft pulping process (3).



*Figure 1: Overview over the Kraft pulping process (3).*

The process to produce the Kraft pulp starts with harvesting of trees and the logs are after harvesting transported to the mills. When the logs reach the mill they are firstly debarked and secondly chipped into small chips. Debarking can also be done in the forest and in that case, the debarked logs are transported to the mills. The typical size of the chips is a length of around 10-30 mm and a thickness of 2-5 mm (4). The chips are thereafter added to the digester together with the white liquor. The main aim of the cooking is to release the fibers by removing the lignin through dissolution. The Kraft cook is performed at around 150-180°C and for around 1-3 hours. After cooking, the pulp is washed and the black liquor is separated from the pulp (5). The black liquor goes further to the chemical recovery cycle of the mill.

The main purpose of the chemical recovery cycle is to convert the black liquor into white liquor again that can be used in the digester. Sodium compounds are generally expensive and it is thus important for the Kraft pulping to recover the cooking chemicals to reduce the costs and thereby be able to compete with other pulping methods. The recovery of the sodium compounds is an advanced technique and has been developed for many years (6).

The recovery cycle of the Kraft pulping process consists of different unit operations, such as the evaporation plant, the recovery boiler and the white liquor preparation plant. The weak black liquor from the digester enters the evaporation plant with a dry content of around 15-20%. Most of the water is evaporated in the evaporation plant and a strong black liquor with a dry content of around 70-80% is formed (7). The strong black liquor is transported to the recovery boiler. The recovery boiler burn the strong black liquor and a smelt that mainly consists of sodium sulfide (Na<sub>2</sub>S), sodium carbonate (Na<sub>2</sub>CO<sub>3</sub>) is formed. Small amount of

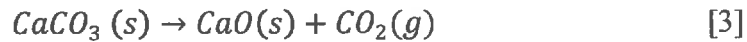
sodium sulfate ( $\text{Na}_2\text{SO}_4$ ) will also be formed. The smelt is thereafter dissolved in a tank together with weak liquor originating from the lime cycle, and the mixture that is formed is called green liquor. The green liquor is thereafter transported to the white liquor preparation plant (8). The aim of the white liquor preparation plant is to convert green liquor ( $\text{Na}_2\text{CO}_3$ ) to white liquor ( $\text{NaOH}$  and  $\text{Na}_2\text{S}$ ). Lime ( $\text{CaO}$ ) and the green liquor is mixed in the slaker and the lime reacts with water and form slaked lime, see *Reaction 1* (9).



The slaked lime is in the next step reacting with the sodium carbonate ( $\text{Na}_2\text{CO}_3$ ) in the green liquor and sodium hydroxide ( $\text{NaOH}$ ) and lime mud ( $\text{CaCO}_3$ ) are formed, see *Reaction 2*.  $\text{CaCO}_3$  and  $\text{NaOH}$  are separated by a filter and the white liquor ( $\text{NaOH}$ ) is transported to the digester and used again while the  $\text{CaCO}_3$  is transported to the lime kiln to generate new  $\text{CaO}$  (8).



After the causticization, the lime mud is transported to the lime kiln, as mentioned previously. The lime kiln converts the lime mud ( $\text{CaCO}_3$ ) into lime ( $\text{CaO}$ ), see *Reaction 3* (8). The formed  $\text{CaO}$  can be used again, see *Reaction 1*.



## 2.1 Recovery boiler

### 2.1.1 Recovery boiler background

The recovery boiler is a complex unit in the chemical recovery cycle and can be around 60-70 m high. The unit has mainly two different aims. The first is to convert all sodium and sulfur into sodium carbonate ( $\text{Na}_2\text{CO}_3$ ) and sodium sulfide ( $\text{Na}_2\text{S}$ ). The second is to extract the heat in the organic material to produce a high pressure steam (10). A schematic figure of a recovery boiler is shown in *Figure 2* (11).

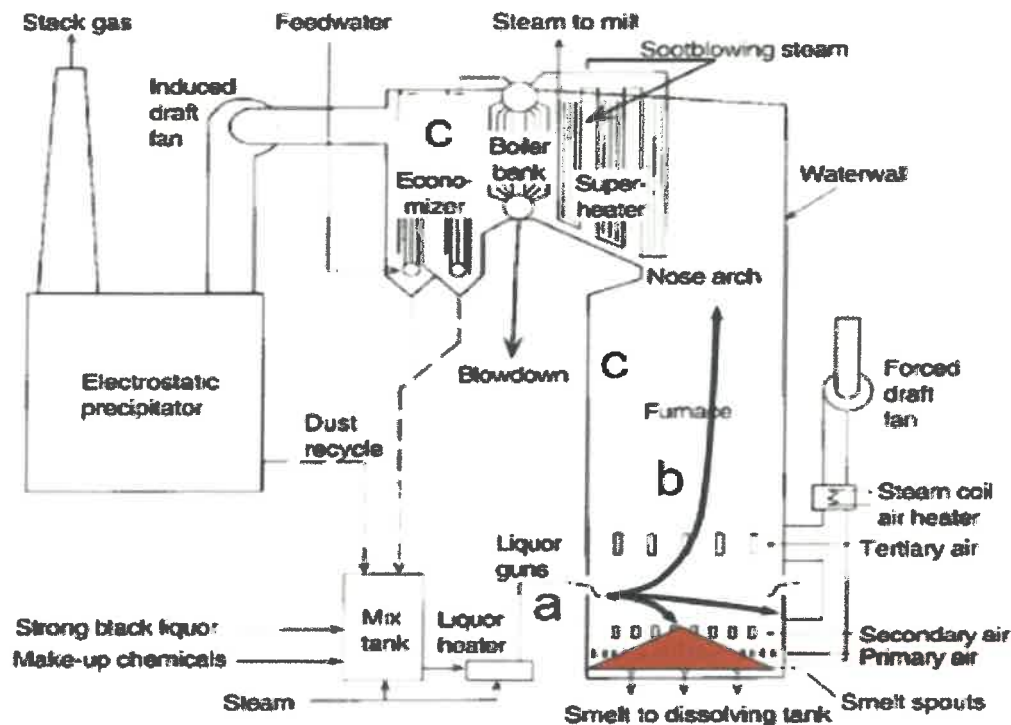


Figure 2: Schematic picture of a recovery boiler (11).

Strong black liquor enters the furnace as droplets through the liquor guns. The droplets undergo different processes in the furnace such as drying, pyrolysis and char combustion. Flue gases are formed during these processes and the gases go up in the furnace and is used to produce a high pressure steam. The heat exchange between the flue gases and the steam occurs both in the furnace and in the convections areas after the furnace (12). The high pressure steam can be used in the mill and the excess steam can be used for electricity production. The formed melt in the bottom of the recovery boiler is transported to the dissolving tank.

### 2.1.2 Recovery boiler construction

The most common recovery boilers some years ago were recovery boilers of two drum design. These types of recovery boilers have usually water screens to protect the super heaters from direct furnace radiation. The modern recovery boilers are of single drum design. The spaces between the tubes in the super heaters are larger which minimize fouling problems. The boiler has also a vertical steam generating bank. These boilers of single drum design are also more resistant to corrosion. The amount of dry solids per day a recovery boiler managed in the beginning of the 1980s was 1 700 tons dry solids per day. However, this number has increased and at the end of the 1990s the amount was 2 500-3 500 tons dry solids per day (12). Some recovery boilers nowadays can have a capacity as high as 11 600 tons dry solids per day (13).

The recovery boilers are built up of different parts. The different parts can be seen in Figure 2. The liquor guns spray droplets of strong black liquor into the furnace. The furnace in modern recovery boilers has a welded wall construction. Buck stays are holding the furnace walls in place and they also make up the furnace farming system. The farming system will withstand the force of a possible fuel explosion within the furnace (14). The vertical pipes in the furnace that is used for heat exchange have a diameter of around 0.06-0.075 m. The

material of the pipes varies depending on the location in the furnace. Pipes in the lower part of the furnace consist of stainless steel at the outer part and of carbon steel at the inner part due to that stainless steel is more resistant to the corrosive environment. Higher up in the furnace where the environment are not so corrosive the pipes are made of carbon steel (15).

Air enters also the furnace at different levels, see *Figure 2*. Primary and secondary air enter the furnace under the liquor gun while tertiary and eventually quaternary air enter the furnace above the liquor gun. The atmosphere in the lower part of the recovery boiler is reductive while in the upper part the atmosphere is oxidizing (above the tertiary air inlet). This means that combustion of organic compounds in the lower part is not complete while combustion of organic compounds in the upper part occur. The air flows can be varied, however the char bed seems to be most affected by the primary air flow and particles can be swept off if the flow is too high (16).

Before the flue gases enter the super heaters it passes the screens which cool the flue gases. The screens protect also the super heaters from direct radiation. The super heaters are placed at the exit of the furnace. The flue gases with a high temperature and steam with a lower temperature enter the super heaters. While passing through the super heater the flue gases are cooled while the steam is heated. Super heaters can have different designs, there exist both platen super heater elements and spaced super heater elements. The platen super heaters consist of tubes that tangents each other which make the tubes like one continuous surface. The spaced super heater elements are more susceptible for fouling since the tubes are set apart from each other. They are also more resistant to soot blowing (14).

The boiler bank is the part between the super heater and the economizer, see *Figure 2*. The boiler bank consists of several tubes for heat transfer between the flue gases and the water. Different spacing between the tubes can be used, a smaller spacing has higher tendency to form plugging (10). The main purpose of the boiler bank is to heat the feed water even more by heat exchange between the flue gases and the water. There exist two different types of boiler banks, two drum and single drum boiler bank. These two different types of boiler banks generates two different types of recovery boilers which are described in the beginning of this chapter (14).

The economizer is the unit where feed water enters and the last unit where heat is absorbed from the flue gases. The modern economizer is large and the vertical tubes are connected both to the top and to the bottom. Feed water is usually entering the tubes in the bottom and leaves the economizer in the top (14). Previously, the economizers were horizontal but they have been replaced with vertical ones to minimize the fouling (12).

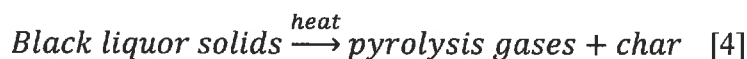
The electrostatic precipitator is located after the economizer, see *Figure 2*. The electrostatic precipitator is used to recover the valuable chemicals present in the flue gases but also to clean the gases from impurities to make sure that the mill follows the regulations regarding emissions. Dust is collected by the electrostatic precipitator and is later mixed with the strong black liquor before it is sprayed in the furnace. The dust consist mainly of sulfate and sodium carbonate and the size of the collected dust is in the sub-micron size. There is a small amount of the dust that leaves by the gaseous emissions (16).



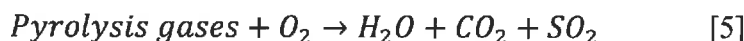
### 2.1.3 The processes in the recovery boiler

Strong black liquor with a dry content of around 65-80% is sprayed into the furnace through the liquor guns. The size of the droplets is important and the diameter of the droplet is usually between 0.5-5 mm. If the droplet is too small, the droplet will go up with the gases in the furnace and if the droplet is too large it may not be completely dried before it hits the char bed (12).

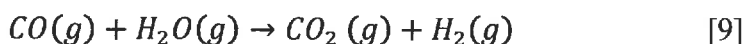
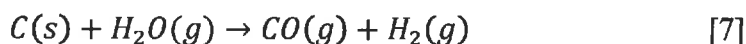
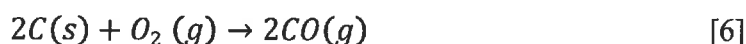
In the recovery boiler, the sodium and sulfur compounds are converted to mainly sodium carbonate ( $\text{Na}_2\text{CO}_3$ ) and sodium sulfide ( $\text{Na}_2\text{S}$ ). The black liquor droplet undergo different stages during the way from the liquor gun to the char bed. The first step is drying of the droplet. During this step water is evaporated from the droplet and it takes around 1-3 seconds. The second step is pyrolysis where the lignin and the carbohydrates are degraded into lower molecular components such as methane and carbon monoxide. Sulfur is also released in the pyrolysis step in form of hydrogen sulfide and mercaptanes carbon disulfide. The pyrolysis step takes around 2 seconds and the particles increase in temperature from  $200^\circ\text{C}$  to  $600^\circ\text{C}$  and the volume increases with 300% during this operation. The reactions during the pyrolysis step can be summarized in *Reaction 4*. The char consist mainly of  $\text{Na}_2\text{CO}_3$ ,  $\text{Na}_2\text{S}$  and  $\text{Na}_2\text{SO}_4$  (17).



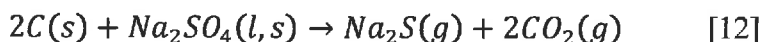
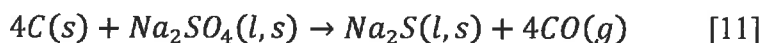
The pyrolysis gases that are formed, mainly  $\text{H}_2$ ,  $\text{CO}$ ,  $\text{CH}_4$ ,  $\text{H}_2\text{S}$  and mercaptanes can react with oxygen, see *Reaction 5* (17).



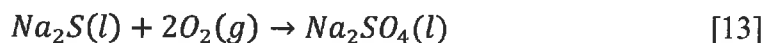
The next stage is the char combustion. This process is a slower process compared to the drying and the pyrolysis. Some of the important reactions in this step are shown in *Reaction 6-10* (18).



The atmosphere inside the particles is reducing which means that inorganic compounds can undergo reduction reactions with carbon. These reactions are however much slower than the organic reactions. The inorganic reduction reactions that can occur during the char combustion are shown in *Reaction 11-12* (12).



During the char combustion sodium sulfide may also react with oxygen, see *Reaction 13*. This is the only inorganic oxidation that is significant during the char burning (17).



It is worth to mention that these operations overlap with each other, for instance can the pyrolysis starts before the drying is complete. Particles will reach the bottom of the recovery boiler after a while in the furnace and a char bed is formed. The char bed is divided into different parts. The surface layer, around 5-10 cm of the surface is the active combustion zone and in this area can oxidation reactions occur and also reduction of sulfur. Under the active combustion zone is the passive zone. In this zone is the access to oxygen limited and the temperature is lower (15). The char is later transported to the dissolving tank.

## **2.2 Deposits in the recovery boiler**

### **2.2.1 Background**

Deposits in the recovery boiler is a common problem for many Kraft pulp mills today. The formation of the deposits are often a result of particles in the flue gases which can be formed in different ways. Low-melting point fly ash is produced when the inorganic compounds are burned and the ash follows the flue gases. Another way to generate particles in the flue gases is to have a too high flow of the primary air. This result in that particles can be swept off from the char bed and follow the flue gases. An additional way is that the particles swell during the pyrolysis and the volume becomes higher and the density lower. Due to these changes, the particles may be carried up by the flue gases. These mechanisms lead to deposits on the heat exchange surfaces in the recovery boiler which lead to a decrease in the heat transfer efficiency and thereby a lower temperature on the produced steam. The rate of the plugging in the recovery boilers tends to increase with furnace load in a non-linear way (17).

Generally, the deposits in all recovery boilers contain the same chemical compounds. However, the composition of the chemical compounds in the deposits may vary. Most of the deposits (around 99%) are water soluble compounds and a small amount of the deposits (around 1%) are insoluble in water. The deposits that are water soluble consist mainly of  $\text{Na}_2\text{SO}_4$  and  $\text{Na}_2\text{CO}_3$  but also of  $\text{K}_2\text{SO}_4$ ,  $\text{K}_2\text{CO}_3$ ,  $\text{Na}_2\text{S}$ ,  $\text{K}_2\text{S}$ ,  $\text{NaCl}$  and  $\text{KCl}$ . The insoluble deposits consist mainly of impurities and of partially burned black liquor residues. The amount of potassium in the deposits can vary between 2-10 wt% depending on the type of wood and the chloride content can vary between 1-20 wt% (16).

The deposits in a recovery boiler are usually a mixture of different compounds and one melting point is hard to determine (17). Usually, two distinct melting points are determined. The first melting point is when the mixture starts to melt and the second melting point is when the mixture is completely molten. There are also two central temperatures between these two melting temperatures. The sticky temperature, ( $T_{\text{STK}}$ ) which is when the mixture consists of 15-20% liquid phase and due to that, the material becomes sticky and adhere to any surface. The radical deformation temperature, ( $T_{\text{RD}}$ ) is when the mixture consist of 70% liquid and the material can run off the surface at that temperature. Enormous depositions can occur in the region between the sticky temperature and the radical deformation temperature due to that the particles are sticky in this region (16).

The sticky temperature is lowered both when the amount of chloride (Cl) and the amount of potassium (K) are increased, see *Figure 3*. The stickiness of the deposits may also be affected by a lot of other factors, for instance particle temperature, tube surface condition and the flue gas velocity (17) (16). However, it has been shown that even if  $\text{Na}_2\text{CO}_3$  is the main component in the deposits, the sticky temperature is not influenced by the content of  $\text{Na}_2\text{CO}_3$  (16).

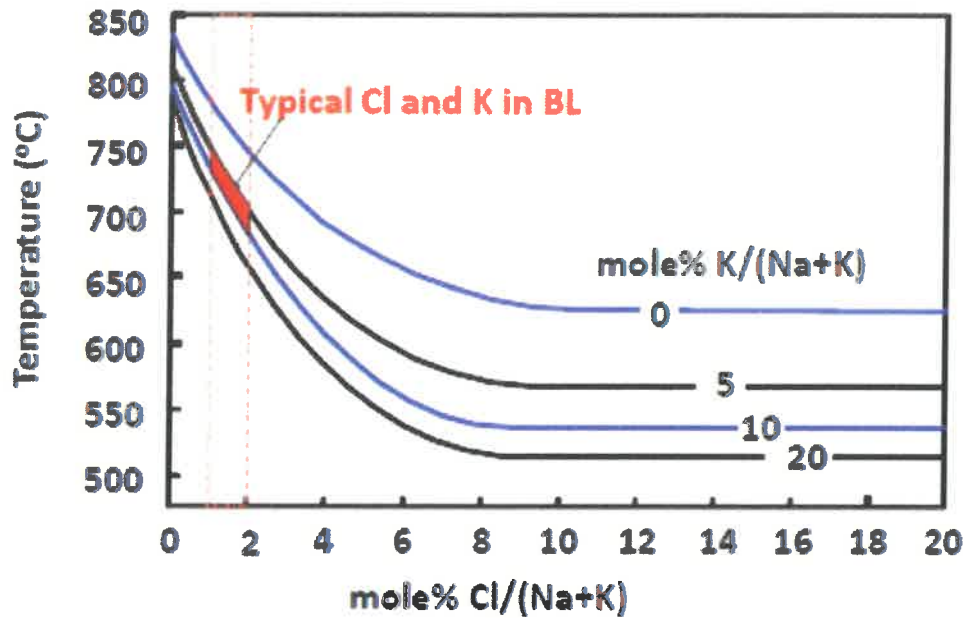


Figure 3: The effect of chloride and potassium on the sticky temperature (16).

### 2.2.2 Carryover and fume

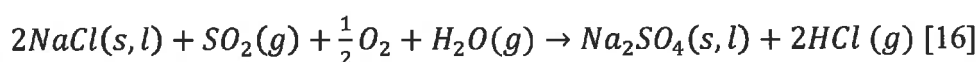
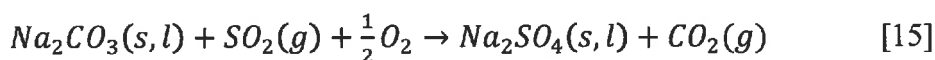
There are mainly two different types of fly ash in the recovery boiler, carryover and fume particles. Usually most of the deposits in a recovery boiler consist of a mixture between them. The fume and the carryover particles are formed in different ways and they have thus different sensitivity to operating and liquor parameters (16).

#### Carryover particles

Carryover particles are in the size from 20  $\mu\text{m}$  to 3 mm and are larger than fume particles. The carryover particles that are larger than 100  $\mu\text{m}$  have probably been swept off the char bed or entrained from the furnace due to low density of the particle. Carryover particles smaller than 100  $\mu\text{m}$  have probably been formed during the burning of the droplet. Carryover deposits are usually a little bit pink or red in the color which is probably due to that they consist of reduced sulfur. The pink color will be changed to a more grey color when the deposits are exposed to air since they will become oxidized. The amount of carryover is usually very low, only 1-2 % of the inorganic input to the furnace. However, the carryover particles can be a problem anyway due to that the carryover particles are relatively large and molten. When the warm particles hit the cold heat exchange surface, the particles form very hard deposits (17) (16).

The composition of the carryover deposits changes depending on location of the deposit in the recovery boiler. Since carryover particles can be swept off from the char bed, the carryover particles consist to the beginning of the same component as the smelt. The smelt consist of mainly of  $\text{Na}_2\text{CO}_3$  and  $\text{Na}_2\text{S}$ . The  $\text{Na}_2\text{CO}_3$  is however the main component and if the deposits have a high amount of  $\text{Na}_2\text{CO}_3$  it is probably carryover deposits. However, during the way up in the furnace,  $\text{Na}_2\text{S}$  can be oxidized to  $\text{Na}_2\text{SO}_4$ , see *Reaction 14*. Some of the  $\text{Na}_2\text{CO}_3$  in the deposits may also react with  $\text{SO}_2$  which is found in the flue gases and  $\text{Na}_2\text{SO}_4$  is formed also in this reaction, see *Reaction 15*.  $\text{Na}_2\text{SO}_4$  can also be formed by reaction between chlorides,  $\text{SO}_2$  and water, see *Reaction 16* (16).





There is usually more  $Na_2SO_4$  in the carryover deposits compared to the oxidized smelt as a result of these reactions (16).

### **Fume particles**

Fume particles are around 0.1  $\mu m$  to 1  $\mu m$  and is thus smaller than the carryover particles. Vapors of sodium and potassium compounds in the flue gases can condensate and fume deposits are usually formed as a result of that. The condensation of the vapors can occur either direct to the surface or by formation of solid particles in the gas and these particles are later transported to the surface. Some features of the fume deposits are that the deposits are white and quite soft, however, they can sinter at high temperatures and in that case become very hard (16).

The gases in the lower furnace region contain a relatively high amount of NaOH and NaCl. The alkaline compounds in the furnace are easily sulfonated when sulfur is present. In the lower part of the furnace the atmosphere is of reducing character which means that low amounts of  $SO_2$  and  $SO_3$  are present and  $H_2S$  is the main form of the sulfur. NaOH and NaCl are not highly reactive in this atmosphere and are therefore common in the deposits in the lower furnace. In the upper furnace is the atmosphere of oxidizing character. This means that the amount of  $SO_2$  and  $SO_3$  is higher and the amount of  $H_2S$  is lower since  $H_2S$  has been converted into  $SO_2$ . NaOH and NaCl react easily with  $SO_x$  in the upper furnace and sulfates are formed. The NaCl and most of the  $Na_2CO_3$  are also reacting with  $SO_x$  to form  $Na_2SO_4$ . These reactions results in a higher amount of  $Na_2SO_4$  and a lower amount of  $Na_2CO_3$ , NaCl and NaOH in the upper furnace compared to the lower furnace (16).

It is beneficial to collect the particles in the recovery boiler to prevent deposits and plugging, however it is difficult. Some of the carryover and fume particles are collected in the bottom of the boiler bank and the economizer by ash hoppers. The electrostatic precipitator is also a unit for collecting dust from the gases. Only the smallest particles travel all the way to the precipitator and are collected there. The precipitated dust contains of around 95% fume dust and 5% carryover dust. This leads to that the precipitated dust consists of similar compounds as the fume deposits, namely a high amount of  $Na_2SO_4$  and smaller amounts of  $Na_2CO_3$ , NaCl and K-salts (16).

#### **2.2.3 Locations of deposits**

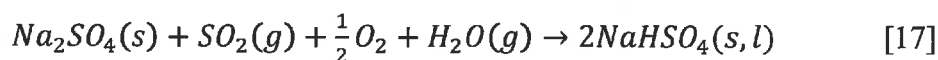
Deposits and plugging occur in most all recovery boilers but to different degrees and different parts of the recovery boiler have problems with different types of deposits.

Generally, carryover deposits are often more of a problem in the parts near the furnace while the fume deposits are generally more of a problem further away from the furnace. In the lower super heater region, including the screen tubes carryover deposits are most common. The temperature of the flue gases in this region is above 800°C which lead to that carryover particles solidify and become hard on the tube surface. The deposits grow to a thickness of 10-15 mm and they reach thereafter a steady-state since the temperature of the flue gases is higher than the radical deformation temperature. This lead to that plugging in this region

normally does not occur. In the upper super heater region is the temperature of the flue gases a little bit lower than in the lower superheated region, around 800°C to 700°C which is in the sticky temperature region. Carryover deposits dominate in this region and the deposits can continue to grow and cause plugging since the flue gas temperature is in the sticky region (16).

The inlet of the boiler bank is the most common place for plugging in two drum boilers due to that the space between the boiler bank inlet tubes is very narrow. When the deposits are formed in the super heater, the super heater becomes less efficient which lead to that the flue gases have a higher temperature when it reaches the boiler bank. The temperature of the flue gases may be higher than the sticky temperature which will lead to that more deposits are formed. The amount of carryover particles are low when the flue gases reach the boiler bank center since carryover deposits have already been formed. Fume deposits are therefore more common in this region. However, the fume deposits are generally quite easily removed by soot blowers. The fume deposits can in some cases sinter and in that case become hard and are also difficult to remove (16).

Plugging occur also in the region from the boiler bank to the first pass of the economizer. However, the reason for this plugging is not clear. Carryover deposits is not the reason since the amount of the carryover particles is low in this region and the temperature of the flue gases is low. One reason can be that acid deposits are formed.  $\text{Na}_2\text{SO}_4$ ,  $\text{SO}_x$  and water vapor may react and form  $\text{NaHSO}_4$ , see *Reaction 17*. The formation of  $\text{NaHSO}_4$  requires a high concentration of  $\text{SO}_3$  in the flue gases. High concentration of  $\text{SO}_3$  can be reached when the bed temperature is low as well as burning of liquor with high sulfidity (16).



#### 2.2.4 Prevention of plugging

There are mainly three different types of deposits that cause plugging, sticky carryover deposits, sintered fume deposits and sticky fume deposits (16). It is important to try to minimize these deposits and thus prevent plugging. There have been a lot of research in this field to try to understand what cause these deposits and also how to prevent them from happening. The overall guideline how to prevent fouling in recovery boilers is to study the amount of Cl and K in the deposits. High amounts of Cl and K decrease the sticky temperature of the deposits, see *Figure 3* (16). It is therefore important to have control of the amount of Cl and K.

Sticky carryover deposits can form plugging in the super heater and at the boiler bank inlet. This is mainly due to two reasons, a high flue gas temperature or a high amount of carryover particles. Minimizing the amount of the carryover particles is one way to prevent the formation of these sticky carryover deposits. Minimizing the amount of carryover can be done by optimizing firing conditions to form a more stable char bed. It can also be done by modifying the air and liquor delivery system to generate a better control of the bed. Additional ways are to install bed cameras and bed pyrometers. Another way to minimize the sticky carryover deposits is to reduce the stickiness of the carryovers. This can be done by minimizing the amount of Cl in the black liquor and also by lowering the flue gas temperature. Lowering the flue gas temperature can be done by increasing the heat exchange area and also to increase the frequency of the soot blowing (16).

Fume sintered deposits is the second type of deposit that cause plugging in the recovery boiler. The plugging caused by fume sintered deposits is generally most a problem in the center of the boiler bank. The formation of these deposits is due to high amount of fume particles, ineffective soot blowing and a high temperature of the flue gas. To minimize the amount of fume particles in the boiler, a lower temperature on the bed can be used. More efficient soot blowing can also be done to prevent plugging. More soot blowers and increasing the frequency of the soot blowers can be done. More advanced soot blower nozzles can also be used. Lowering of the flue gas temperature can be done by increasing the heat exchange area and to optimizing firing conditions (16).

The third cause of plugging is due to sticky fume deposits. This is a problem in the economizer and is mainly due to that a high amount of  $\text{SO}_2$  and  $\text{SO}_3$  in the flue gas. To lower the sulfidity of the black liquor and to use a high bed temperature will minimize the amount of  $\text{SO}_2$  and  $\text{SO}_3$  in the flue gas (16).

### **2.2.5 Removal of deposits**

Plugging occur when the growth of the deposits is higher than the removal of the deposits. It is therefore important to remove the deposits to prevent plugging and also to make sure that a high efficiency is obtained in the recovery boiler (16). Usually, the recovery boiler is stopped and the surfaces are being cleaned. The cleaning of the recovery boilers can be carried out in several different ways. Soot blowing is one alternative which is a lance equipped with steam nozzles which blow off the dust from the tubes by using a high pressure steam. This method can be used in the super heaters, in the boiler bank and in the economizer. Soot blowers consist of a lance tube and is around 9 cm in diameter and 4 to 6 meter long. The high pressure steam that is used has a mass flow rate between 4 500 to 9 000 kg/hr. How well the soot blower works is correlated with the peak impact pressure (PIP) of the jet. PIP is the pressure of the steam out from the nozzles. The PIP value decreases fast in the axial direction. The velocity of the high pressure steam at the nozzle throat is at the speed of the sound. The effectiveness of the soot blowers is not only depending on the PIP. Additional factors that also affect the effectiveness are for instance the distance between the nozzles and the deposits and the mechanical strength and the thickness of the deposits (16). There are between 60-120 soot blowers in a recovery boiler and the soot blowers consume around 3-12 % of the total steam production of the recovery boiler (19).

Another way to remove deposits is by performing a thermal shock. The black liquor flow is stopped and the deposits are rapidly cooled. The deposits are released from the tubes and can easily be blown off by soot blowers. The procedure takes around 8 hours but can vary between 4 to 24 hours. This method works for some mills and not at all for others. There are also an uncertainty about how the thermal shock affect the tubes. There are concerns about cracking of the tubes and also floor tube damage due to that large pieces of deposits are falling down when they are released from the tubes. Other names for this procedure are thermal shedding, chill-and-blow, shed, dry clean and bump (16).

Shot cleaning is an additional way to remove deposits. Shot cleaning can be used in the economizer and is a method that uses metal spheres to remove the deposits. The spheres fall down in the boiler and the dust is removed when the spheres hit the tubes. The dust and the spheres are later separated (15).

## **2.3 Montes del Plata**

### **2.3.1 Background**

Montes del Plata is a joint venture between Stora Enso and Arauco. Both Stora Enso and Arauco own 50% each of Montes del Plata. Arauco is a Chilean forestry company and Stora Enso is a Swedish/Finnish forestry company. Montes del Plata is located on the south coast in Uruguay. Around 700 employees work at the company which was founded 2009. The mill started 2014 and is thus one of the most modern pulp mills in the world. Montes del Plata owns around 190 000 ha of land and of them are around 115 000 ha planted with trees that are used in the process. The pulp produced at the mill is sold all over the world, for instance to Asia, Europe and North America (20) (21).

### **2.3.2 The process and the production**

Montes del Plata uses eucalyptus as raw material and produces eucalyptus fiber pulp by using the Kraft process. The mill uses elemental chlorine free light (EFC light) bleaching and has an annual production of 1.3 million tons. The renewable energy production at the mill is around 170 MW. Around 90 MW of these 170 MW are consumed by the mill which lead to that around 80 MW are produced in excess. The power that is produced in excess can be used as energy for 200 000 homes nearby the mill (22) (23).

### **2.3.3 The recovery boiler at Montes del Plata**

The recovery boiler at Montes del Plata is a single drum recovery boiler and burn approximately 6 600 tons dry solids per day and produces around 240 kg/s of superheated steam with a temperature of around 485 °C and a pressure of around 95.5 bar (24). The boiler has been operating under somewhat unstable condition during the start-up phase. During the last year the recovery boiler has been operating under more stable conditions.

The operators at the mill experience that the fouling problems starts in super heater 1A which is the part of the super heater closest to the boiler bank. The fouling results in higher temperature on the flue gases entering the boiler bank which lead to that more sticky particles and thus also fouling in the boiler bank. The fouling problem in the boiler bank is the main problem. One possible reason for the fouling that the mill has worked with is that the sulfidity of the white liquor is too high. The sulfidity target was reduced during 2016 from 35% to 32% in order to improve the recovery boiler conditions. The levels of Cl and K in the processes have also been investigated. However, the levels of Cl and K are low and the fouling is most likely not due to that.

The mill performs water washes during the annual stops. The recovery boiler has had one unscheduled stop due to the fouling which was in October 2016. During 2017, the mill has had several unexpected recovery boiler trips which have resulted in deposits cleaning by thermal shocks. *Figure 4* shows a photo of the fouling on the stabilization bars in the boiler bank at Montes del Plata (25).

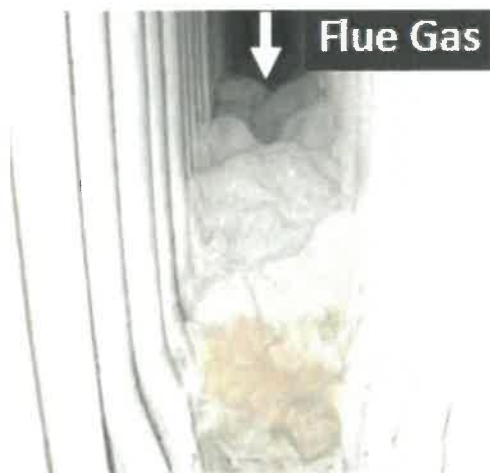


Figure 4: Photo of the fouling on the stabilization bars in the boiler bank at Montes del Plata (25).

## 2.4 Multivariate data analysis

### 2.4.1 Background

Today, usually a large amount of data is collected during processes to control the operations. Due to the large amount of data, it can be difficult to see any trends of what causes the fouling in a recovery boiler and in that case multivariate data analysis may be a valuable tool to use. Multivariate data analysis is suitable when more than 6 different variables are used. A huge amount of different input parameters (X parameters) are analyzed in order to find out reasons for changes in the output parameters (Y parameters). Two different types of multivariate statistical techniques that can be used are Principal Component Analysis (PCA) and Partial Least Square Projection (PLS) (26).

### 2.4.2 Principal Component Analysis (PCA)

PCA can be used to visually understand the interactions between variables in a complex system (27). In a PCA all the variables are defined as X variables. A number of variables (K) are varied according to experimental design and a number of observations (N) for every variable are added to a K dimensional space. An example is a model with three different variables, see *Figure 5*. A graph in a three dimension space is plotted and for every observation, a data point is added to the graph (27). Every data point in the graph represent three data values, one for each variable. In a model with K number of variables, N data points with K numbers of factors in a K dimensional space will be formed (26).



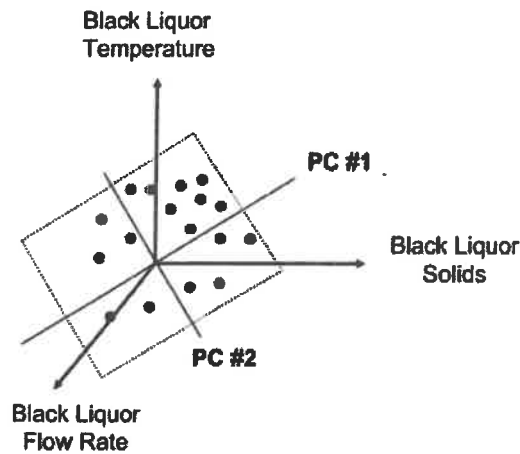


Figure 5: Example of PCA in a three dimensional space (27).

An average point in the  $K$  dimensional space is also calculated. The average point includes the average values of all variables. The average point is subtracted from all data points, including the average point. This leads to that all the observations are centered. The variables are thereafter divided with the standard deviations which means that the variables are scaled. This leads to that parameters with different units can be compared which is called UV-scaling (unit variance). Principal components (PCs) are also added to the  $K$  dimensional space. PCs are new variables that are formed by using the data points (27). The first PC is a line in the space through the average point and the direction of the line is in the direction where the most variance is. The second PC is orthogonal to the first and is in the direction of the second most variance, see Figure 5. Additional PCs can be formed to represent the data, however, maximum number of PCs are the same number as variables (26).

The PCs can be plotted against each other and the plot formed is called the score plot and is a two dimensional plot, see Figure 6. From the score plot it is possible to visualize variations in the variables and also to compare high and low fouling periods.

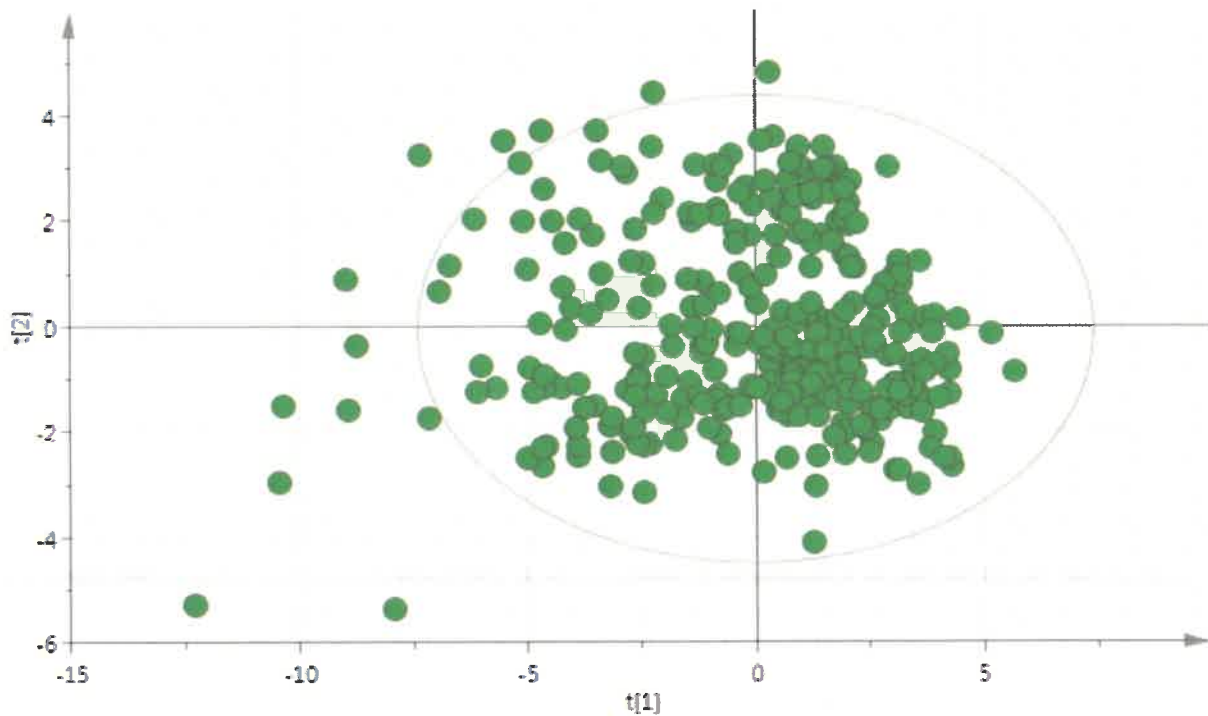


Figure 6: Example of a score plot with the two first PCs. Every point in the score plot is one observation. The figure is from simulations done in the project.

The loading plot is shown in Figure 7 and is usually used to interpret the score plots. The loadings show how the old variables are linearly combined in order to form the PCs. From the loading plot, it is possible to study the correlations between the variables. Variables with large absolute values in the loading plot dominate the projection. The variables that are situated close to each other in the loading plot have positive correlation while variables opposite to each other have negative correlation (26).

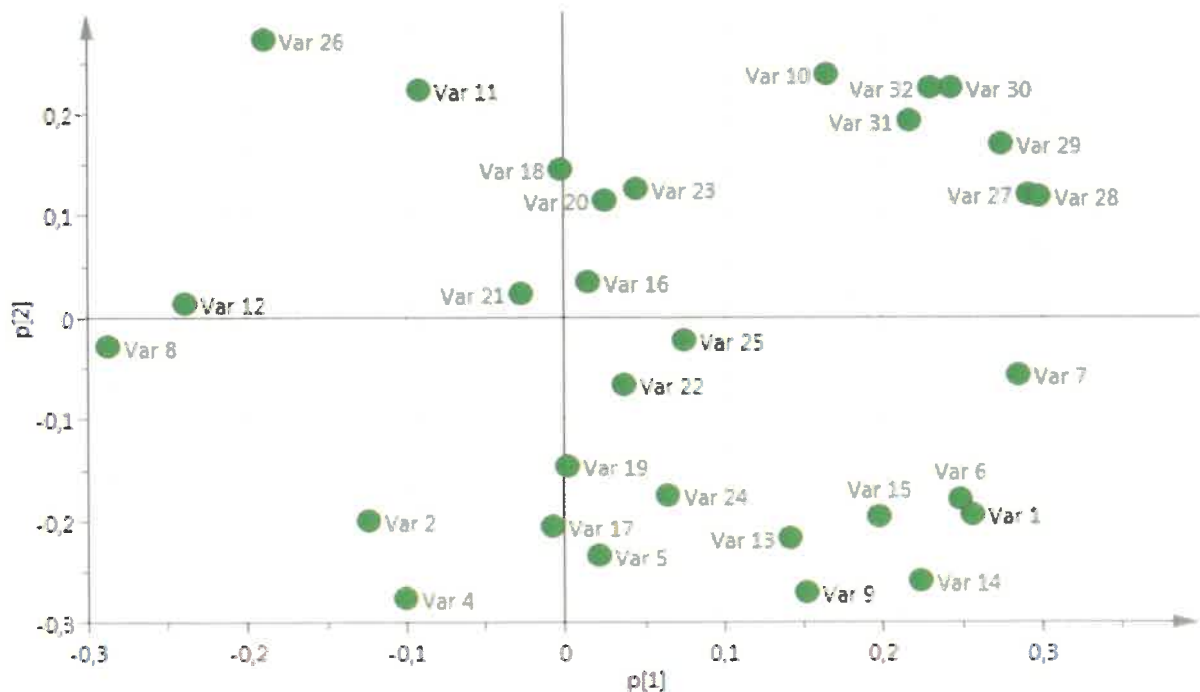


Figure 7: Example of a loading plot. The figure is from simulations done in the project.

### 2.4.3 Partial least squares (PLS)

PLS is another method for reducing the dimensions and is a regression extension of PCA. PLS uses the principal components to determine correlations between input and output variables (27). The PCA and PLS techniques are similar, however in PLS some of the variables are defined as Y variables. Both the X and the Y data are projected to new spaces in the PLS model. This means that each observation is represented as one point in the X space and one point in the Y space. The average point is calculated also in the PLS model and the average point is also subtracted from every point, both in the X space and in the Y space. The parameters are thereafter divided with the standard deviations which means that the parameters are scaled. This is called UV-scaling. One PLS-component is added to both the X space and the Y space. The line is predicted to fit both the X space and the Y space as best as possible which leads to a link between X and Y. The projection coordinates can be connected in a two dimension space and correlated by an inner relation. The second PLS-component is added to both the spaces, in the X space is the second component orthogonal to the first component. The second projection coordinates can also be plotted against each other in the two spaces, however, the correlation is usually less compared to the first projection coordinates (26). The PLS-components can be plotted against each other and form a score plot. The relation between the scores and the original variables can be studied by the coefficients of the PLS-components. The loading plots show how the different variables influence the PLS-components (1).

The main difference between PCA and PLS is that the correlation structure between X and Y parameters can be studied more detailed in PLS. Important plots for studying the correlation structure in the PLS are the Variable Importance for the Projection (VIP) plot, the Y Observed vs. Y Predicted plot and the coefficient plot. The VIP plot is a plot that describes the importance of the different X parameters to explain X and to correlate to Y. An example of a VIP plot can be seen in *Figure 8*. A value in the VIP plot higher than 1 indicates that the variable is important and a value lower than 0.5 indicates that the variable is unimportant. Importance of parameters with VIP values between 0.5 and 1 depends on the size of the data set (26).

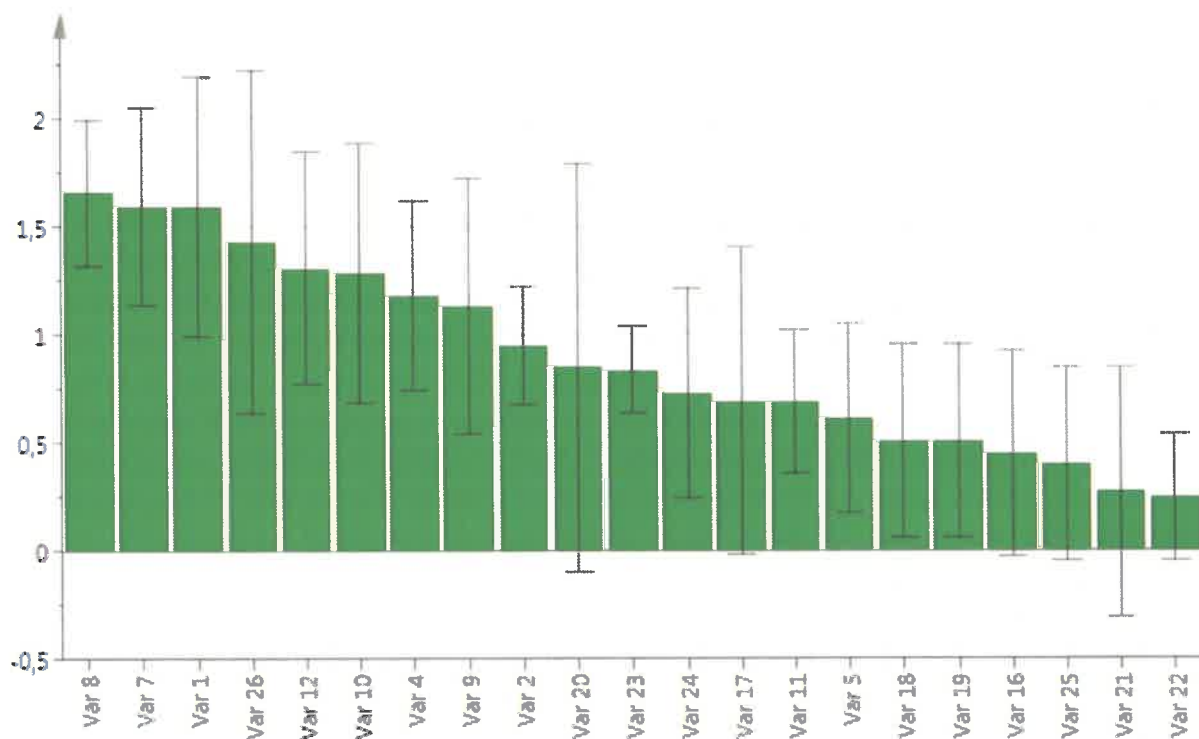


Figure 8: Example of a VIP plot. The figure is from simulations done in the project.

The Y Observed vs. Y Predicted plot can be seen in Figure 9. A regression line can be inserted in the plot and the  $R^2$  value for every Y parameter can be calculated. The  $R^2$  value describes the goodness of fit for the Y parameter. A good model has a  $R^2$  value close to 1 (26).

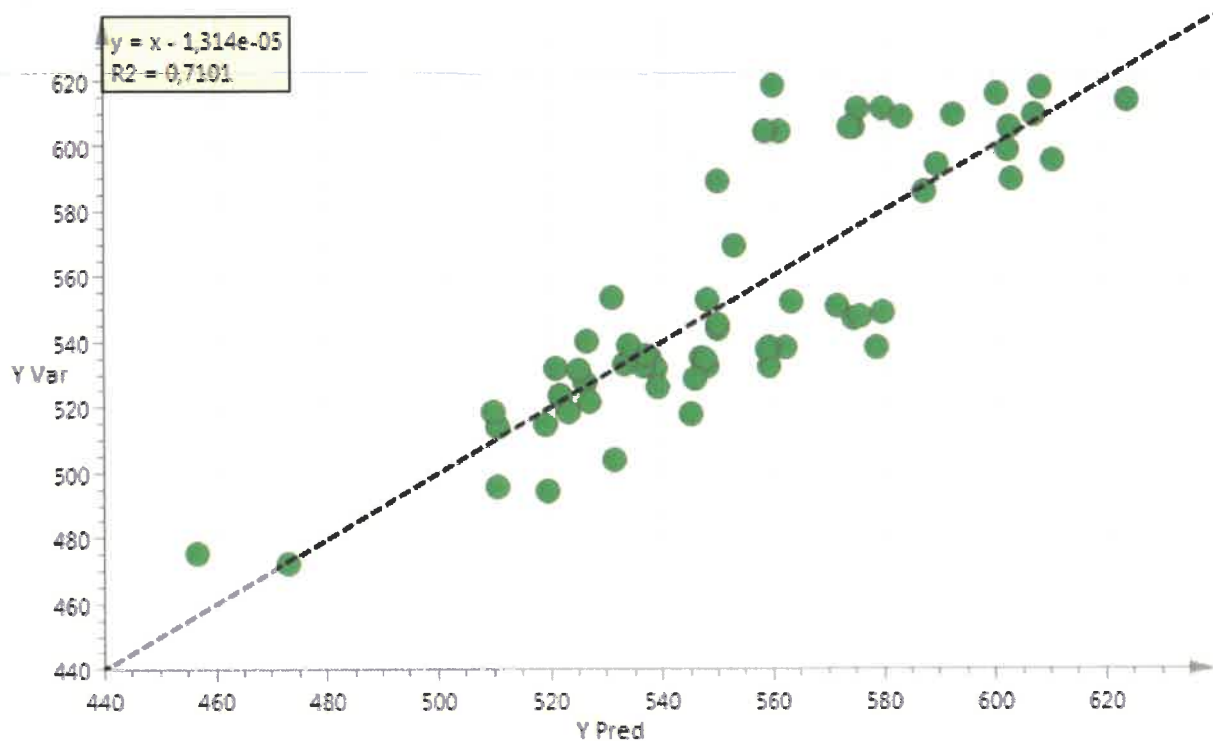


Figure 9: Example of a Y Observed vs. Y Predicted plot. The figure is from simulations done in the project.

The coefficient plot can be studied in *Figure 10*. The plot describes the correlation structure between the X parameters and the Y parameter. The coefficients are scaled and centered which means that the coefficients can be compared. The coefficient represent the change in the Y parameter when the X parameters change between 0 and 1 if experimental design is used. If the error bars include 0, the coefficient is not significant (26).

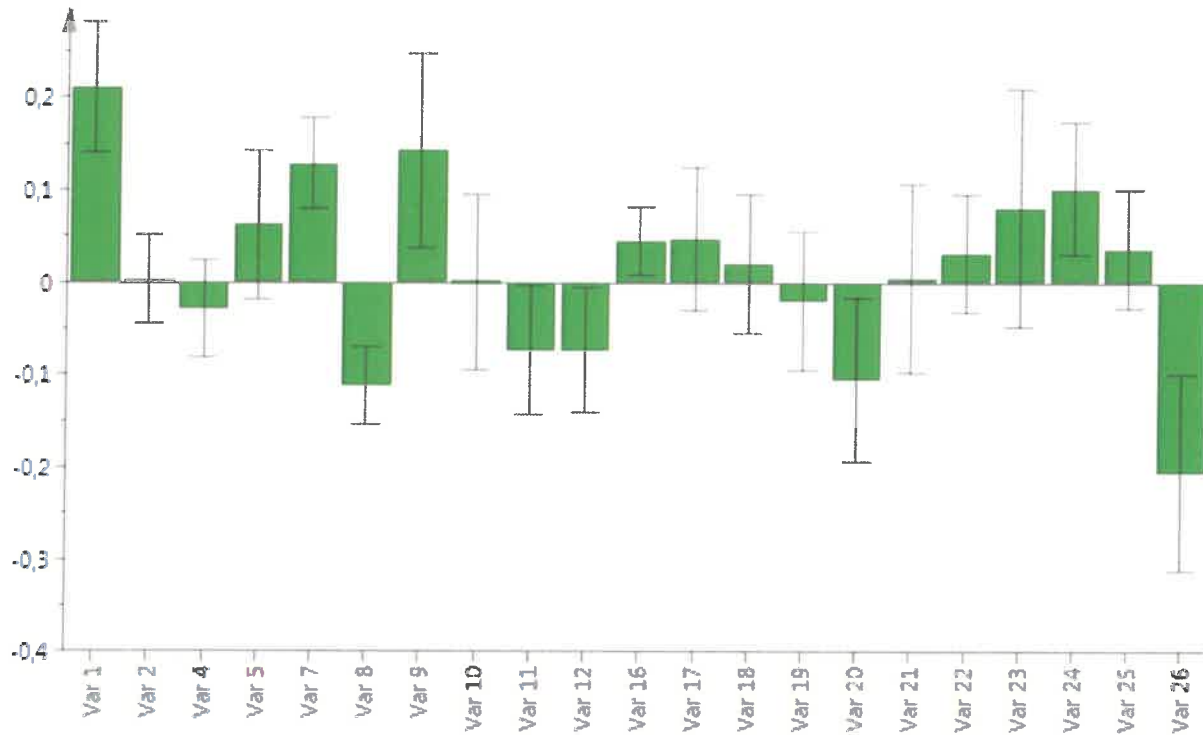


Figure 10: Example of a coefficient plot. The figure is from simulations done in the project.

#### 2.4.4 Evaluation of the models

The fit of the models can be determined by the calculation of  $R^2$ . This is a value between 0 and 1 and describes how well the model fits. The  $R^2X$  is the fraction of X variation modeled in the component and the  $R^2X(\text{cum})$  is the cumulative  $R^2X$  up to the specified component. The  $R^2Y$  is the fraction of Y modeled in the component and the  $R^2Y(\text{cum})$  is the cumulative  $R^2Y$  up to the specified component. The prediction of the model can be estimated by calculation of the  $Q^2$  value. The  $Q^2$  value is the overall cross validated  $R^2$  and the  $Q^2(\text{cum})$  is the cumulative  $Q^2$  up to the specified component. Both the  $Q^2$  value and the  $R^2$  value should be high to have a good model. Generally, a  $Q^2$  value higher than 0.5 is good and a  $Q^2$  value higher than 0.9 is excellent. However, these values are general and they depend on the application of the model (26).

Strong outliers in the model can be detected by Hotelling's  $T^2$  and they are detected in the score plots, see *Figure 6*. Hotelling's  $T^2$  is a multivariate generalization of student's t-test and is a circle in the score plot that represent 95% confidence interval (26). The strong outliers, located outside the Hotelling's  $T^2$  have a tendency to influence the PCs in an incorrect way. Moderate outliers are harder to determine in the score plots and can be detected by a distance to model plot (DModX). DModX is a model that represent the unexplained variation. The distance to model should preferably be as small as possible. When the distance between the data point and the model plane is large, the model displays largest portion of unexplained variation (26).



### 3 Method

#### 3.1 Collection of data

Flow sheets for the recovery boiler were collected and studied in order to figure out measured parameters. The data of the parameters were thereafter collected from Wedge (Savcor Wedge Standard Edition 8.1.4, Dec 8 2014). Daily average data between January 1, 2016 and December 12, 2017 were collected.

The parameters included in the analysis are listed in *Table 1*. The X parameters are input parameters that are expected to affect the fouling. The Y parameters are output parameters that are expected to generate a difference due to fouling problems. Most of the parameters are measured by online instruments and daily average values were accessible. However, some of the parameters are measured in the laboratory at the mill and are measured as infrequently as once a week.

*Table 1: Parameters used in the analysis*

<b>X parameters</b>	<b>Y parameters</b>
Black liquor flow	ID fan speed
Black liquor pressure	$\Delta P$ BB right
Black liquor temperature	$\Delta P$ BB left
Black liquor solid content	$\Delta P$ ECO1
Black liquor Cl and K content	$\Delta P$ ECO2
Black liquor heating value	Temp. BB left
Black liquor organic/inorganic content	Temp. BB right
Fraction of primary, secondary and tertiary air	
Total air	
Primary and tertiary air temperature	
Reduction of green liquor	
Sulfidity of white liquor	
Excess O <sub>2</sub>	
TRS, SO <sub>2</sub>	

The amount of Cl and K in black liquor is not measured, however there is a well-known factor to convert wt% Cl in ash to wt% Cl in black liquor. The data with Cl in ash was multiplied by 0.24 to obtain the Cl content in black liquor. The same was done with K but the factor for K is 0.4 (28).

The parts of primary, secondary and tertiary air have been calculated by first calculating the total air and then divide respective flow with the total air flow.

The excess of O<sub>2</sub> in the recovery boiler is measured at three different locations, left, center and right. An average value of these three values has been calculated.

There are four parallels ID fans in the recovery boiler and they are connected with the pressure in the furnace. Due to this, the pressure in the furnace is not included in the analysis. An average value for the ID fan speeds has been calculated.

The boiler bank draft ( $\Delta P$  BB) and the economizer draft ( $\Delta P$  ECO) are measured both on the left and the right side in the recovery boiler. When studying the process data, the pressure differences for the left and the right side in economizer 1 and 2 correspond to each other.

Therefore, an average value of the  $\Delta P$  over economizer 1 and 2 have been calculated to reduce the output parameters. However, the pressure difference in the boiler bank for the left and the right side differ significantly. An average value for these values has therefore not been taken. A high difference between left and right might indicate fouling problems.

The flue gas temperature entering the boiler bank (Temp. BB) is also measured on the left and the right side. An average value of these values has not been taken due to differences between the sides which might indicate fouling problems.

### **3.2 Selection of analysis program**

There exist several programs that can be used to perform a multivariate data analysis. Two programs were discussed in this work, Minitab (Minitab 17.2.1) and SIMCA (Version 15, Umetrics). SIMCA has been chosen in this work based on that both PCA and PLS could be performed in the program and also due to that SIMCA is more frequently used in previous reports in the subject.

### **3.3 Selection of periods with high and low fouling**

Two years process data were plotted in excel in order to be able to find interesting time periods to investigate. Discussions with operators and employees at the mill were also performed in order to find time periods with high and low fouling.

### **3.4 Analyses in SIMCA**

After studied the data in excel the data from interesting time periods were imported into SIMCA. Data before, after and during stops were removed as well as outliers. Elimination of outliers were done together with the mill and experts in the area.

#### **3.4.1 PCA**

PCA models were built by using the *Autofit* functionality in SIMCA. UV-scaling was used for all the parameters in order to be able to compare the parameters. One of the Y parameters in *Table 1* was included in every model. Totally, 7 different PCA models were built. All the parameters were set to X parameters in the PCA analysis. The PCs, the score plots and the loading plots were analyzed. Moreover, the data were divided into two groups, high and low fouling and the average values were compared.

#### **3.4.2 PLS**

PLS models were built based on the same data as the PCA models by using the *Autofit* functionality in SIMCA. The parameter that was planned to be the Y parameter was redefined to Y parameter before the models were built. The Y Observed vs Y Predicted plots, the VIP plots and the coefficient plots were analyzed in order to study the correlation structure between the parameters.

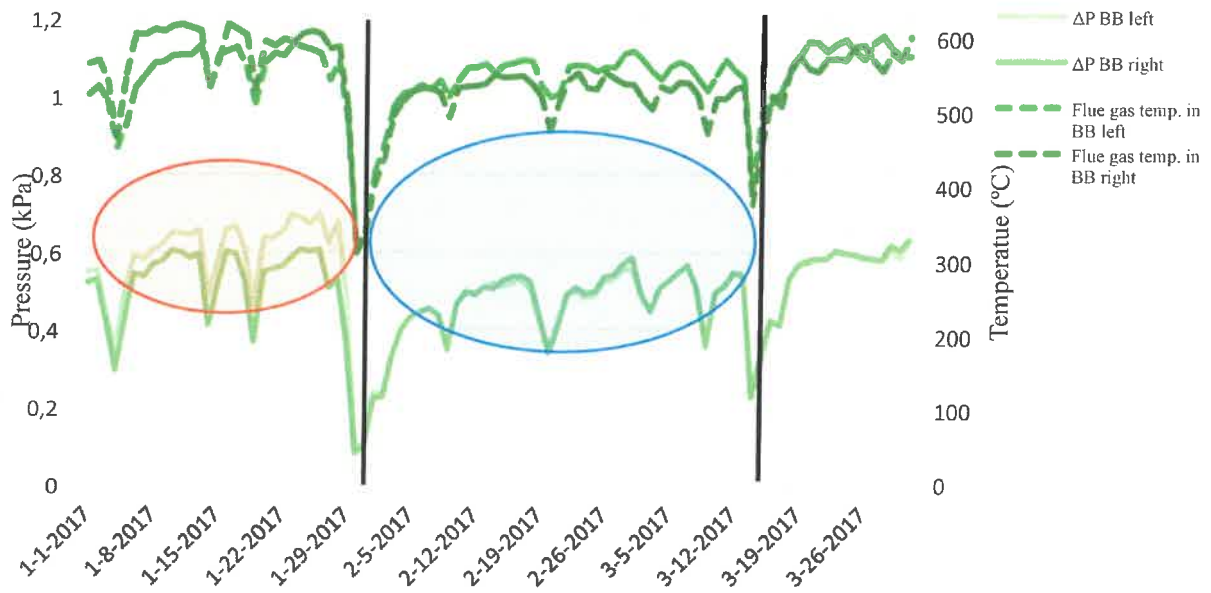


## 4 Results and discussion

### 4.1 Periods with high and low fouling

Time periods with high and low fouling were needed to be identified to be able to perform the analysis. As the mill had some problems during start-up, the values during the first years were unstable and were undesirable to include in the analysis. Data during 2017 has been analyzed in order to find time periods. Interesting data are presented below.

At the mill, the main parameter to study the fouling problems is the  $\Delta P$  over the boiler bank ( $\Delta P$  BB). Another parameter that the mill point out as an important parameter for the fouling problems is the flue gas temperature entering the boiler bank (Temp. BB). Data from the first quarter of 2017 (Q1) for these parameters and the other parameters were plotted. *Figure 11* shows the  $\Delta P$  BB and the Temp. BB. *Figure 12* shows the black liquor flow and the  $\Delta P$  BB. The black vertical lines in *Figures 11-14* symbolize recovery boiler trips. The red ellipses in the figures indicate high fouling and the blue ellipses indicate low fouling.



*Figure 11:  $\Delta P$  BB and Temp. BB during Q1 2017. The black vertical lines in the plot symbolize recovery boiler trips. The red ellipses indicate high fouling time period. The blue ellipses indicate low fouling time period.*

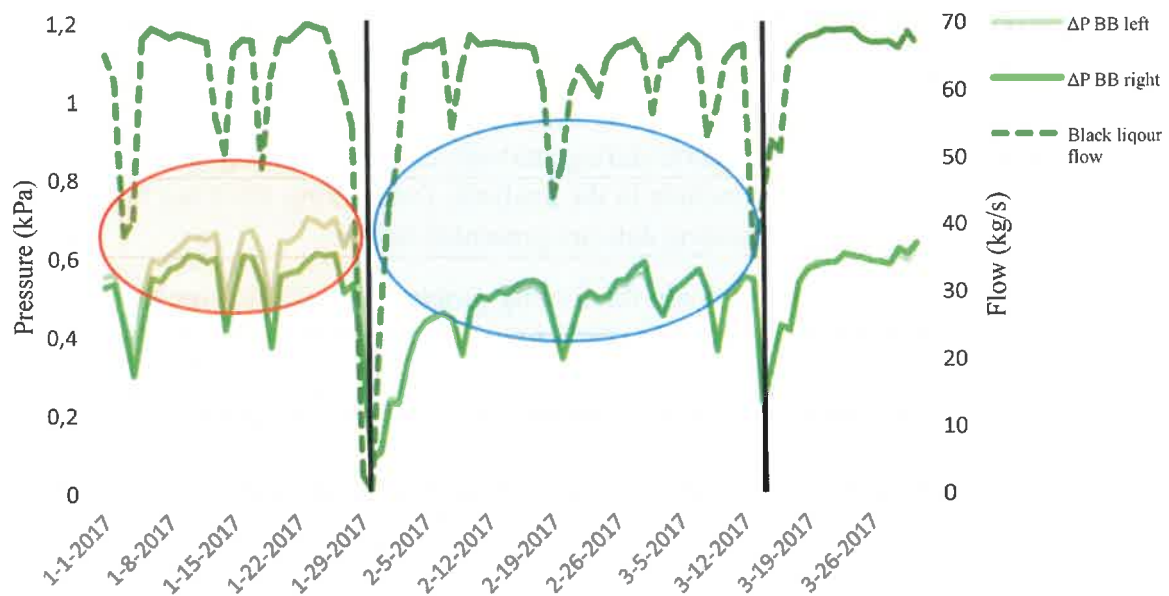


Figure 12:  $\Delta P$  BB and black liquor flow during Q1 2017. The black vertical lines in the plot symbolize recovery boiler trips. The red ellipses indicate high fouling time period. The blue ellipses indicate low fouling time period.

The time period before the first trip, see red ellipses in Figure 11-12, was defined as a high fouling period due to that both the main parameters that indicate fouling were at higher levels. Furthermore, unbalance between the two sides might also indicate fouling. From Figures 11-12 it can be concluded that the  $\Delta P$  BB left and right differ more before the first trip (red ellipses) compared to after the first trip (blue ellipses) as the values almost overlap.

The time period after the first trip, see blue ellipses in Figure 11-12, was defined as a low fouling period. The  $\Delta P$  BB and the Temp. BB were lower compared to data before the first trip. Furthermore, the  $\Delta P$  BB right and left follow each other fairly good. Dates for the time periods are summarized in Table 2. Data two days before and after the trips were excluded.

Interesting time periods to include were also found in the second quarter of 2017 (Q2). Figure 13 shows the  $\Delta P$  BB and Temp. BB. Figure 14 shows the black liquor flow and the  $\Delta P$  BB. The black vertical lines symbolize recovery boiler trips. The red ellipses in the figures indicate high fouling and the blue ellipses indicate low fouling.

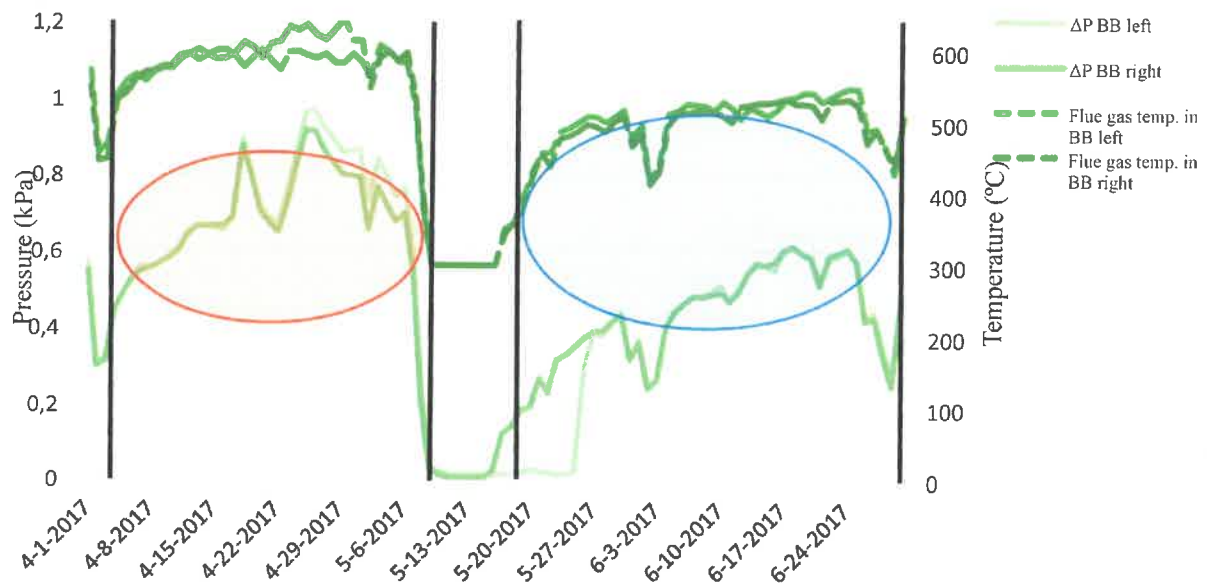


Figure 13:  $\Delta P$  BB and Temp. BB during Q2 2017. The black vertical lines in the plot symbolize recovery boiler trips. The red ellipses indicate high fouling time period. The blue ellipses indicate low fouling time period.

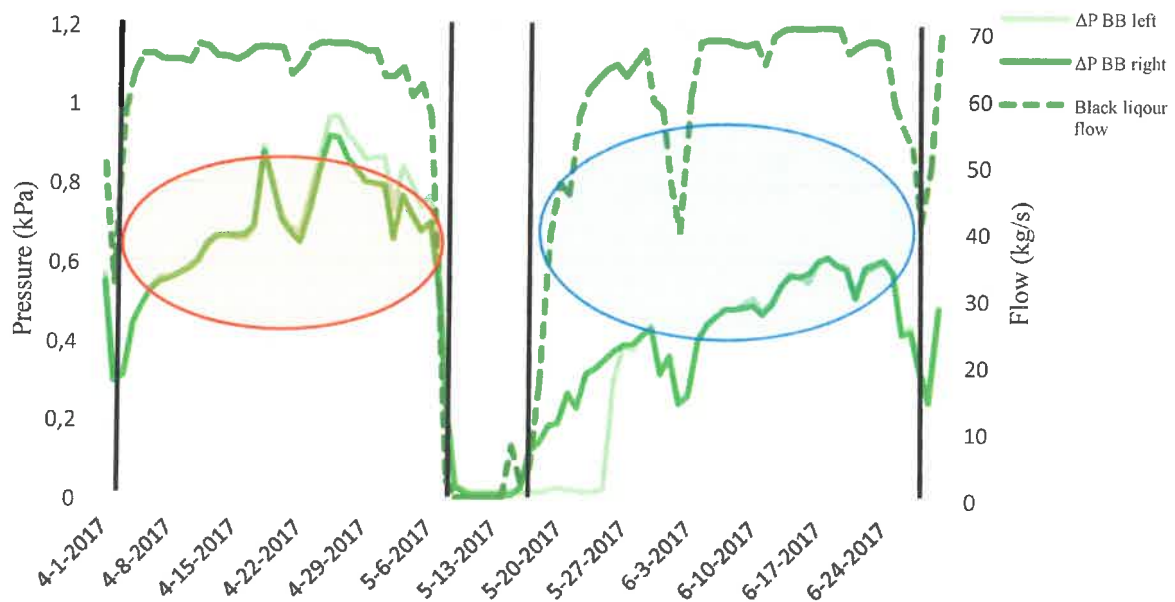


Figure 14:  $\Delta P$  BB and black liquor flow during Q2 2017. The black vertical lines in the plot symbolize recovery boiler trips. The red ellipses indicate high fouling time period. The blue ellipses indicate low fouling time period.

From the result in Figure 13-14, one period with high fouling and one period with low fouling can be determined. In the beginning of May 2017 the annual mill shut down took place and before this stop, see red ellipses in Figure 13-14, the boiler was operating with a higher  $\Delta P$  BB and higher Temp. BB compared to after the stop, see blue ellipse in Figure 13-14. The data for the left and the right side of the parameters vary more before the annual mill shut down which also might indicate higher fouling. One thing to highlight from Q2 2017 is that the black liquor flow was stable compared to the other time periods. Dates for the time periods are summarized in Table 2. Two days before and after the stop/trip were removed.

Table 2: Time periods with high and low fouling.

	High fouling	Low fouling
Model 1	January 5, 2017 to January 28, 2017	February 3, 2017 to March 12, 2017
Model 2	April 4, 2017 to May 5 2017	June 4, 2017 to June 25, 2017

## 4.2 Model 1 (first time period)

For every Y parameter in *Table 1*, one model was built for the period in Model 1. All the models showed similar results, however only one of the models is presented in this report (results from  $\Delta P$  BB left). Additional results from the PLS for each model can be find in the *Appendix 8.1*.

### 4.2.1 PCA

A PCA model was first built in order to analyze the data. The PCA model had 2 PCs and the values of the  $R^2X(\text{cum})$  and  $Q^2(\text{cum})$  for the PCs are shown in *Table 3*.

Table 3: The summary of fit for the PCA model.

PC	$R^2X(\text{cum})$	$Q^2(\text{cum})$
1	0.228	0.0826
2	0.405	0.181

According to guidelines, a  $Q^2$  value higher than 0.5 is good and a  $Q^2$  value higher than 0.9 is excellent. The difference between the  $R^2$  value and the  $Q^2$  value should preferably not be too large. (26) However, how good the values are depend on the applications. From *Table 3* it can be seen that the values for this model are low compared to the guidelines. In this work, process data have been used which include noise. Noise in the data decreases the values. In this work, the aim was not to build a perfect model of the data, instead the aim was to get indications of important parameters. It is always desirable to build models with high  $R^2$  and  $Q^2$  values, nevertheless the  $R^2$  and  $Q^2$  values for this model are adequate for these type of analyses.

The score plot of the first two PCs is shown in *Figure 15*. The first PC, which symbolizes the greatest variability, is the x axis and the second PC, which symbolizes the second greatest variability, is the y axis. Some of the observations are placed outside the Hotelling's  $T^2$  which would indicate that the observations are outliers. However, these observations have not been excluded due to the assumption that these observations are variation in the data.

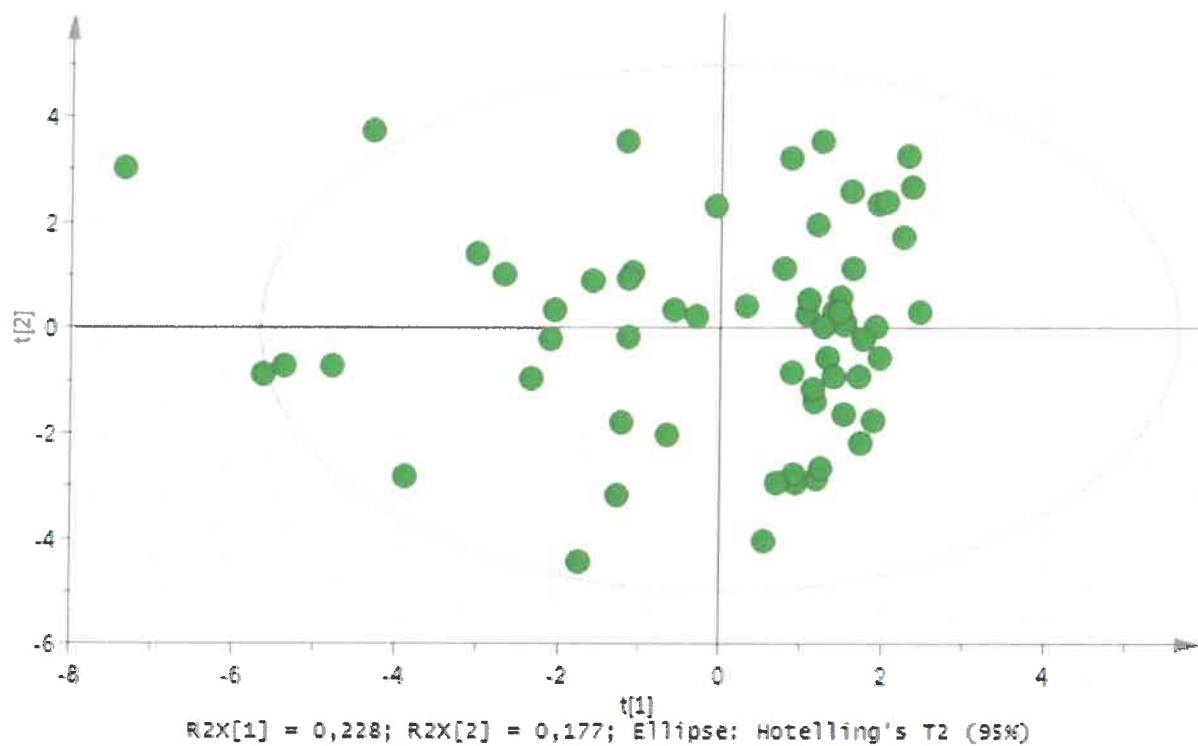


Figure 15: The score plot for Model 1.

The loading plot for Model 1 was investigated to get an insight into the first two PCs. The loading plot shows the first two loadings and is shown in Figure 16.

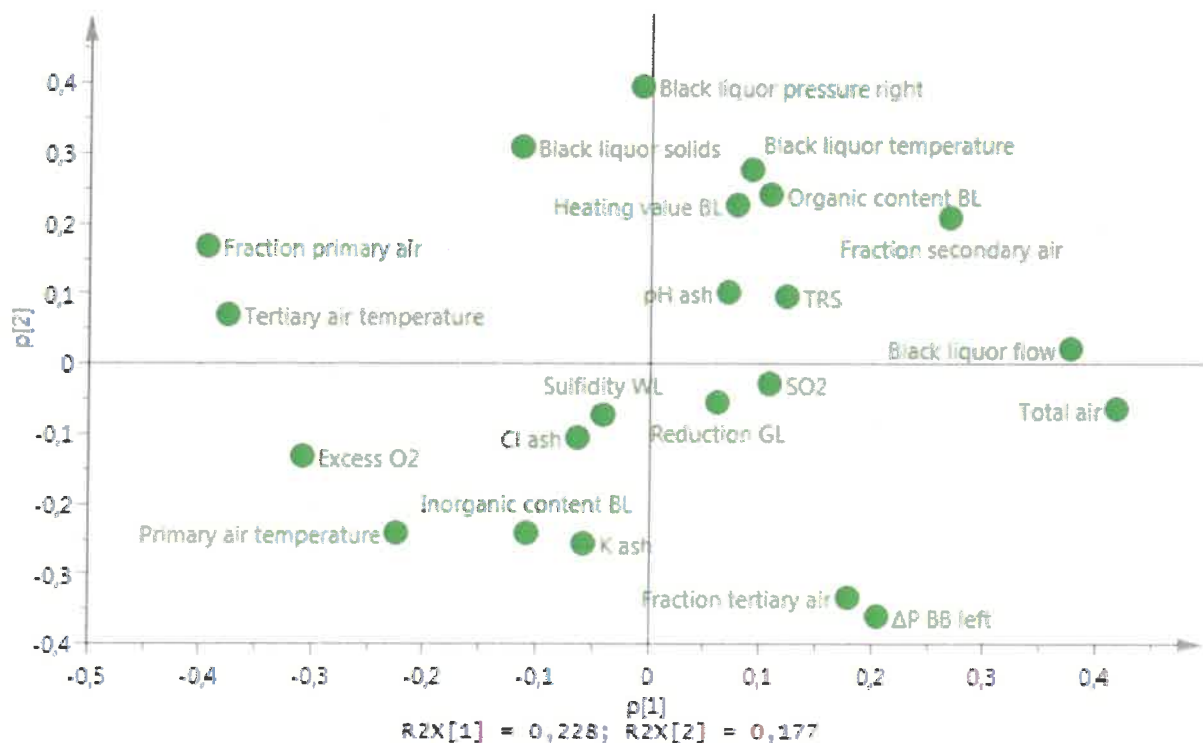
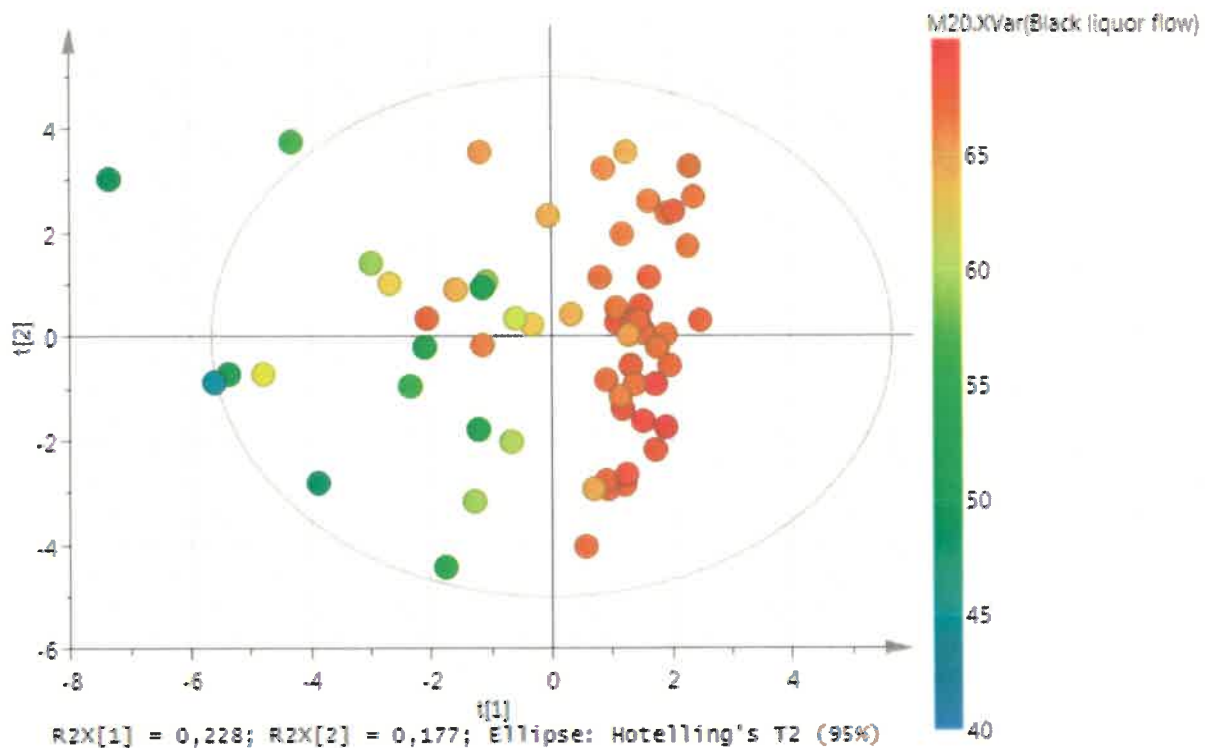


Figure 16: The loading plot for Model 1.

The black liquor flow is located to the right in the loading plot along the first loading. This indicates that the black liquor flow has a high influence on the first PC. The score plot can

also be colored according to the black liquor flow, see *Figure 17*. From that, it can be concluded that the black liquor flow increases to the right in the score plot. The total air is located close to the black liquor flow in the loading plot which would symbolize that these two variables are positively correlated. The correlation structure will be further discussed in the section about the PLS.



*Figure 17: The score plot for Model 1, colored according to the black liquor flow.*

The  $\Delta P$  BB left is located in the lower part of the loading plot. The score plot can be colored also according to the  $\Delta P$  BB left which is shown in *Figure 18*. As can be seen,  $\Delta P$  BB left is higher in the lower part of the score plot and lower in the upper part (especial high in the lower right quadrante). A high  $\Delta P$  BB left indicates fouling according to the mill. This would mean that the observations located in the lower part of the score plot have more problems with fouling compare to the observations located in the upper part. The fraction of tertiary air is located close to the  $\Delta P$  BB left in the loading plot, *Figure 16*. This indicates that the parameters are positively correlated. The black liquor dry solids are located opposite to the  $\Delta P$  BB left which would indicate negative correlation.



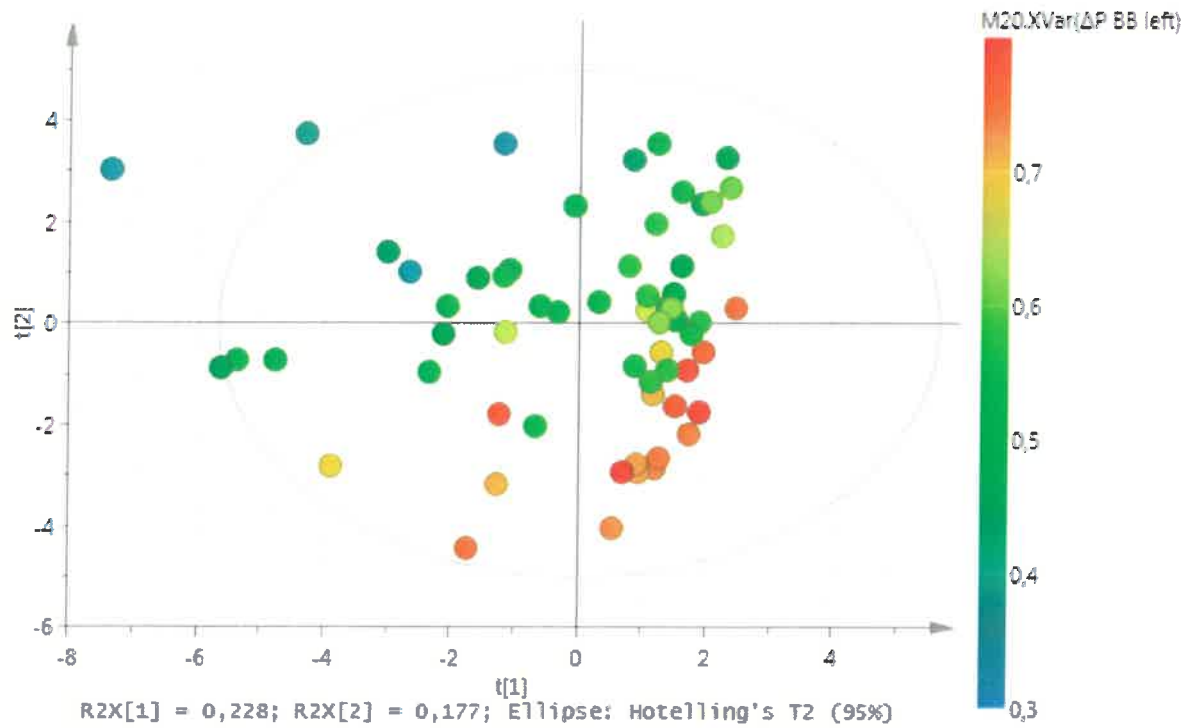


Figure 18: The score plot for Model 1, colored according to  $\Delta P$  BB left.

Figure 16 shows that the sulfidity is located close to the origo. This indicates that the sulfidity does not affect none of the two first PCs to a high extend. The sulfidity is not located close to the  $\Delta P$  BB left which means that the sulfidity does not highly correlate with the  $\Delta P$  BB left. However, since the range of the sulfidity have been limited during the time period, see Table 4 the theory regarding that too high level of sulfidity is used cannot be completely rejected.

The results above indicate that the upper right quadrate symbolizes ideal days. During these days the recovery boiler runs with high black liquor flow and with high thermal efficiency.

#### 4.2.2 High and low fouling average values

To analyze the data further, the data was divided into two groups, high and low fouling according to Table 2. The same dataset was used for all the different models built with data from the first time period which means that the average values for the parameters were the same. The average values for the other Y parameters in Table 1 have not been reported in the report. The score plot colored according to the two groups are shown in Figure 19. The data points with high fouling are mostly located in the lower part with focus in the lower right quadrate. The data points with low fouling are mostly located in the upper part of the plot. The results in Figure 19 correspond well with the previous results. However, the time periods with high and low fouling are based on the  $\Delta P$  BB which probably lead to the correspondence. Nevertheless, the results from the other models indicate the same results which increase the validity.

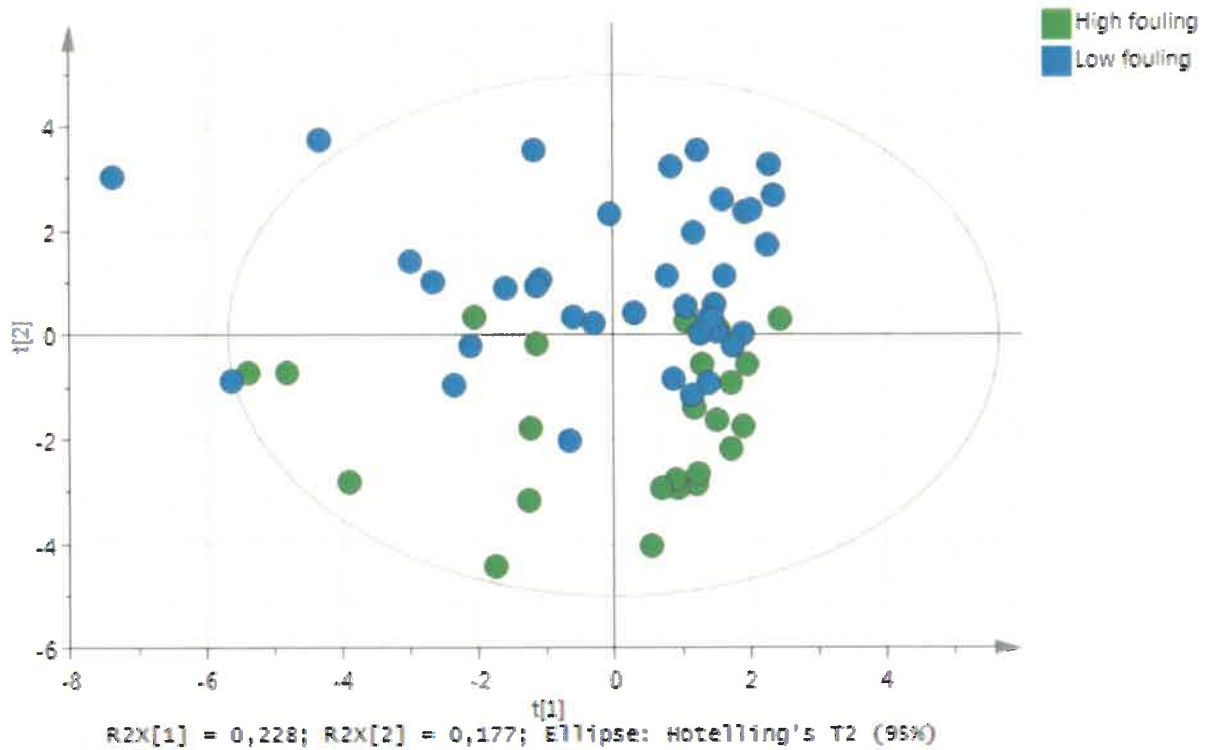


Figure 19: The score plot for Model 1, colored according to classes.

The average values together with the standard deviations for the two classes were calculated. Table 4 shows the results. The confidence intervals for the parameters have not been reported in this report. The results in Table 4 between high and low fouling overlap each other to a high extend. The confidence intervals will be even larger compared to the standard deviations and therefore, there are no interest to studying the confidence intervals.

Table 4: Average values and standard deviations for high and low fouling.

Parameter	Average low fouling	Std. dev. Low fouling	Average high fouling	Std. dev. High fouling
Black liquor flow (l/s)	63.1	5.57	64.5	6.19
Black liquor solids (%)	80.0	0.61	79.6	0.80
Black liquor pressure right (bar)	1.61	0.04	1.52	0.06
Black liquor temperature (°C)	142	0.25	142	0.43
ID fan speed (rpm)	722	56.2	745	47.8
Total air (Nm <sup>3</sup> /s)	239	10.0	239	9.28
Part primary air (%)	0.20	0.01	0.20	0.01
Part secondary air (%)	0.37	0.01	0.37	0.01
Part tertiary air (%)	0.43	0.01	0.43	0.01
Primary air temperature (°C)	164	0.60	164	0.53
Tertiary air temperature (°C)	149	1.88	149	1.53
Steam temp. (°C)	475	4.41	476	6.74
Steam flow (kg/s)	249	19.1	249	20.3
Steam pressure (bar)	95.4	0.19	95.5	0.16
Sulfidity WL (%)	29.7	3.56	31.2	0.72
Heating value BL (MJ/kg)	11.9	1.47	11.5	0.61
Inorganic content BL (%)	50.6	4.20	55.3	7.95
Organic content BL (%)	49.4	4.20	44.7	7.95
Reduction GL (%)	94.2	2.13	92.3	2.98
Cl ash (%)	1.97	0.12	2.00	0.17
pH ash	11.5	0.31	11.5	0.12
K ash (%)	3.22	0.13	3.49	0.26



TRS (mg H <sub>2</sub> S/Nm <sup>3</sup> al 7%)	1.17	1.25	0.95	0.59
SO <sub>2</sub> (mg/Nm <sup>3</sup> al 7%)	0.63	1.14	0.74	1.49
Excess O <sub>2</sub> (%)	2.93	0.48	2.95	0.63
Flue gas ΔP BB left (kPa)	0.48	0.06	0.62	0.06

Results from *Table 4* show that almost all of the parameters overlap with each other and therefore can no clear conclusions be drawn. To improve the analysis and be able to compare the high and the low fouling periods, longer time periods will probably be required. Shorter time periods have been used in this work due to lack of stable process data for longer times. In a previous report, data from 3.5 and 4.5 years have been used. (1) The average values when using longer periods will probably be more stabilized and the standard deviations lower. When comparing average values for longer time periods, differences in outcome can probably be seen. A good idea for the mill might be to use the average values during low fouling time periods as operational targets. However, the variables might be positive or negative correlated so caution must be taken. This means that when one variable increases, other variables can increase or decrease to various degrees. This lead to that if one parameter is changed, the boiler can enter into a new operational mode which can lead to unexpected consequences. Hence, the model is not universal as a short term period has been used here, but the validity of the model may be extended using longer time periods.

#### 4.2.3 PLS

A PLS model was formed from the PCA model. The PLS model had 1 PC and the R<sup>2</sup>X(cum), R<sup>2</sup>Y(cum) and the Q<sup>2</sup>(cum) are shown in *Table 5*.

*Table 5: The summary of fit for the PLS model.*

PC	R <sup>2</sup> X(cum)	R <sup>2</sup> Y(cum)	Q <sup>2</sup> (cum)
1	0.176	0.643	0.59

The values in *Table 5* indicates that the model is not a perfect model. However, the aim of this work was to find indications of important parameters and for that aim, the values in *Table 5* are sufficient. Although, higher R<sup>2</sup> and Q<sup>2</sup> values would generate a model with higher accuracy. Due to the fact that process data are used, noise will generate in lower R<sup>2</sup> and Q<sup>2</sup> values. The Y Observed vs. Y Predicted plot are shown in *Figure 20*. The plot describes how good the model fits. The R<sup>2</sup> value of the regression line is 0.6435 which is the same as the R<sup>2</sup>Y(cum).

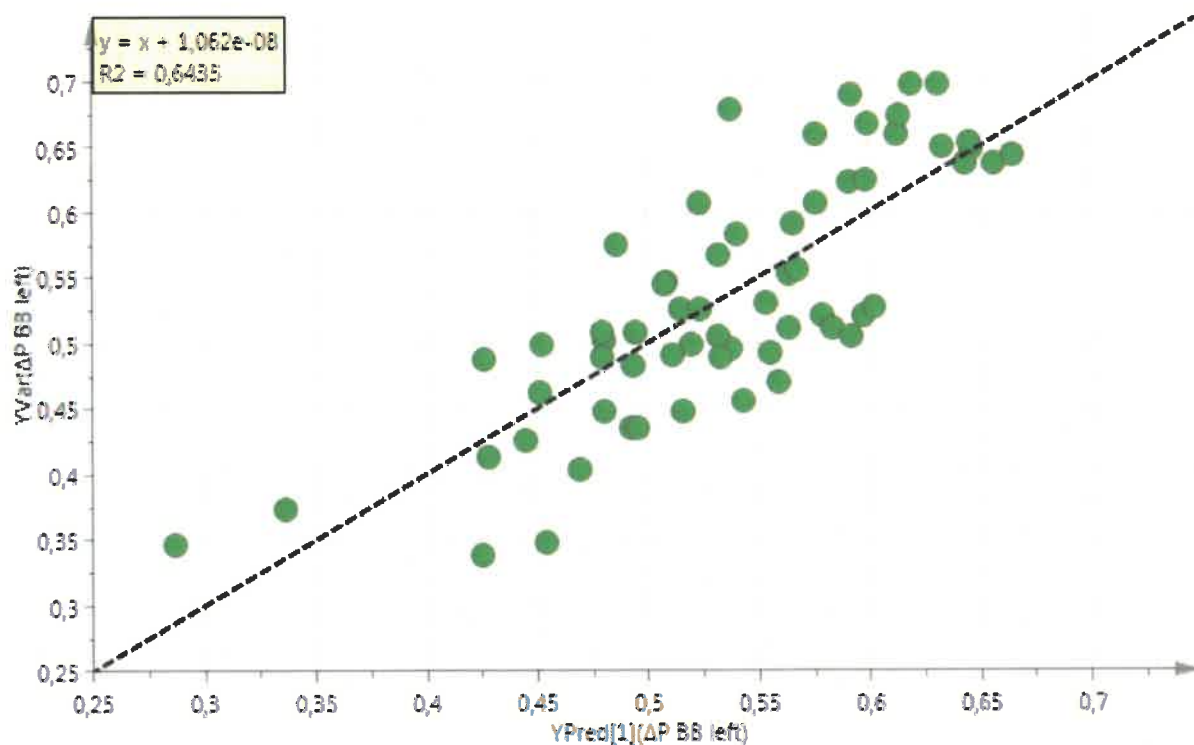


Figure 20: The Y Observed vs. Y Predicted plot for Model 1.

The correlation structure between the X and the Y parameters was studied by using the VIP plot and the coefficient plot. The VIP plot is shown in Figure 21 and the coefficient plot is shown in Figure 22.

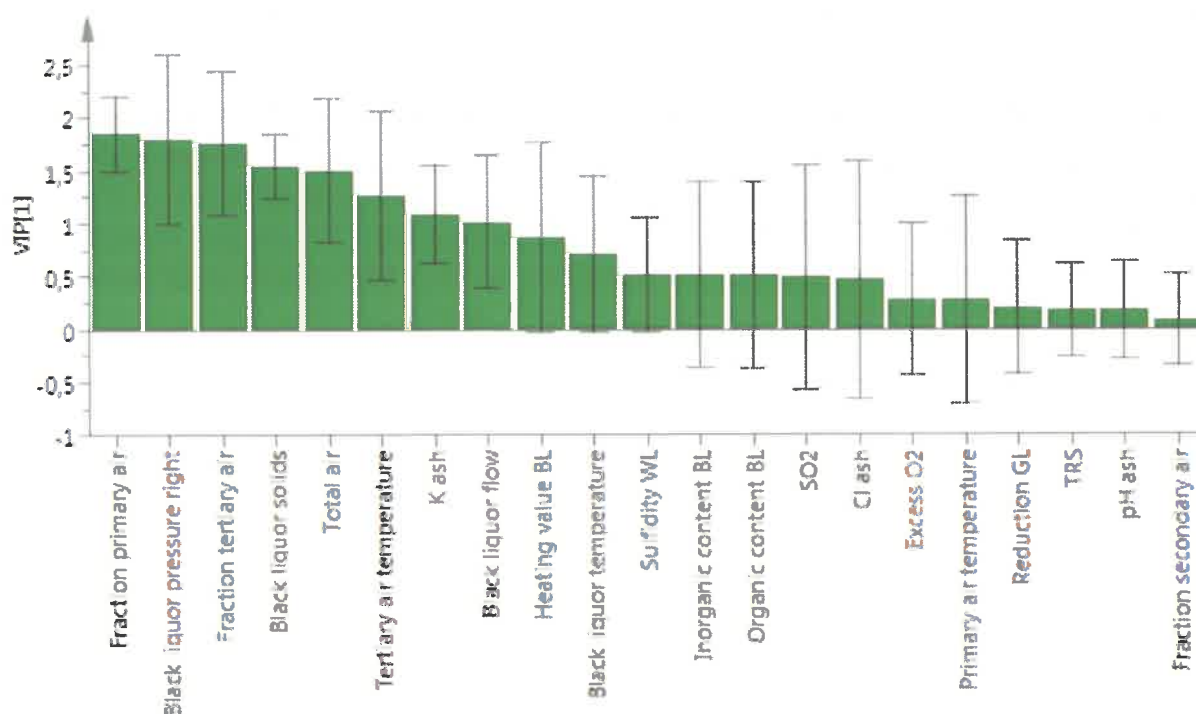


Figure 21: The VIP plot for Model 1.

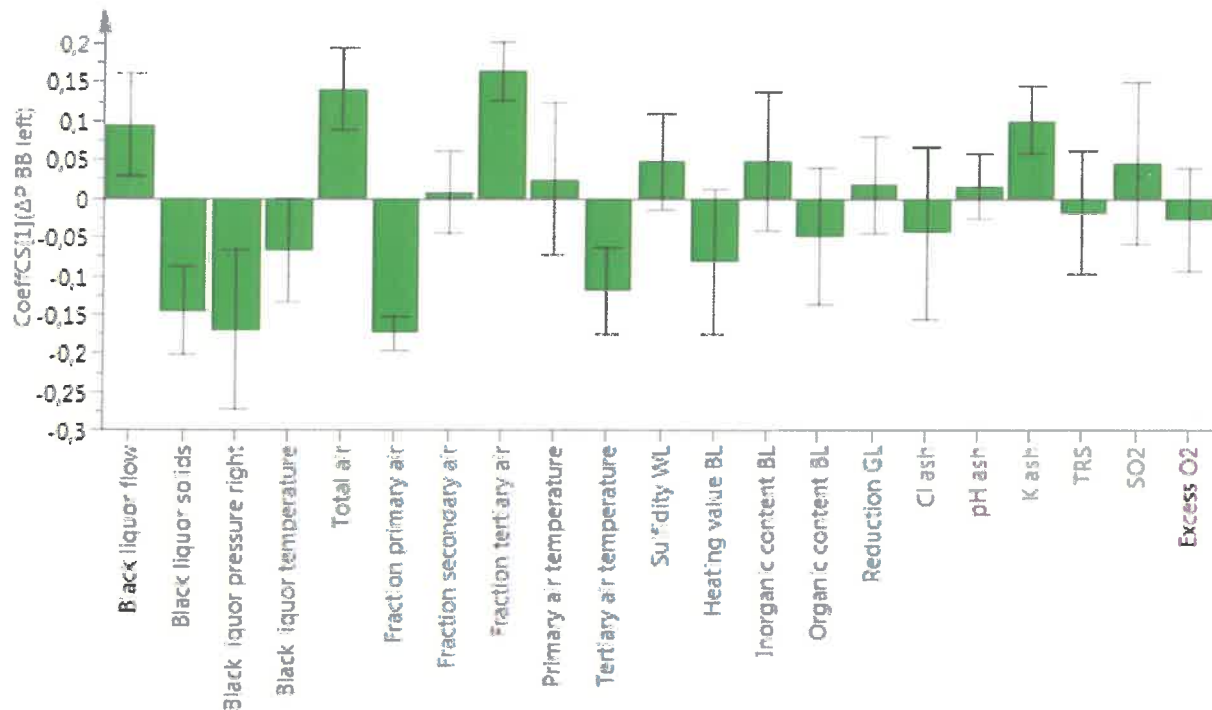


Figure 22: The coefficient plot for Model 1.

X parameters with high VIP-values are important and from the VIP plot it can be concluded that the most important X parameters are the fraction of primary air, the black liquor pressure, the fraction of tertiary air, the black liquor dry solids and the total air. The results from the VIP plot indicate also that the sulfidity does not affect the fouling problems severely. The error bar for the sulfidity includes zero which means that the coefficient is not significant. This might be due to that the sulfidity was stable during the time period, see *Table 4*. If the sulfidity varies to a larger extent, the results might be different and might show correlation with the  $\Delta P$  BB left.

The coefficient plot was studied in order to see how the X parameters correlate to the Y parameter. The fraction of primary air has a negative correlation with  $\Delta P$  BB left which means that the  $\Delta P$  BB left increases when the fraction of primary air decreases. The fraction of tertiary air has a positive correlation with the  $\Delta P$  BB left which means that the  $\Delta P$  BB left increases when the fraction of tertiary air increases. *Figure 23* shows the fraction of primary air plotted against  $\Delta P$  BB left and *Figure 24* shows the fraction of tertiary air plotted against  $\Delta P$  BB left.

Some of the error bars for the X parameters includes 0 in the coefficient plot. That means that the parameters are not significant and would usually be removed from the model in order to form an optimal model. However, in this work the parameters that include 0 in the coefficient plot have been left in the model. That is mainly due to two reasons. First, the aim is not to build a perfect model. The model should indicate important parameters for the fouling. Second, the parameters that indicate unimportant for the fouling can also be seen.

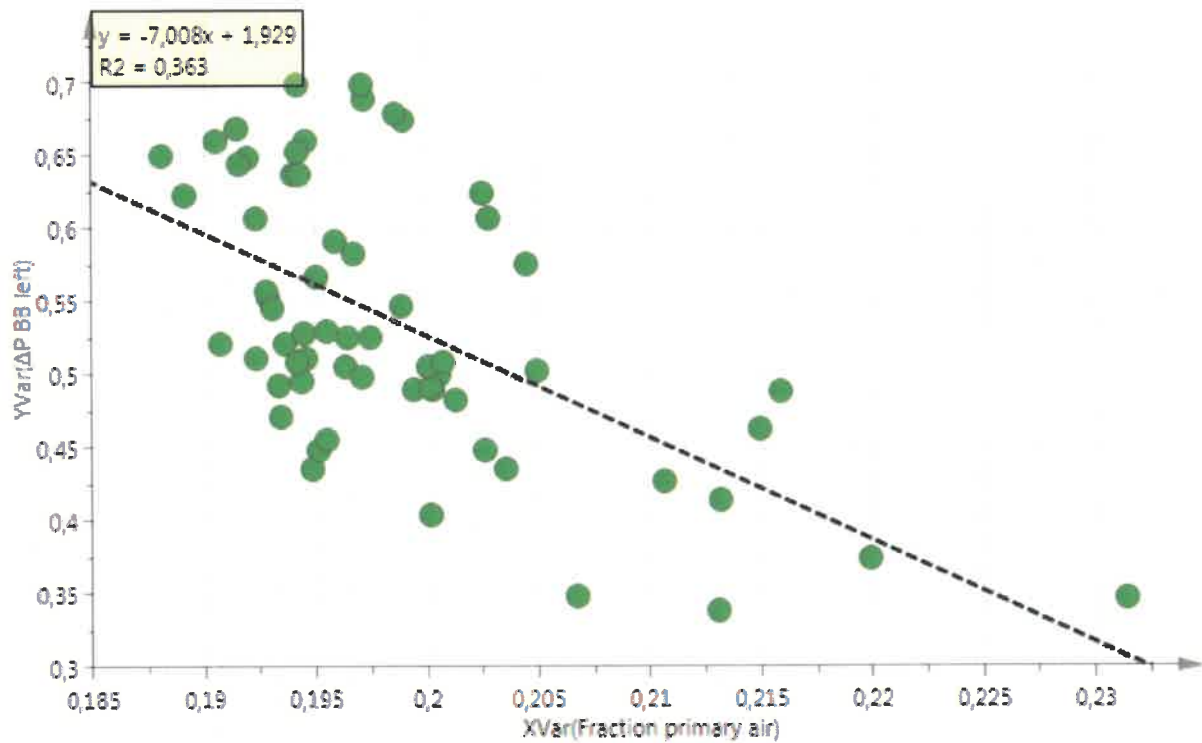


Figure 23: Fraction of primary air plotted against  $\Delta P$  BB left.

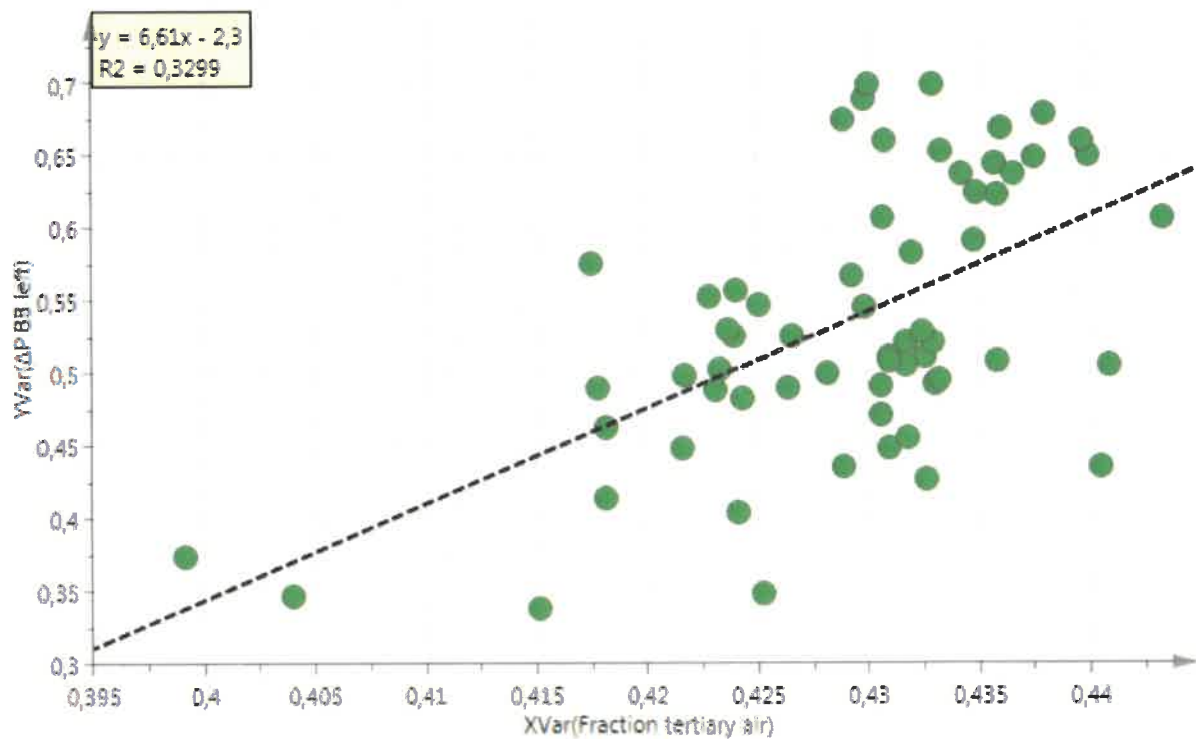
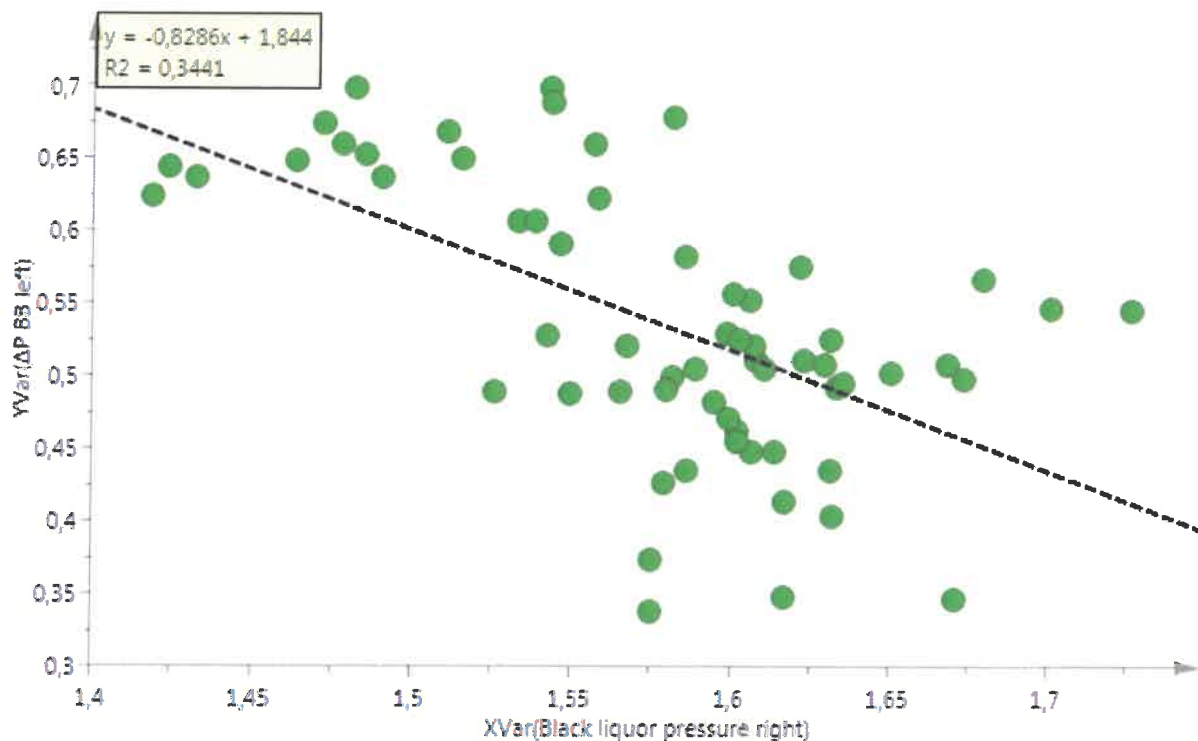


Figure 24: Fraction of tertiary air plotted against  $\Delta P$  BB left.

The results from the coefficient plot and Figure 23-24 indicate that the mill might run the boiler at too low fraction of primary air and a too high fraction of tertiary air. An incorrect distribution of the air can generate problems. A too low fraction of primary air will probably result in insufficient amount of oxygen in the lower part of the furnace and thereby less reactions between the pyrolysis gases and the oxygen. The pyrolysis gases might go up in the

furnace and result in fouling. However, the distribution of the air is a controversial question. Nowadays, a more modern way for reducing the  $\text{NO}_x$  emissions is to add more air higher up in the furnace. More air higher up in the furnace completes the burning of the combustible gases which lead to lower emissions. However, the variation in fractions between high and low fouling is fairly small, see x-axes in *Figure 23-24*.

The coefficient plot also indicates that the black liquor pressure and the black liquor dry solids have a negative correlation with the Y parameter. This means that when the  $\Delta P$  BB left is high, the black liquor pressure and the black liquor dry solids are low. The black liquor pressure is plotted against  $\Delta P$  BB left in *Figure 25* and the black liquor dry solids against  $\Delta P$  BB left in *Figure 26*.



*Figure 25: Black liquor pressure plotted against  $\Delta P$  BB left.*

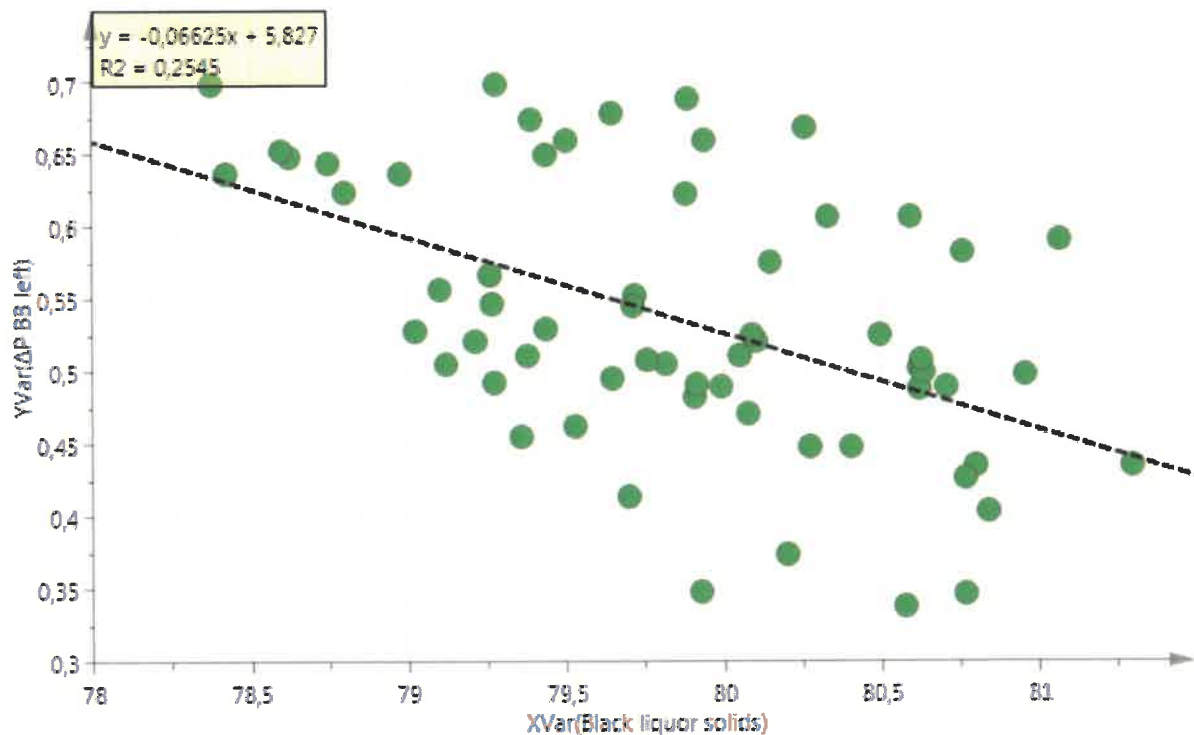


Figure 26: Black liquor dry solids plotted against the  $\Delta P$  BB left.

The results in Figure 25 show that when lower black liquor pressure is used,  $\Delta P$  BB left is higher. In order to deliver sufficient amount of liquor to the boiler, the black liquor temperature must be higher when a lower black liquor pressure is used. The temperature of the black liquor might lead to that the droplets swell more rapidly which could lead to that the density becomes lower and the particles follow the gases up in the furnace. However, the black liquor temperature in the coefficient plot includes zero so no clear conclusions can be drawn for that parameter. There are also other factors that influence the black liquor pressure, for instance the black liquor dry solids. Additional consideration that needs to be done when studying the results is the variation in the black liquor pressure, see Table 4.

The black liquor dry solids have a negative correlation with the  $\Delta P$  BB left. When lower black liquor dry solids content are used, more water enters the recovery boiler. During the processes in the recovery boiler, the water needs to evaporate which lead to a higher  $\Delta P$  BB left. When higher black liquor dry solids are used, less water enters the recovery boiler. Less water needs to evaporate in this case which result in lower  $\Delta P$  BB left. The results from this work correspond therefore with the theory.

The black liquor flow has a positive correlation with  $\Delta P$  BB left which corresponds with the theory. When more black liquor enters the recovery boiler, more particles go up in the furnace and the  $\Delta P$  BB left increases.

The results concerning the black liquor flow and the black liquor dry solids indicates that model tends to be valid since the correlation between these parameters and the Y parameter follow the main theories regarding the fouling in the recovery boiler.

However, for making any changes in the process, more investigations need to be done and the results from the correlation structure between the X and Y parameters is not sufficient since only shorter time periods have been used.



### 4.3 Model 2 (second time period)

For every Y parameter in *Table 1*, one model was built with data from the second time period, Model 2 in *Table 2*. All the models show similar results, however only one of the models will be present in this report (results from  $\Delta P$  BB left side). Additional results from the PLS models can be found in *Appendix 8.2*.

#### 4.3.1 PCA

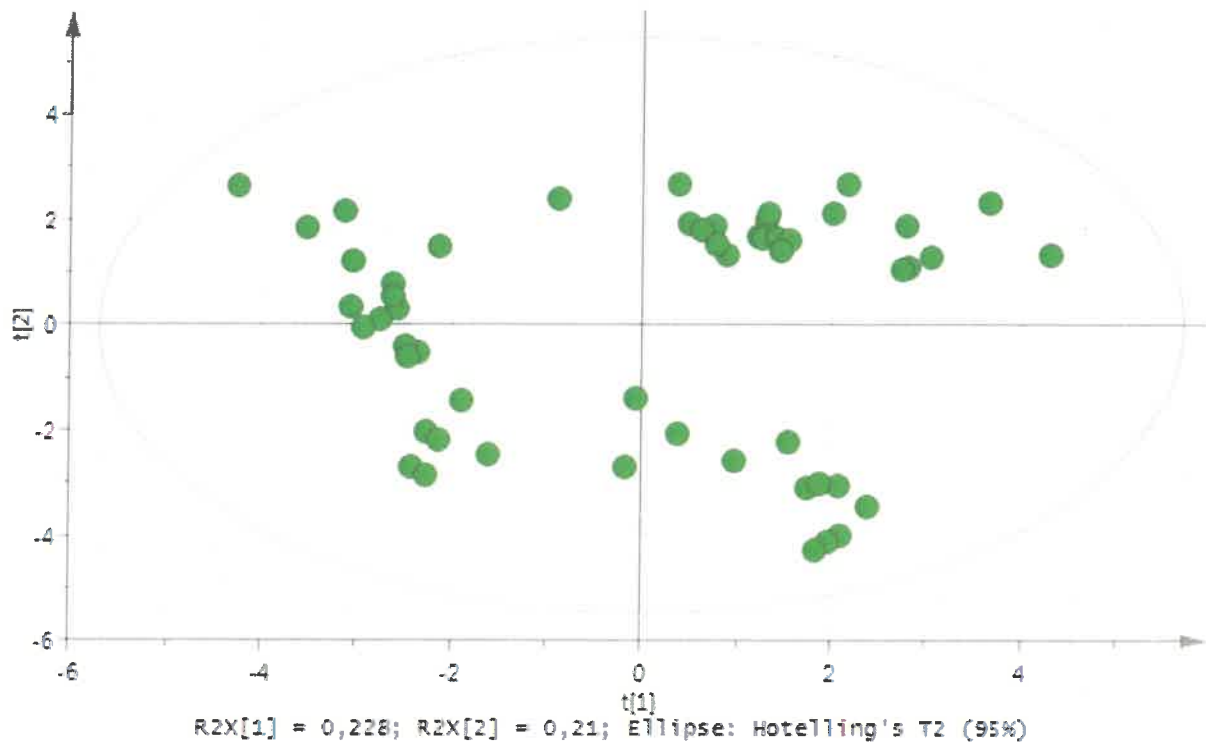
A PCA model was first built in order to analyze the data. The PCA model had 4 PCs and the values of the  $R^2X(\text{cum})$  and  $Q^2(\text{cum})$  for the PCs are summarized in *Table 6*.

*Table 6: The summary of fit for the PCA model.*

PC	$R^2X(\text{cum})$	$Q^2(\text{cum})$
1	0.228	0.0996
2	0.438	0.23
3	0.573	0.289
4	0.671	0.299

The values in *Table 6* indicate that the built model is not a perfect model. However, the aim of this work was to find indications of important parameters and for that aim, the values in *Table 6* are sufficient. Although, higher  $R^2$  and  $Q^2$  values would generate in a better model. Due to the fact that process data are used, noise will generate in lower  $R^2$  and  $Q^2$  values.

The score plot of the first two PCs is shown in *Figure 27*. The first PC, which symbolizes the greatest variability, is the x axis and the second PC, which symbolizes the second greatest variability, is the y axis. All the observations are placed inside the Hotelling's  $T^2$  which indicate that no outliers are included in the analysis.



*Figure 27: The score plot for Model 2.*

The loading plot for the model was investigated to get an insight into the first two PCs. The loading plot shows the first two loadings and is shown in *Figure 28*. The loadings show how the parameters contribute to the PCs.

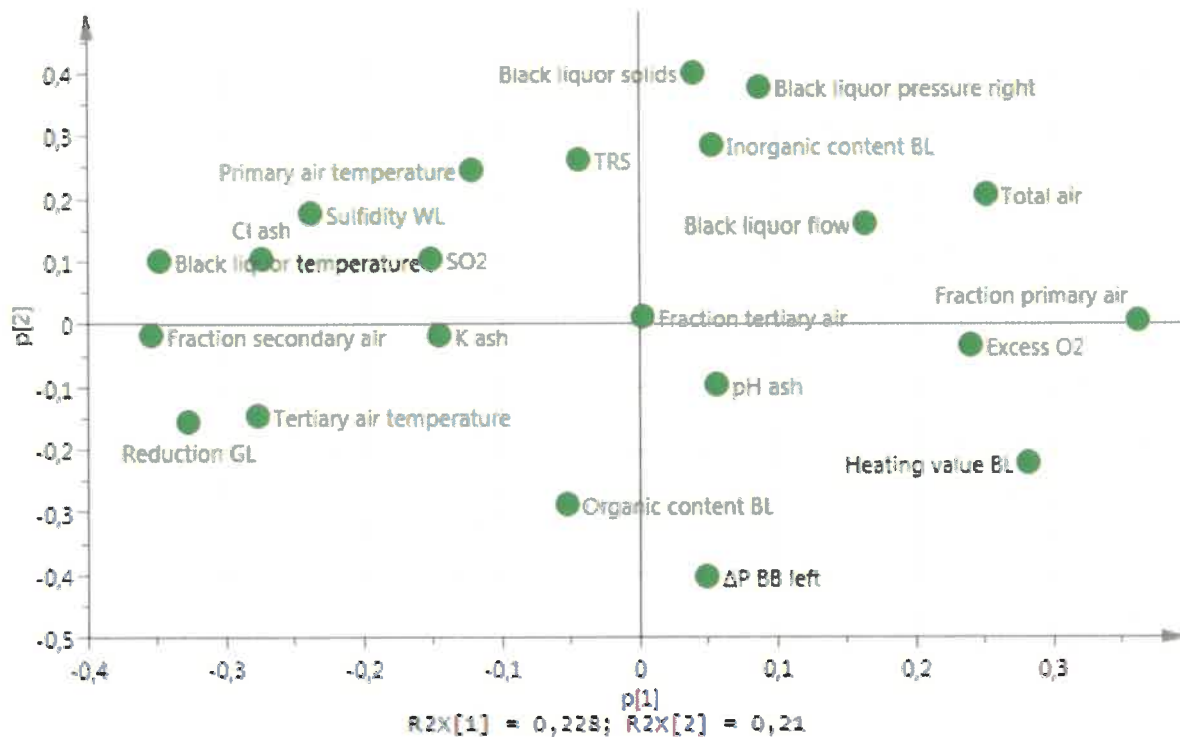


Figure 28: Loading plot for Model 2.

The fraction of primary air can be found to the right in the loading plot. This indicates that the fraction of primary air highly influences the first PC. The fraction of secondary air is located to the left along the first PC which means that parameter has a negative correlation with the fraction of primary air.

From the loading plot it can be concluded that the  $\Delta P$  BB left is located along the second PC, in the lower part of the loading plot. The loading plot indicates that observations with low  $\Delta P$  BB left are in the upper part and observations with higher  $\Delta P$  BB left are located in the lower part. The black liquor dry solids and the TRS are located on the opposite side from the  $\Delta P$  BB left which indicates that these two parameters would have a negative correlation. The correlation structure will be further investigated in the PLS.

For this model, the black liquor flow was fairly stable and is therefore located closer to the center in the loading plot. This means that the black liquor flow does not highly correspond with the fouling problems. The sulfidity is located in the upper left quadrant. The absolute value for the sulfidity is not that high, however there seems to be some negative correlation between the sulfidity and the  $\Delta P$  BB left. The range of the sulfidity has not been changed to a high degree during this time period either, see *Table 7* which might affect the results.

#### 4.3.2 Average values between high and low fouling

To analyze the data further, the data was divided into two groups, high and low fouling according to *Table 2*. The same dataset was used for all the different models built with data



from the second time period values which means that the average values for the parameters were the same. The average values for the other Y parameters in *Table 1* have not been reported in the report. The score plot colored according to the two groups are shown in *Figure 29*. The data points with high fouling are mostly located in the lower part of the plot and the data points with low fouling in the upper part of the plot. The results in *Figure 29* correspond well with the previous results. However, the time periods with high and low fouling are based on the  $\Delta P$  BB which probably lead to the correspondence. Nevertheless, the results from the other models indicate the same results which increase the validity.

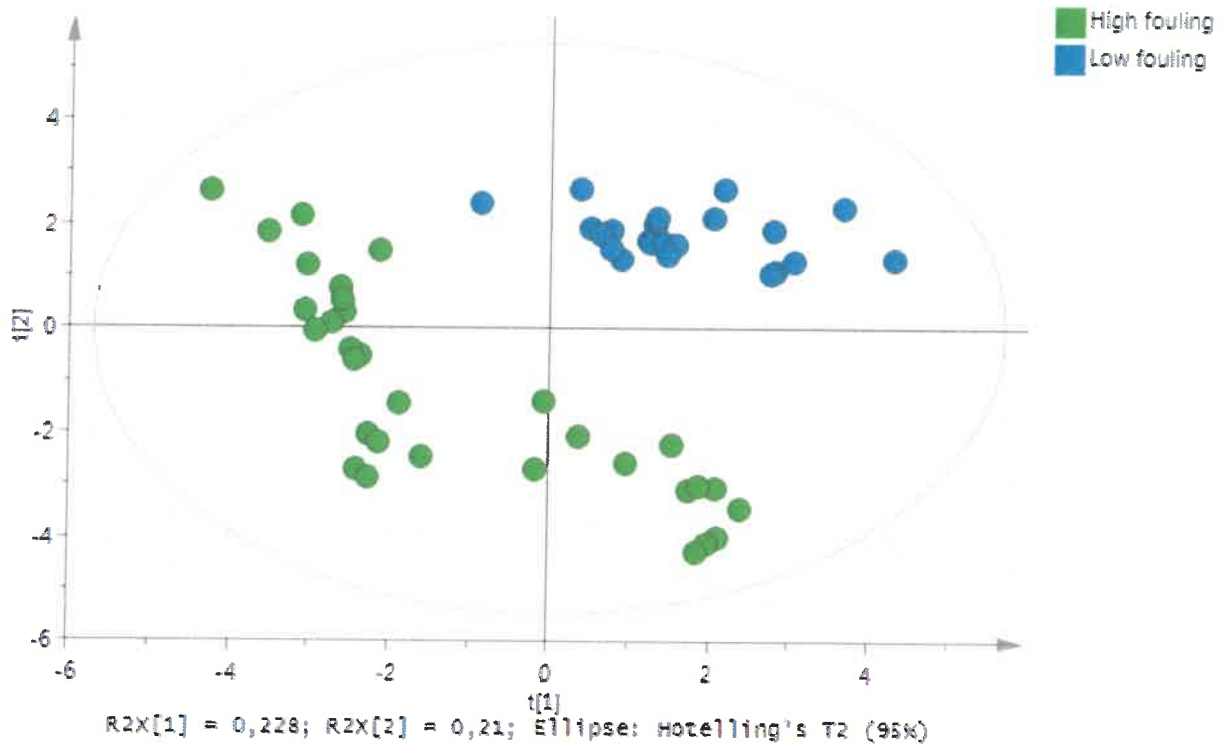


Figure 29: The score plot for Model 2, colored according to the classes.

The average values together with the standard deviations for the two groups have been calculated and are shown in *Table 7*. The confidence intervals for the parameters have not been reported in this report. The results in *Table 4* between high and low fouling overlap each other to a high extent. The confidence intervals will be even larger compared to the standard deviations and therefore, there are no interest to studying the confidence intervals.

Table 7: Average values and standard deviations for high and low fouling.

Parameter	Average low fouling	Std. dev. Low fouling	Average high fouling	Std. dev. High fouling
Black liquor flow (l/s)	68.5	2.50	66.0	1.98
Black liquor solids (%)	80.6	0.37	79.6	0.70
Black liquor pressure right (bar)	1.72	0.05	1.61	0.05
Black liquor temperature (°C)	142	0.17	142	0.21
ID fan speed (rpm)	719	23.9	763	30.1
Total air (Nm <sup>3</sup> /s)	255	5.45	246	5.05
Part primary air (%)	0.21	0.002	0.20	0.005
Part secondary air (%)	0.37	0.005	0.37	0.005
Part tertiary air (%)	0.42	0.005	0.42	0.004
Primary air temperature (°C)	139	1.36	138	1.54

Tertiary air temperature (°C)	145	1.30	147	1.16
Steam temp. (°C)	483	2.99	476	2.07
Steam flow (kg/s)	263	10.0	254	8.02
Steam pressure (bar)	95.8	0.13	95.6	0.09
Sulfidity WL (%)	30.6	1.02	30.7	1.30
Heating value BL (MJ/kg)	13.2	1.03	13.2	1.08
Inorganic content BL (%)	53.8	6.28	47.2	9.80
Organic content BL (%)	46.2	6.28	52.8	9.80
Reduction GL (%)	90.1	1.40	93.5	2.30
Cl ash (%)	2.07	0.10	2.10	0.17
pH ash	11.6	0.04	11.6	0.07
K ash (%)	2.93	0.38	3.05	0.20
TRS (mgH <sub>2</sub> S/Nm <sup>3</sup> al 7%)	0.90	0.41	0.64	0.37
SO <sub>2</sub> (mg/Nm <sup>3</sup> al 7%)	0.54	1.23	0.57	0.93
Excess O <sub>2</sub> (%)	3.17	0.21	3.03	0.20
ΔP BB left (kPa)	0.53	0.06	0.72	0.14

Results from *Table 7* show that almost all of the parameters overlap with each other and therefore can no clear conclusions be drawn. To improve the analysis and be able to compare the high and the low fouling periods, longer time periods will probably be required. Shorter time periods have been used in this work. The average values when using longer periods will probably be more stabilized and the standard deviations lower. When comparing average values for longer time periods, differences can probably be seen. A good idea for the mill might be to use the average values during low fouling time periods as operational targets. However, the variables might be positive or negative correlated so caution must be taken. This means that when one variable increases, other variables can increase or decrease to various degrees. This lead to that if one parameter is changed, the boiler can enter into a new operational mode which can lead to unexpected consequences. Hence, the model is not universal as a short term period has been used here, but the validity of the model may be extended using longer time periods.

#### 4.3.3 PLS

A PLS model was formed from the PCA model. The PLS model built had 1 PC and the  $R^2X(\text{cum})$ ,  $R^2Y(\text{cum})$  and the  $Q^2(\text{cum})$  for the model are shown in *Table 8*.

*Table 8: The summary of fit for the PLS model.*

PC	$R^2X(\text{cum})$	$R^2Y(\text{cum})$	$Q^2(\text{cum})$
1	0.182	0.752	0.719

The values in *Table 8* indicates that the model is not a perfect model but fairly good. However, the aim of this work was to find indications of important parameters and for that aim, the values in *Table 8* are sufficient. Although, higher  $R^2$  and  $Q^2$  values would generate a better model. Due to the fact that process data are used, noise will generate in lower  $R^2$  and  $Q^2$  values. The Y Observed vs Y Predicted plot is shown in *Figure 30*.

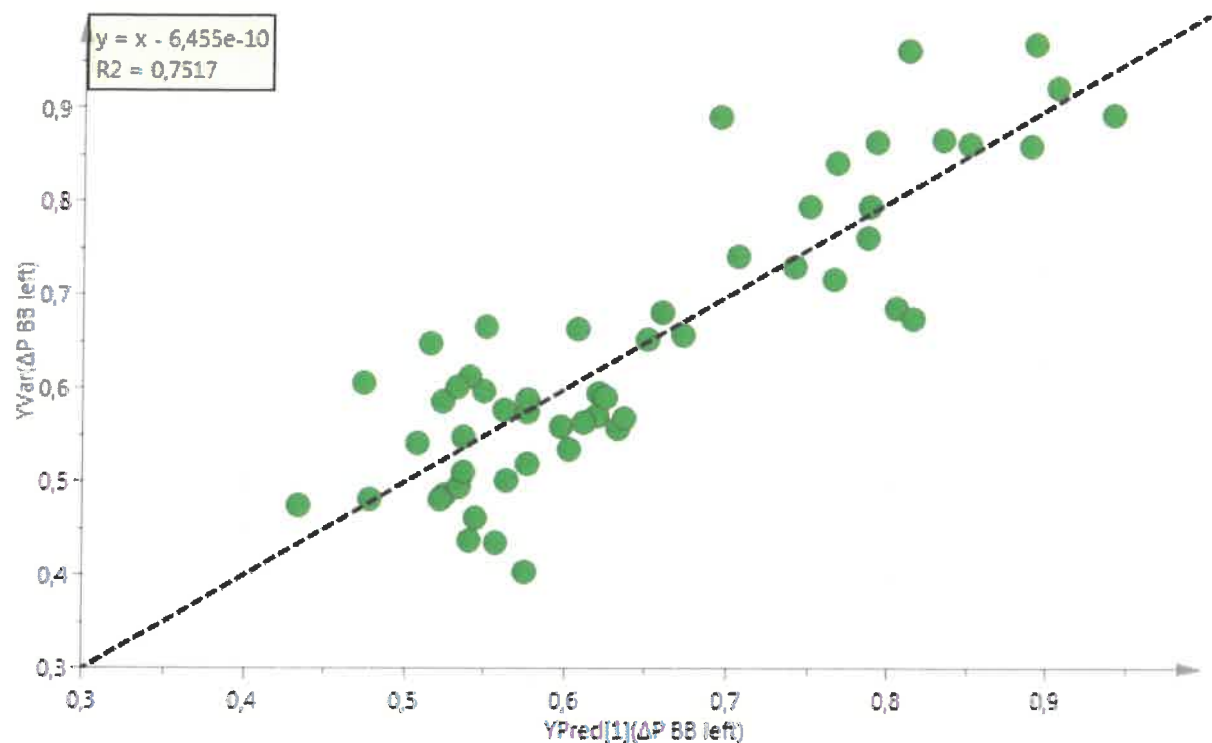


Figure 30: The Y Observed vs. Y Predicted plot for Model 2.

The correlation structure of the model was studied by using the VIP plot and the coefficient plot. The VIP plot is shown in Figure 31 and the coefficient plot is shown in Figure 32.

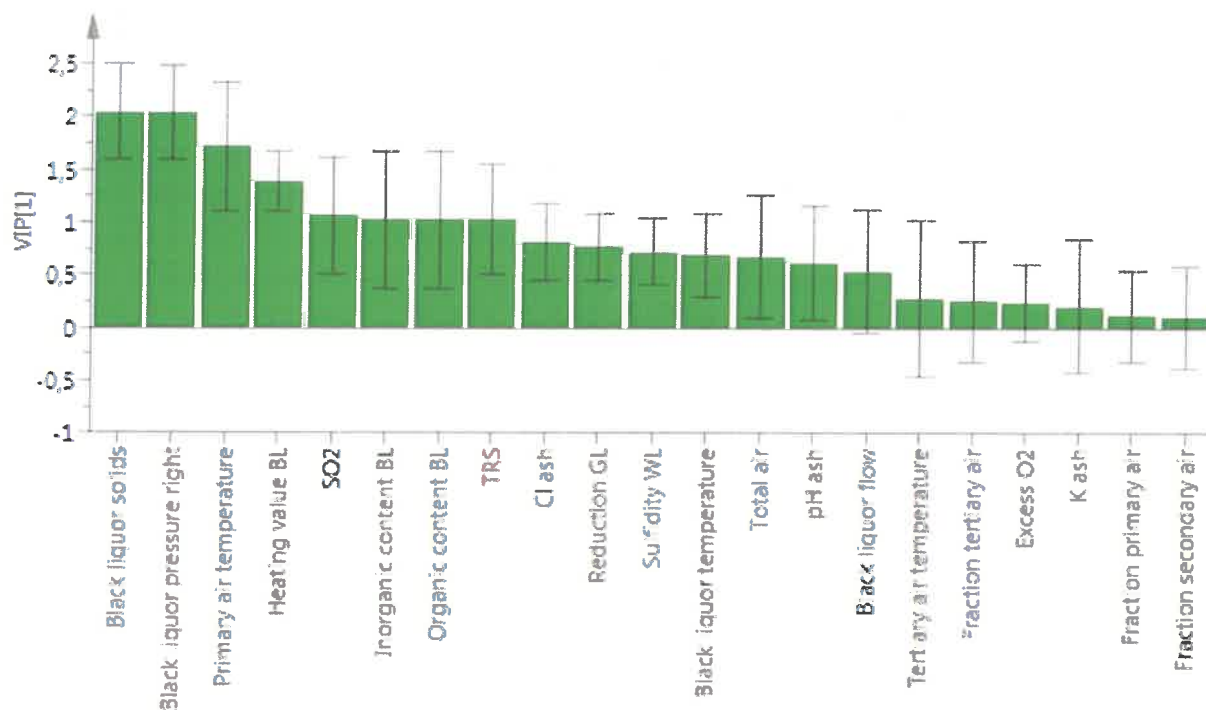


Figure 31: The VIP plot for Model 2

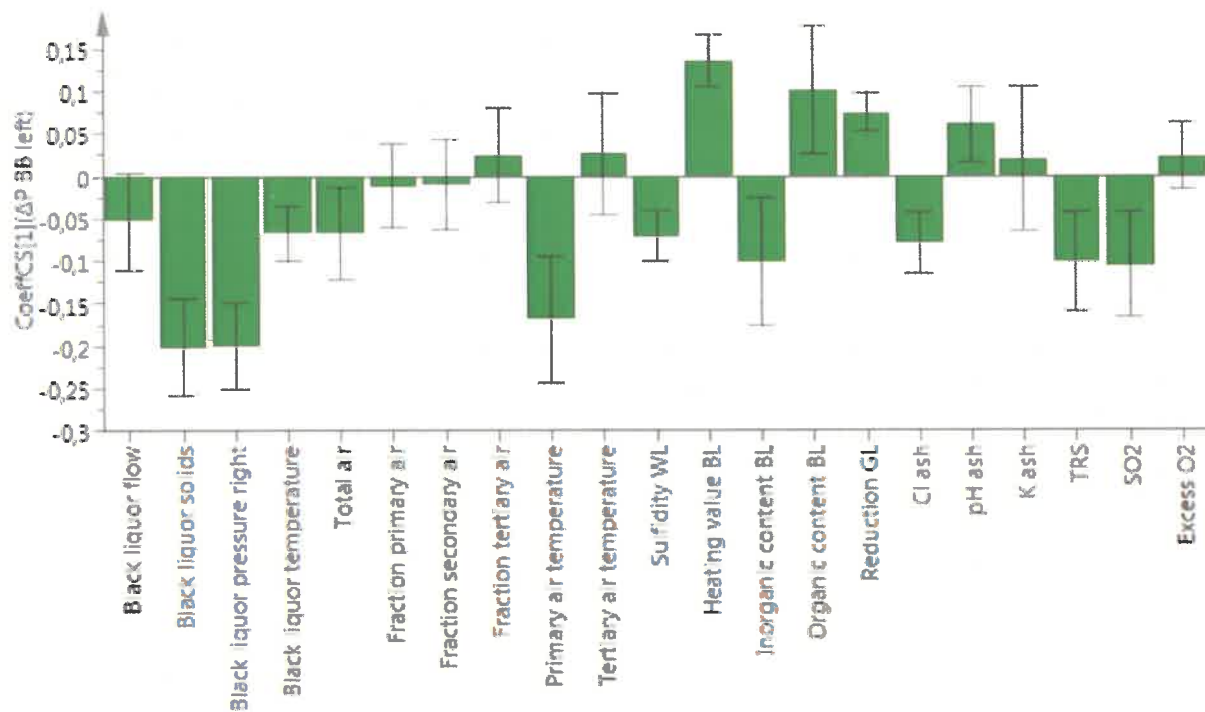


Figure 32: The coefficient plot for Model 2.

X parameters with high VIP-values are important and from the VIP plot it can be concluded that the most important X parameters are the black liquor dry solids, the black liquor pressure, primary air temperature and the black liquor heating value. The VIP value of the sulphidity is between 0.5 and 1 which means that the parameter might be interesting depending on the size of the data set. However, the range of the sulphidity during the time period was very limited, see Table 7.

Some of the error bars for the X parameters includes 0 in the coefficient plot. That means that the parameters are not significant and would usually be removed from the model in order to form an optimal model. However, in this work the parameters that include 0 in the coefficient plot have been left in the model. That is mainly due to two reasons. First, the aim is not to build a perfect model. The model should indicate important parameters for the fouling. Second, the parameters that indicate unimportant for the fouling can also be seen.

The coefficient plot was studied in order to see how the X parameters correlate to the Y parameter. The black liquor dry solids have a negative correlation to the Y parameter. The black liquor dry solids have been plotted against the  $\Delta P$  BB left, see Figure 33. The  $R^2$  value of the regression line is 0.5496.

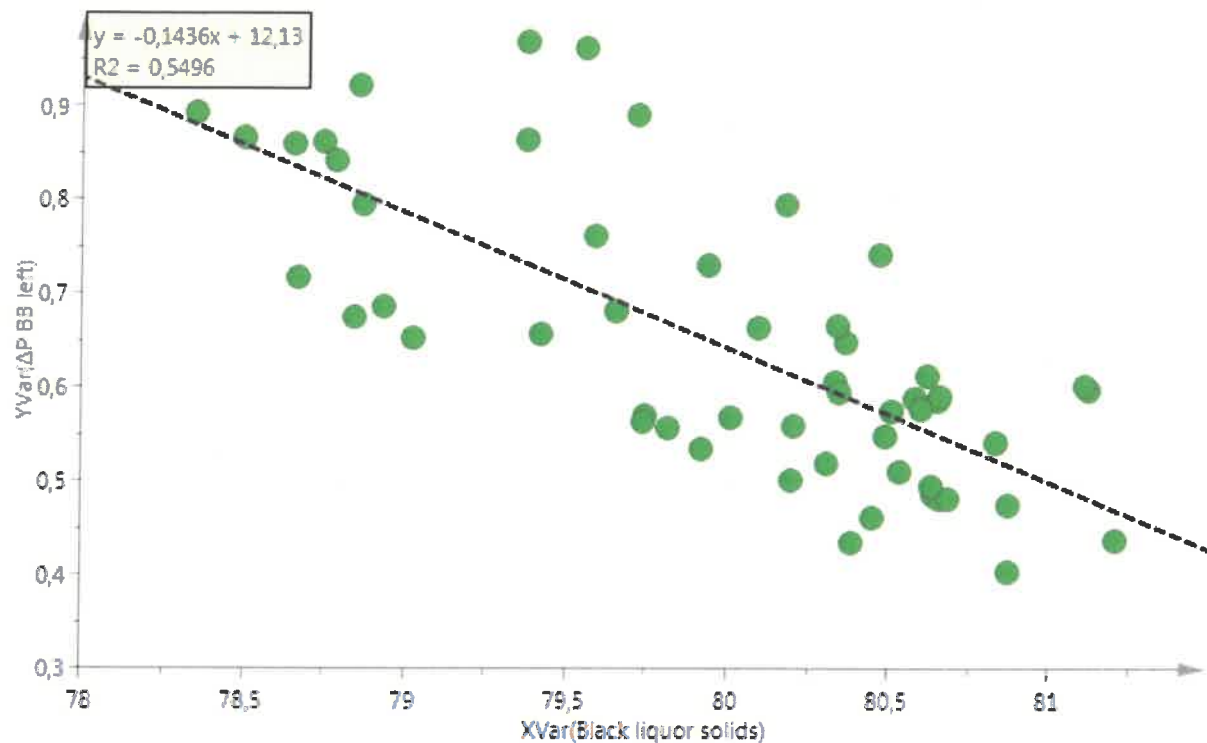


Figure 33: Black liquor dry solids plotted against  $\Delta P$  BB left.

The result in Figure 33 indicates that when the black liquor dry solids are lower, the recovery boiler tend to has higher  $\Delta P$  BB left which correspond whit the theory. When lower black liquor dry solids enter the recovery boiler, more water enters the recovery boiler. The water needs to evaporate which means that more particles are going up in the furnace. This lead probably to that the  $\Delta P$  BB left increases. When higher amount of black liquor dry solids is used, less water needs to be evaporated and thereby less particles in the furnace.

The black liquor pressure shows also negative correlation with the fouling. The black liquor pressure is plotted against  $\Delta P$  BB left in Figure 34.

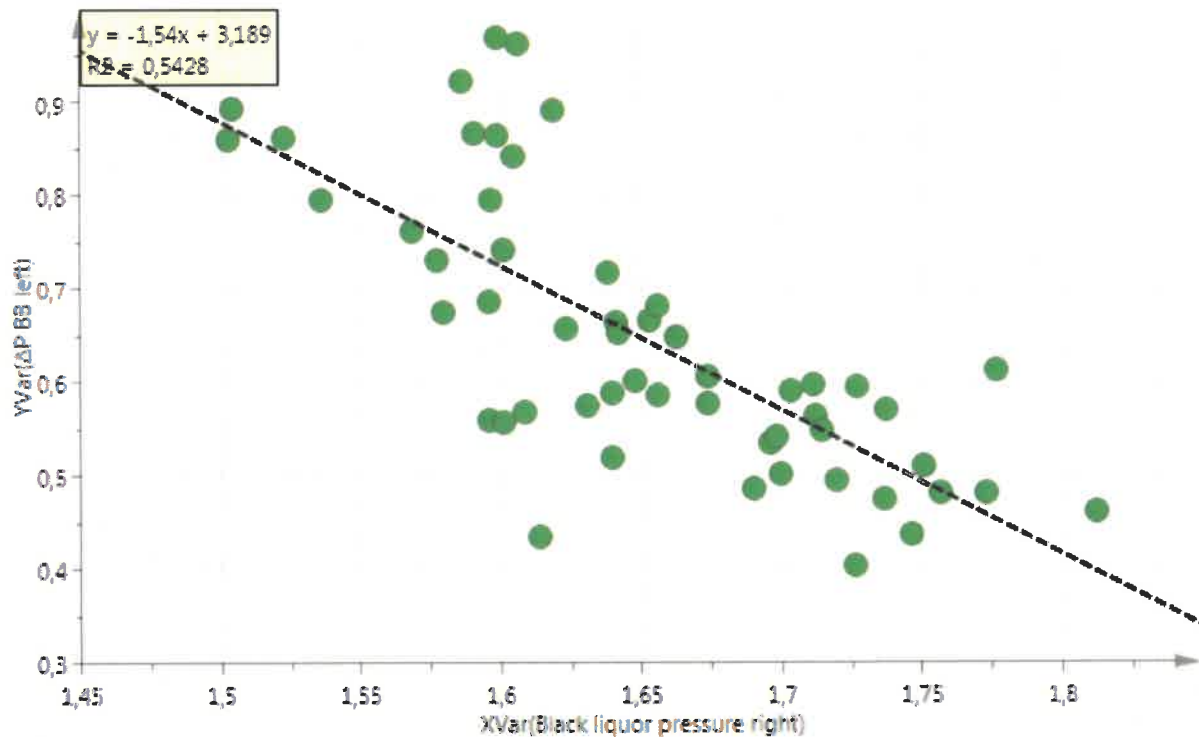


Figure 34: Black liquor pressure plotted against  $\Delta P$  BB left.

The results in Figure 34 show that when lower black liquor pressure is used,  $\Delta P$  BB left is higher. In order to deliver sufficient amount of liquor to the boiler, the black liquor temperature must be higher when a lower black liquor pressure is used. A higher temperature of the black liquor might lead to that the droplets swell more rapidly which could lead to that the density becomes lower and the particles follow the gases up in the furnace. More particles in the furnace will probably generate a higher  $\Delta P$  BB left. However, the coefficient plot shows that the  $\Delta P$  BB left increases when the black liquor temperature decreases. The short time periods are probably affecting the results which make that no clear conclusion can be drawn. There are also other factors that influence the results, for instance the black liquor dry solids. Additional consideration that needs to be done when studying the results is the variation in the black liquor pressure, see Table 4.

However, for making any changes in the process, more investigations need to be done and the results from the correlation structure between the X and Y parameters are not sufficient since only shorter time periods have been used.

The two models indicate different interesting parameters. One explanation for that might be that there are different explanations for the fouling problems. Furthermore, the results might be due to that too short time periods have been used.



## **5 Conclusions and recommendations for future work**

### **5.1 Conclusions**

- From the first model, Model 1, the results indicate that the distribution of the air might be a reason for fouling and should therefore preferably be investigated further. Furthermore, the black liquor dry solids and the black liquor pressure show also clear correlation with the  $\Delta P$  BB left and would also be interesting parameters for further investigation. The results from the second model, Model 2, indicates that the black liquor pressure and the black liquor dry solids are parameters that should preferably been analyzed further.
- The results do not show that the sulfidity is a main problem for the fouling. However, the theory should not be rejected. There is a limited amount of data that has been investigated in this work. The experiences from the operators at the mill are valuable to take into consideration.
- Multivariate data analysis seems to be a powerful tool to use when analyzing large amounts of data. Correlation between the parameters can be studied as well as following data during operation.
- Interesting parameters to investigate further are different between the two models.

### **5.2 Recommendations for future work**

- The mill had some issues with the production during the start-up which resulted in unstable process data. To perform analyses similar to this one, it is desirable to use stable data for long time. It is therefore important for the mill to try to stabilize the production.
- It would be beneficial to use longer periods with stable production. In this work, only short periods have been used. The same analysis of the recovery boiler would preferably been done in the same way in a few years with longer periods with more stable production.
- To determine the fouling problems it is important to include all the parameters that can affect the fouling. It is therefore important to make sure that as many parameters as possible are measured. In this work, some parameters have been left out due to lack of data, for instance the air pressures and the secondary air temperature. In a future work it is beneficial to include more parameters.
- The mill would take into consideration the results from this work and to further investigate if the explanations found in this report are variables that would be changed in order to improve the heat transfer efficiency of the boiler. The best would be to perform trials with the variables found most interesting in this study.
- It is also important for the mill to follow the recovery boiler and clearly define periods with high and low fouling periods. In this work, the high and low fouling periods are

based on the  $\Delta P$  BB and the flue gas temperature entering the BB. These parameters might also be affected by other factors that change the data.

- Average values have been taken for the ID fan speed, the excess  $O_2$  and  $\Delta P$  ECO1 and ECO2 to minimize the number of parameters. In future work, it would be interesting to analyze the different parameters separately to see if the results differs.
- Some of the parameters used in this analysis was measured as infrequently as once a week. To generate a more valid model, it is important to use frequently measured values. The results might be affected if these parameters are measured more frequently.
- For the future it is recommended to study the movement of the data points in the score plot. From the score plot it would be possible to follow the data when it goes from higher efficiency to lower efficiency. Days before and after this change can be compared in order to analyze the fouling.
- In this analysis average daily values have been used. Important changes in the data during a day will in this case be lost. In order to include these changes hourly average data values can be used.
- Another theory the mill has for the fouling problems is that the co-firing with fuel oil might be a reason. This theory has not been studied in this work but it would be interesting to study in the future.
- To reduce the fouling problems the soot blowing system might also be investigated in order to improve the efficiency.
- Further investigations could also be done while considering the time delay during the process.



## **6 Abbreviations and symbols**

$\Delta P$  -Pressure differences

$\Delta T$  -Temperature differences

BB -Boiler bank

ECO -Economizer

ID fan speed -Induced draft fan speed

PCA- Principal Component Analysis

PLS -Partial Least Squares Projection

SH -Super heater

Temp. BB –Temperature of the flue gas entering the BB

TRS -Total reduced sulfur

UV-scaling –Unit variance scaling

VIP- Variable Importance for the Projection

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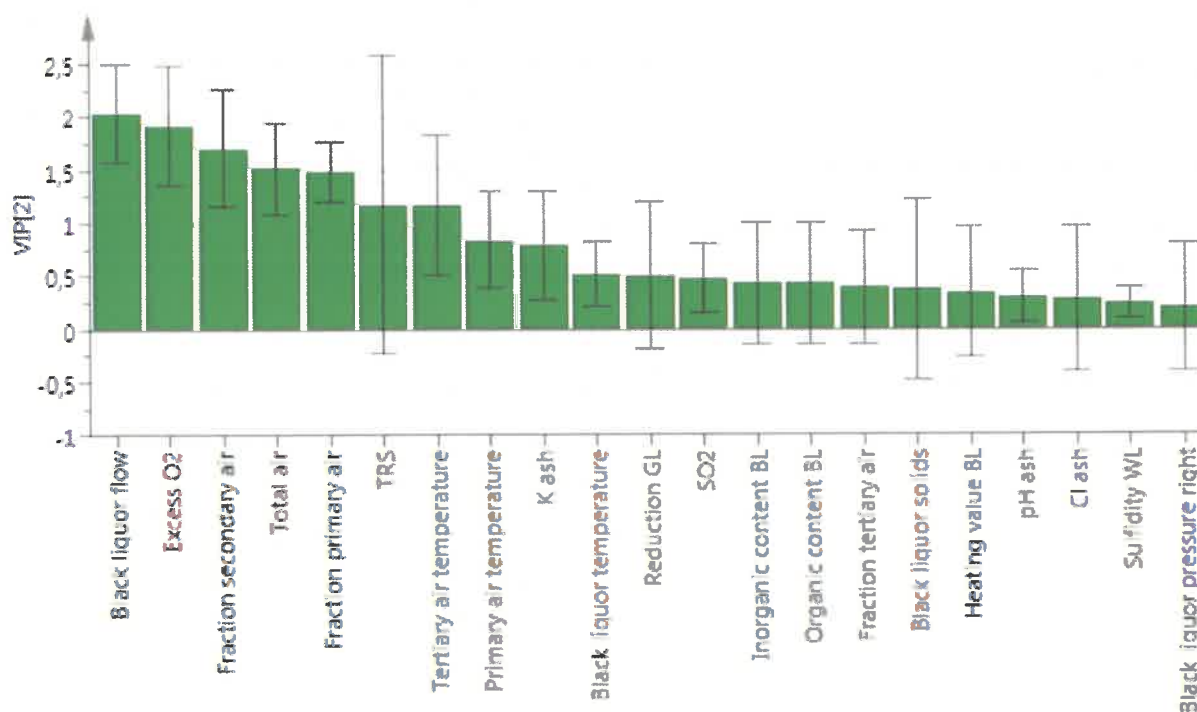
## 8 Appendix

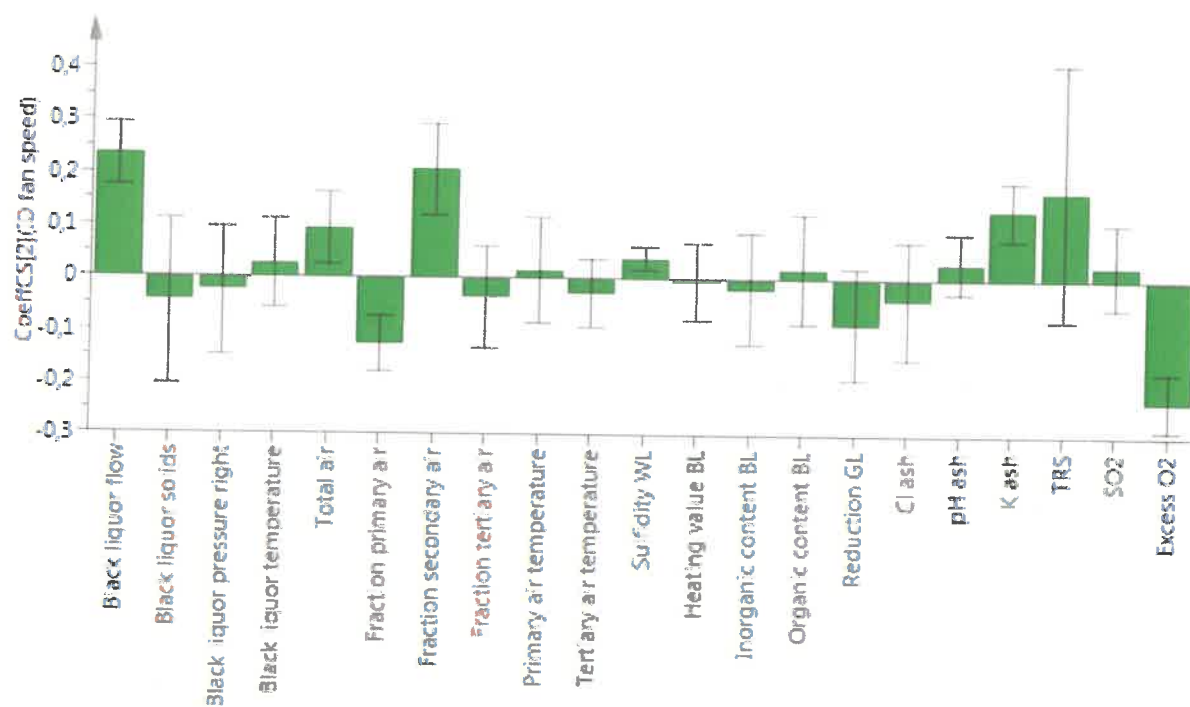
Results from the additional PLS models built with other Y parameters are shown in *Appendix 8.1 and 8.2*. The summary of fit, VIP plots and coefficient plots for respective Y parameter are shown.

### 8.1 Model 1

#### 8.1.1 ID fan speed

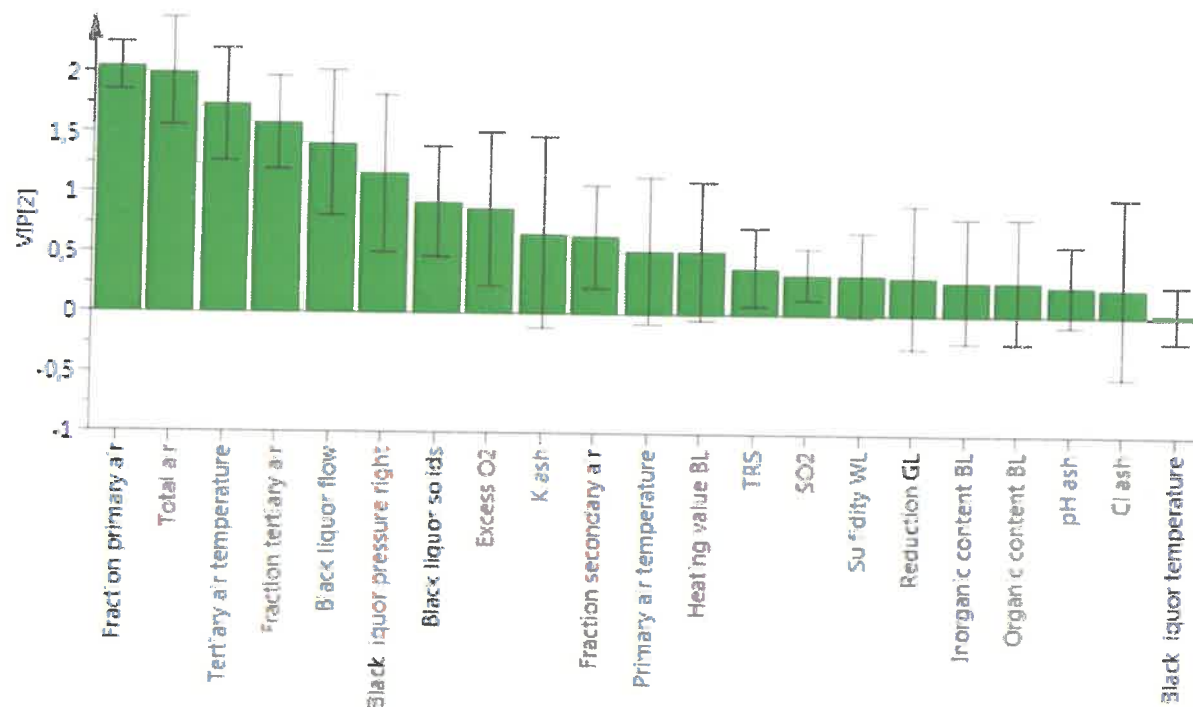
Y parameter in the model	PCs in PLS	R2X(cum)	R2Y(cum)	Q2(cum)
ID fan speed	2	0.329	0.793	0.724

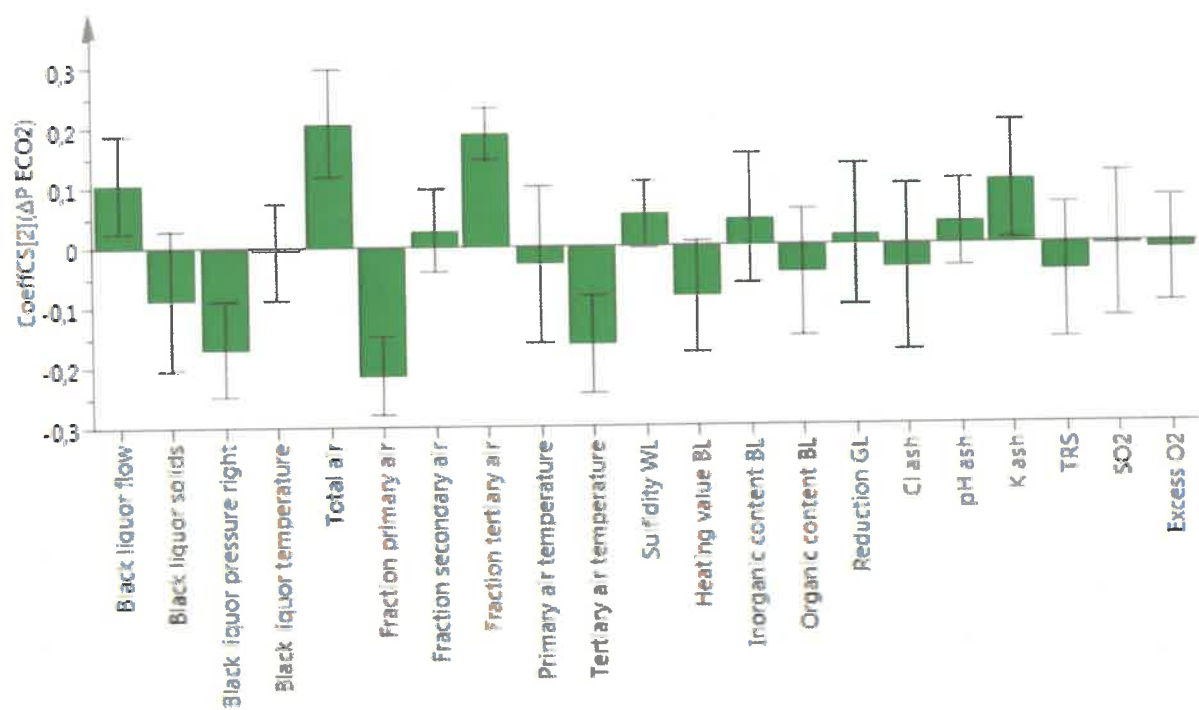




### 8.1.2 AP ECO2

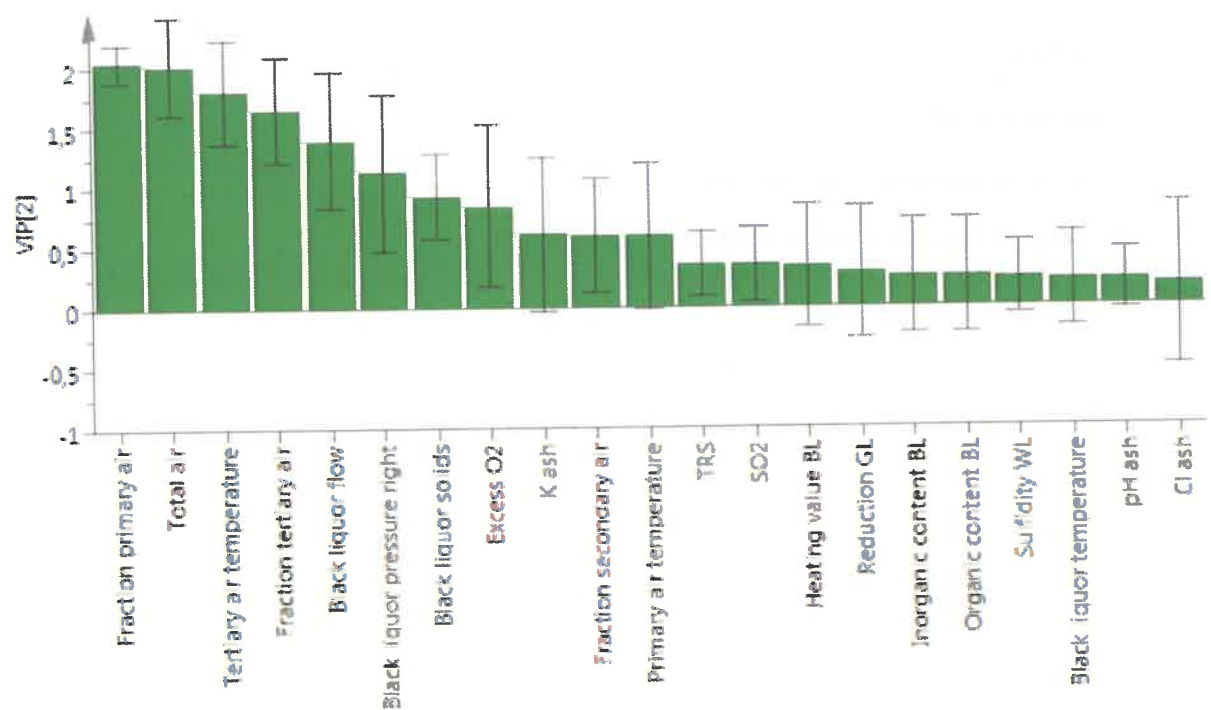
Y parameter in the model	PCs in PLS	R2X(cum)	R2Y(cum)	Q2(cum)
AP ECO2	2	0.372	0.792	0.725

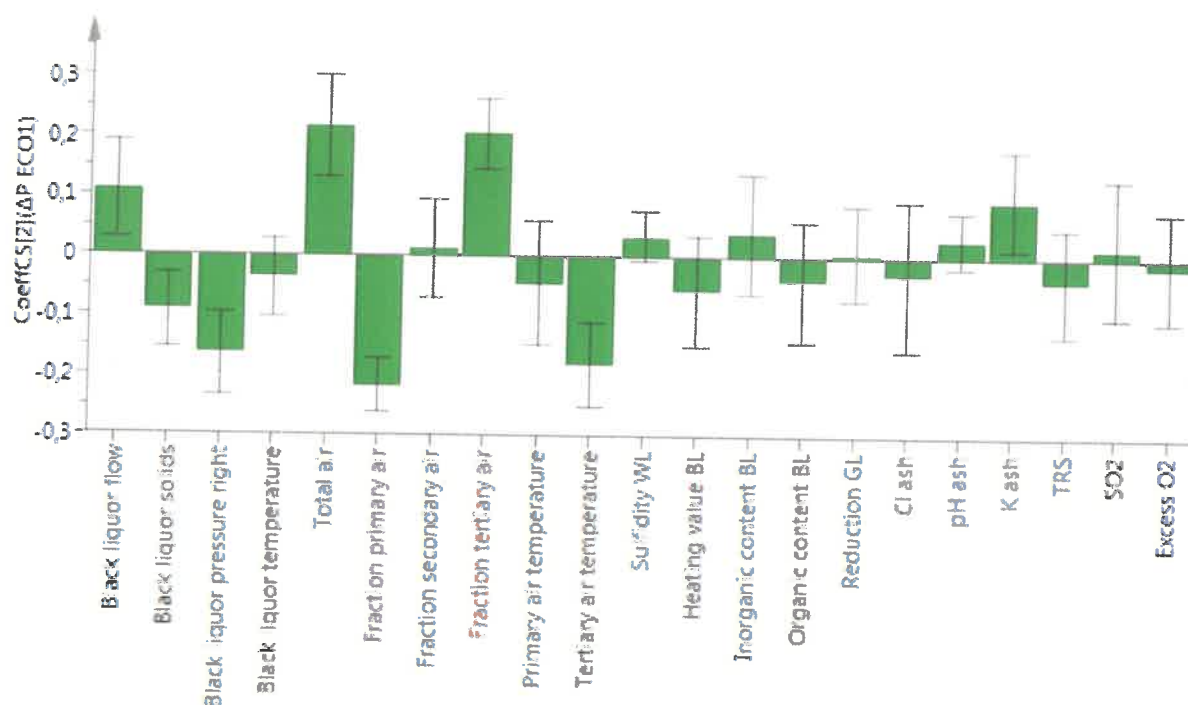




### 8.1.3 ΔP ECO1

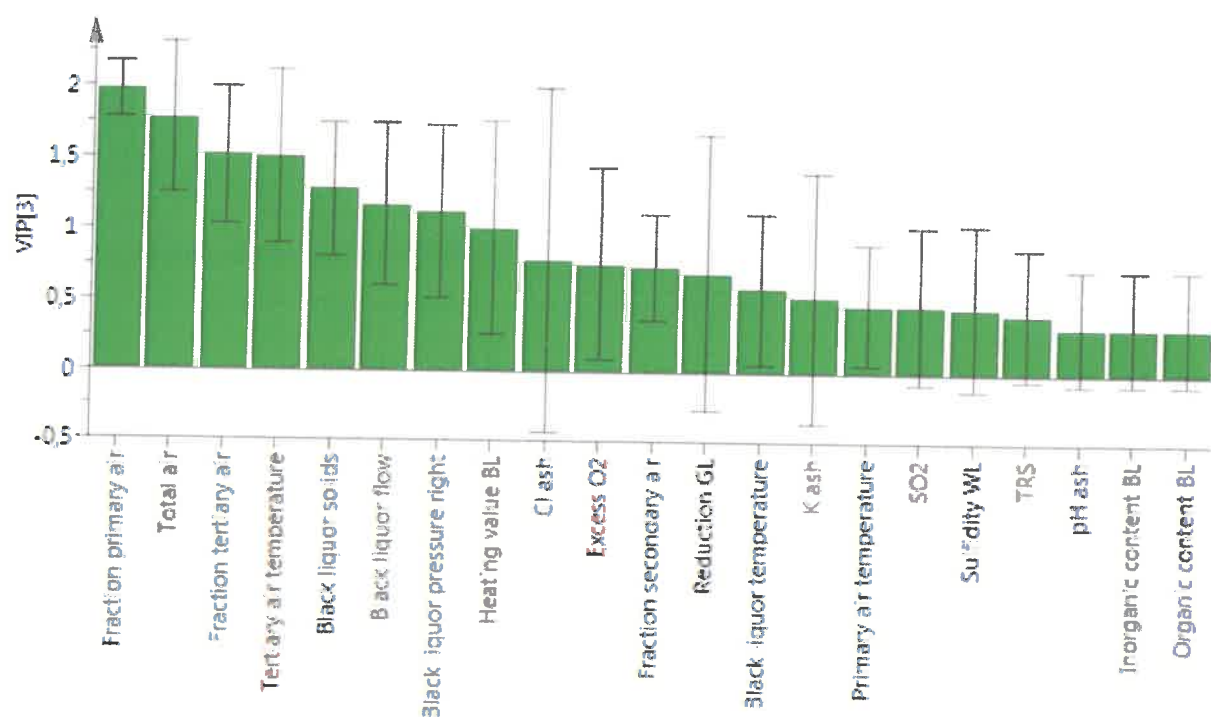
Y parameter in the model	PCs in PLS	R2X(cum)	R2Y(cum)	Q2(cum)
ΔP ECO1	2	0.377	0.865	0.818

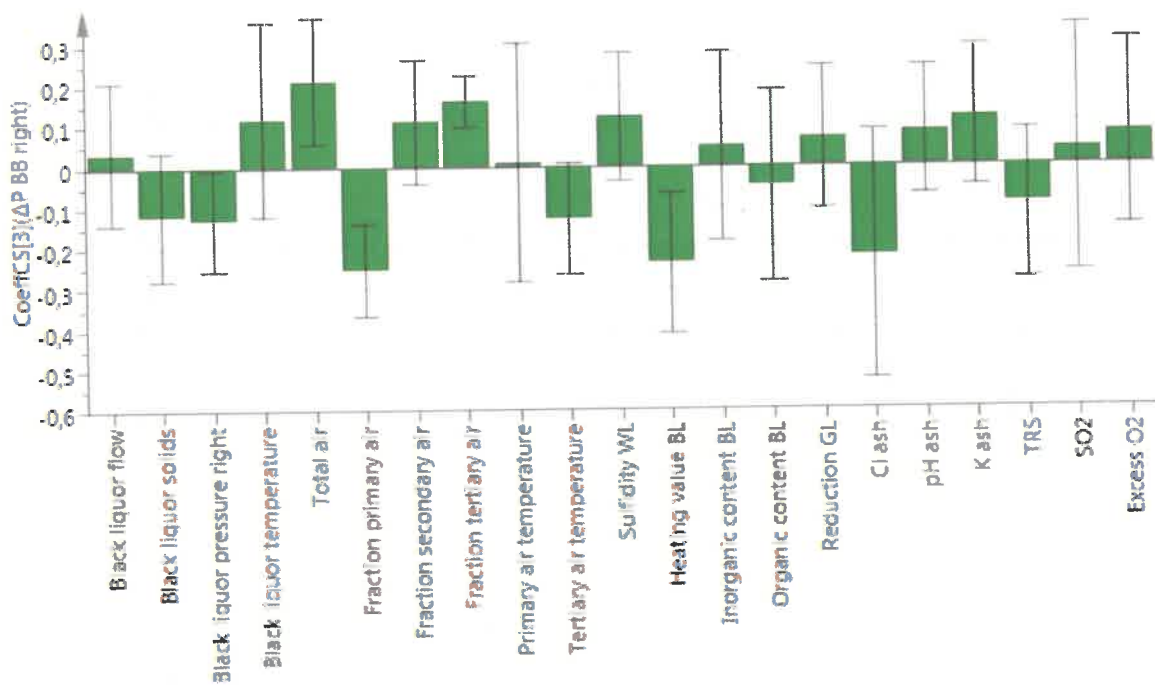




#### 8.1.4 AP BB right

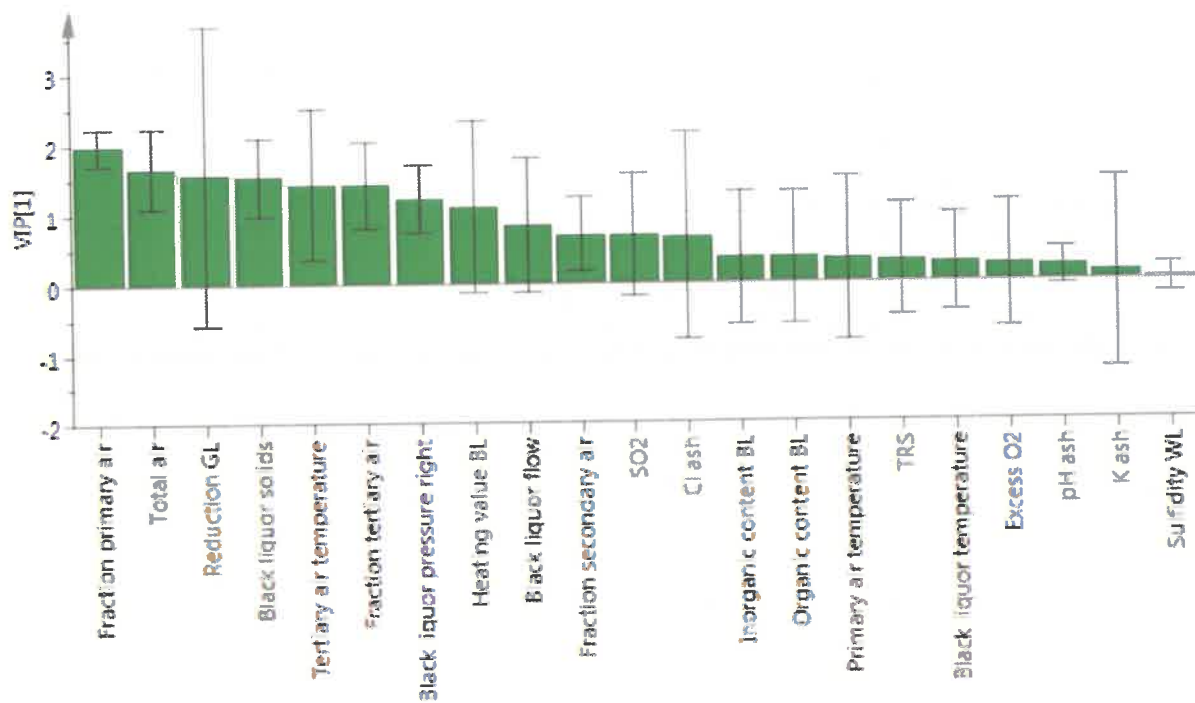
Y parameter in the model	PCs in PLS	R2X(cum)	R2Y(cum)	Q2(cum)
AP BB right	3	0.446	0.848	0.737



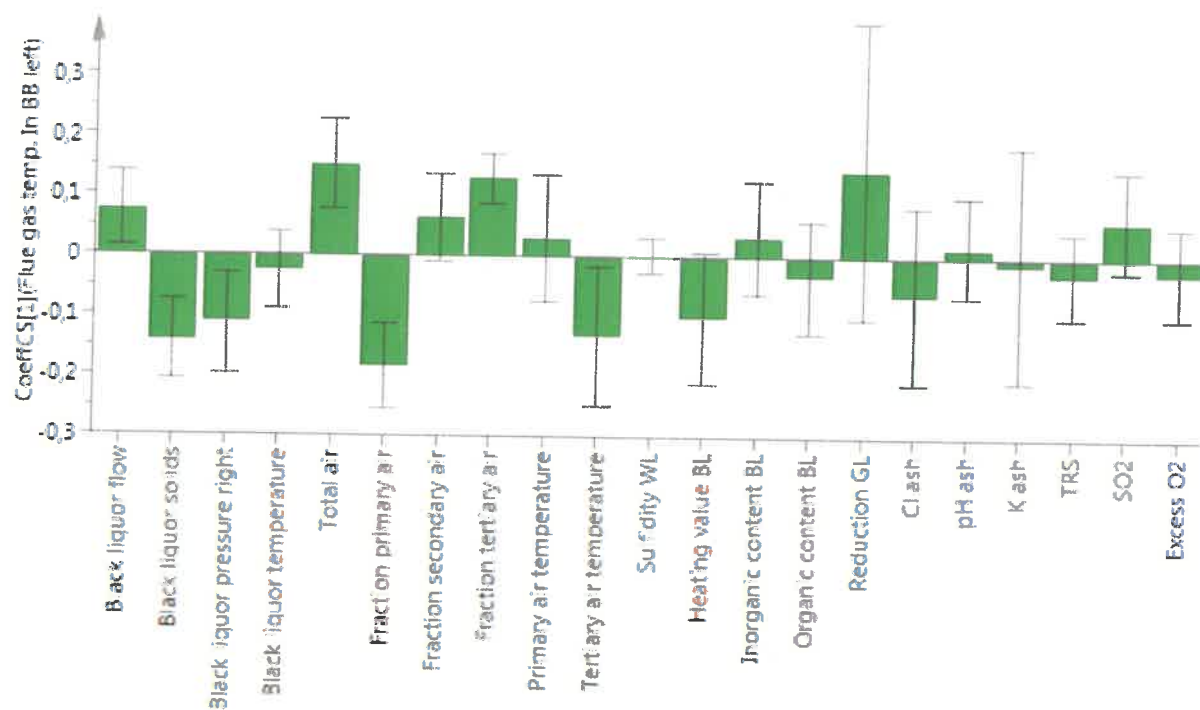


### 8.1.5 Temp. BB left

Y parameter in the model	PCs in PLS	R2X(cum)	R2Y(cum)	Q2(cum)
Temp. BB left	1	0.183	0.620	0.481

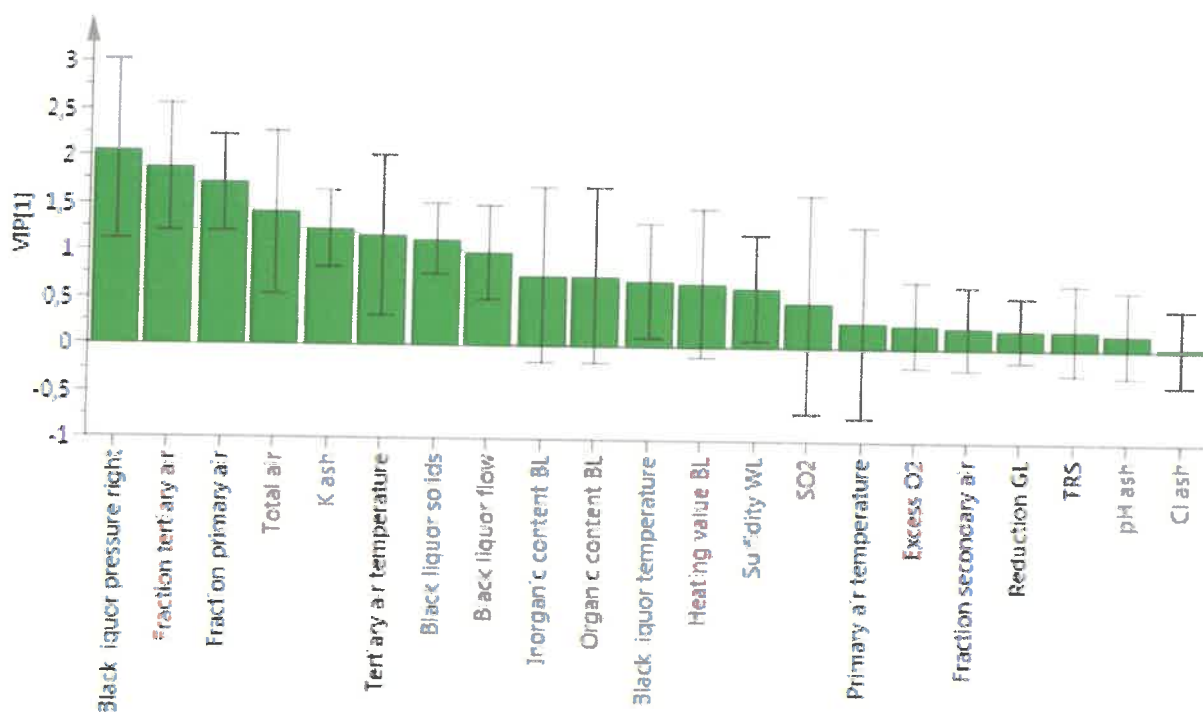


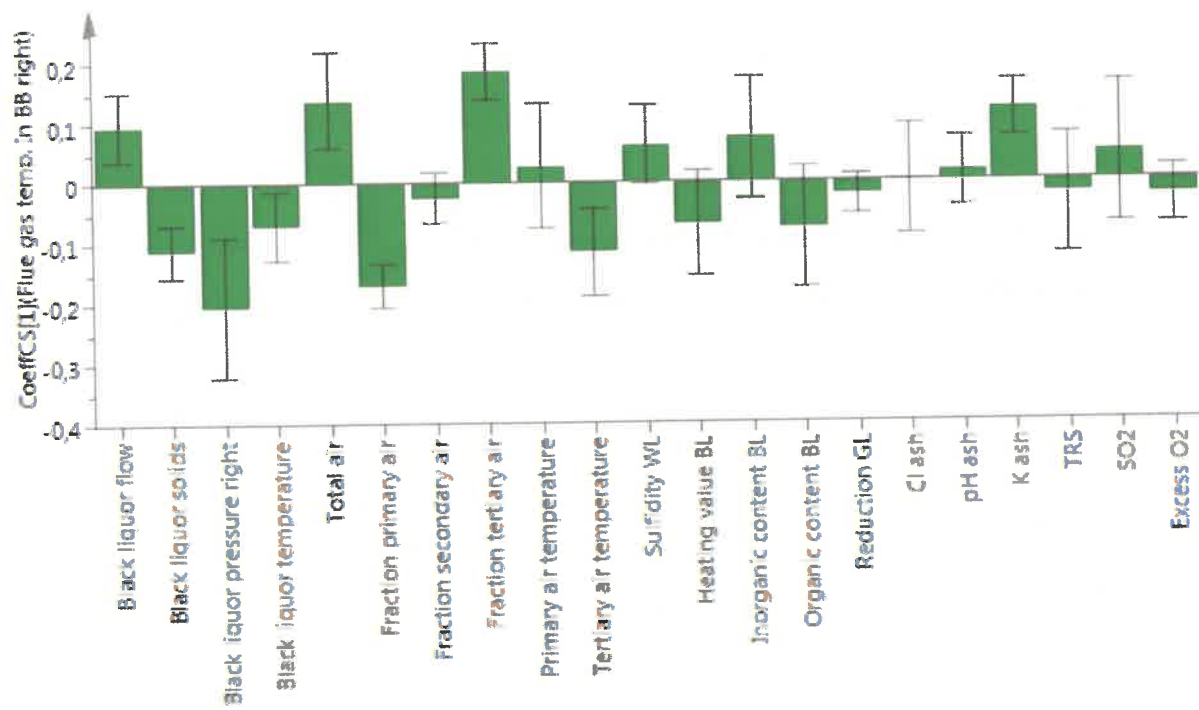




### 8.1.6 Temp. BB right

Y parameter in the model	PCs in PLS	R2X(cum)	R2Y(cum)	Q2(cum)
Temp. BB right	1	0.170	0.682	0.617

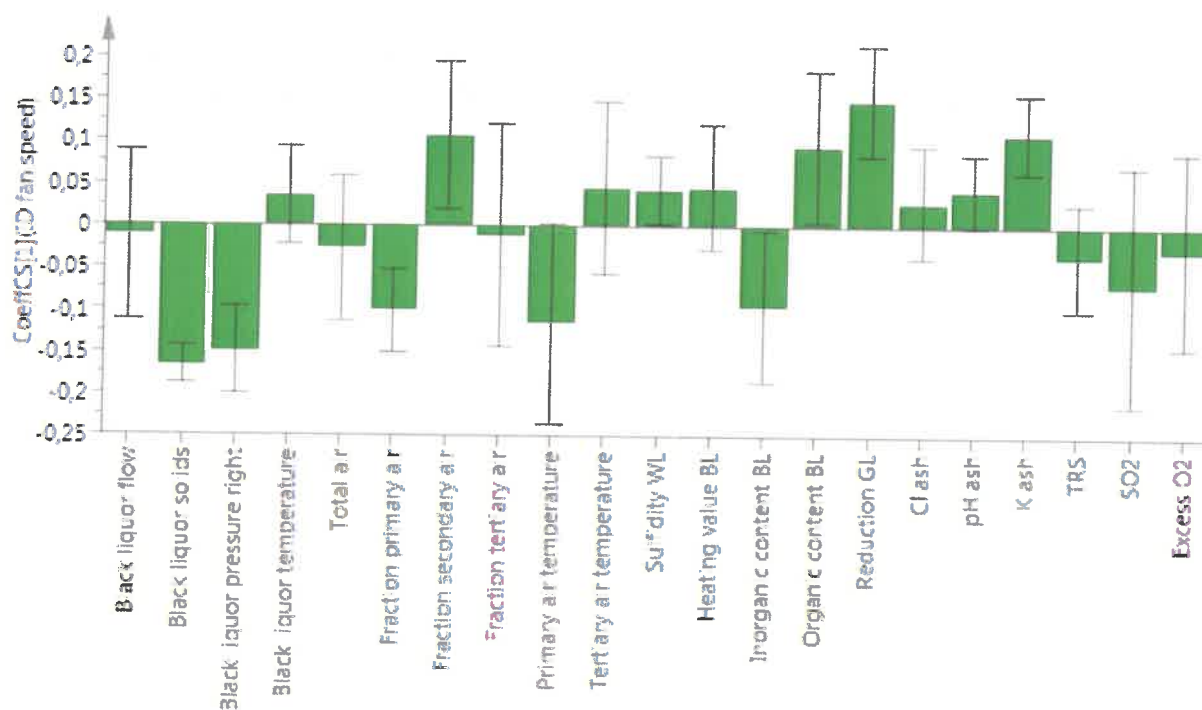
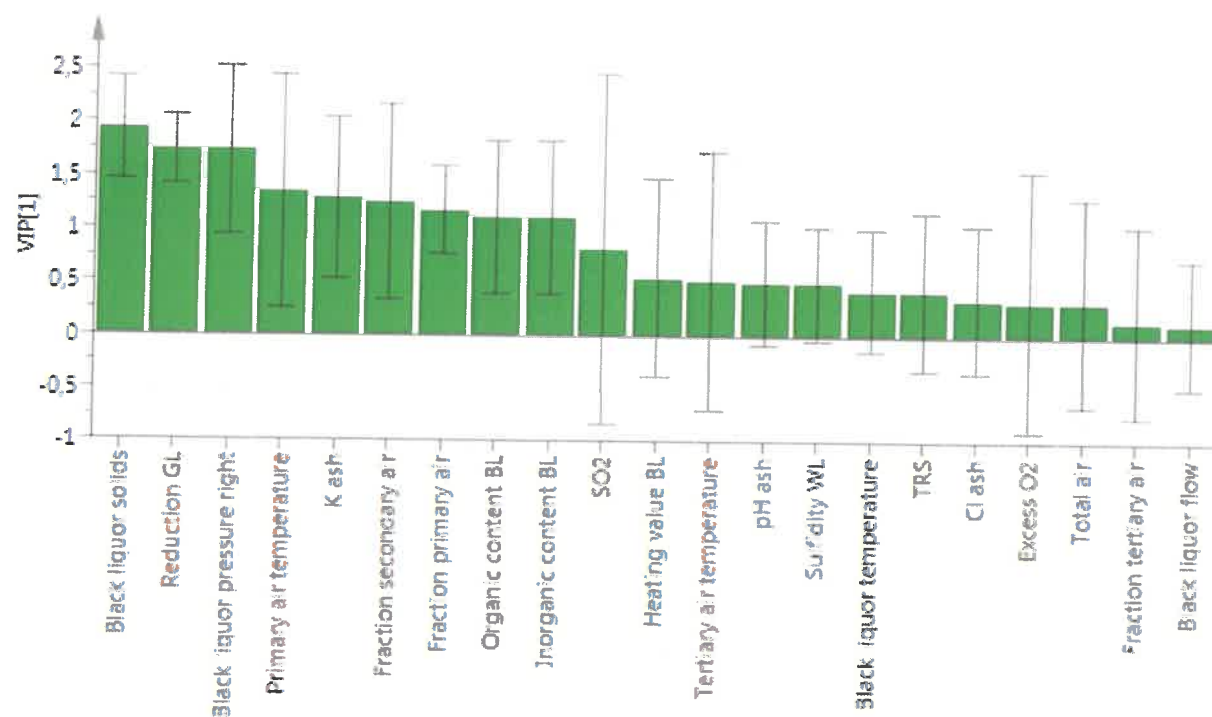




## 8.2 Model 2

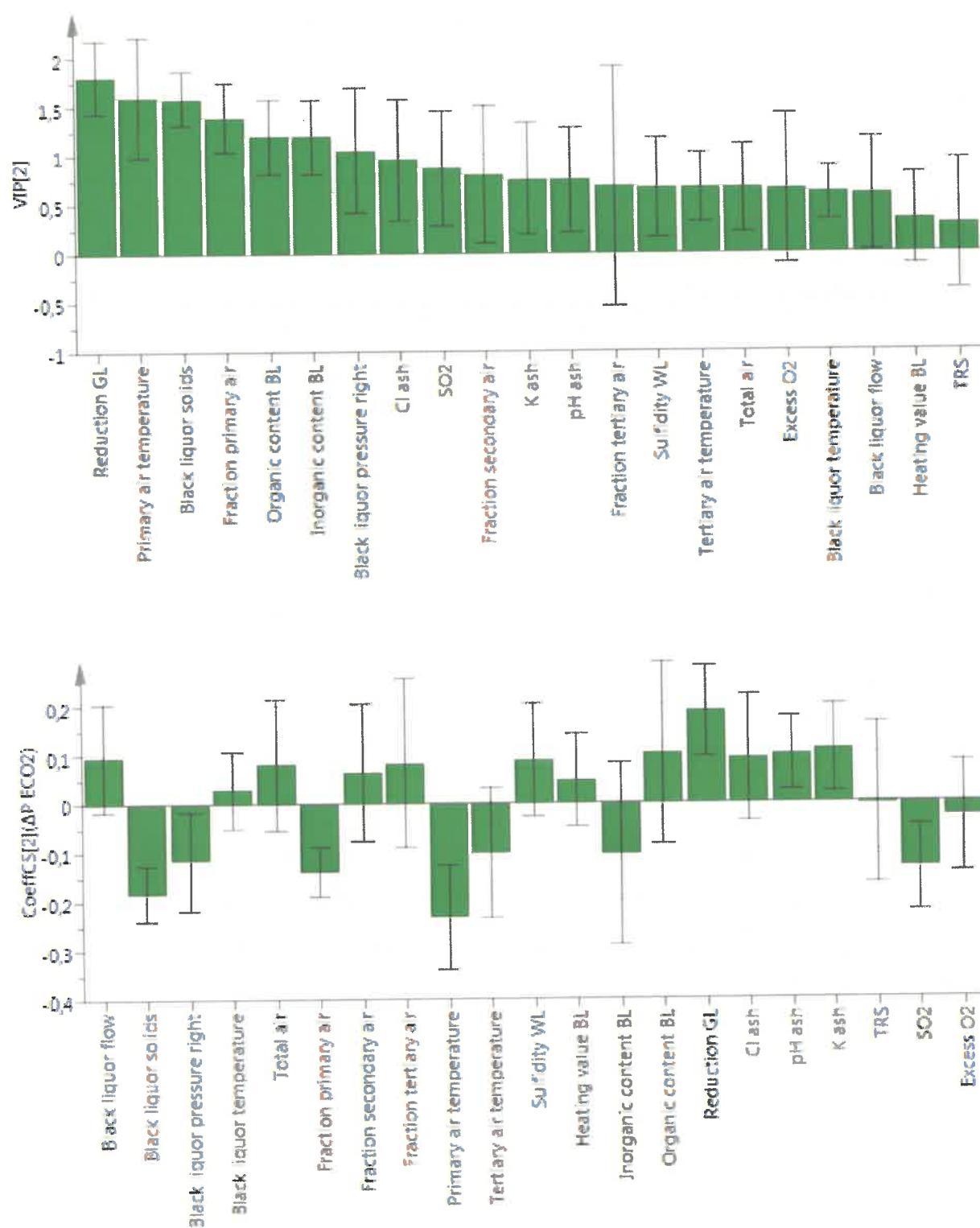
### 8.2.1 ID fan speed

Y parameter in the model	PCs in PLS	R2X(cum)	R2Y(cum)	Q2(cum)
ID fan speed	1	0.194	0.554	0.401



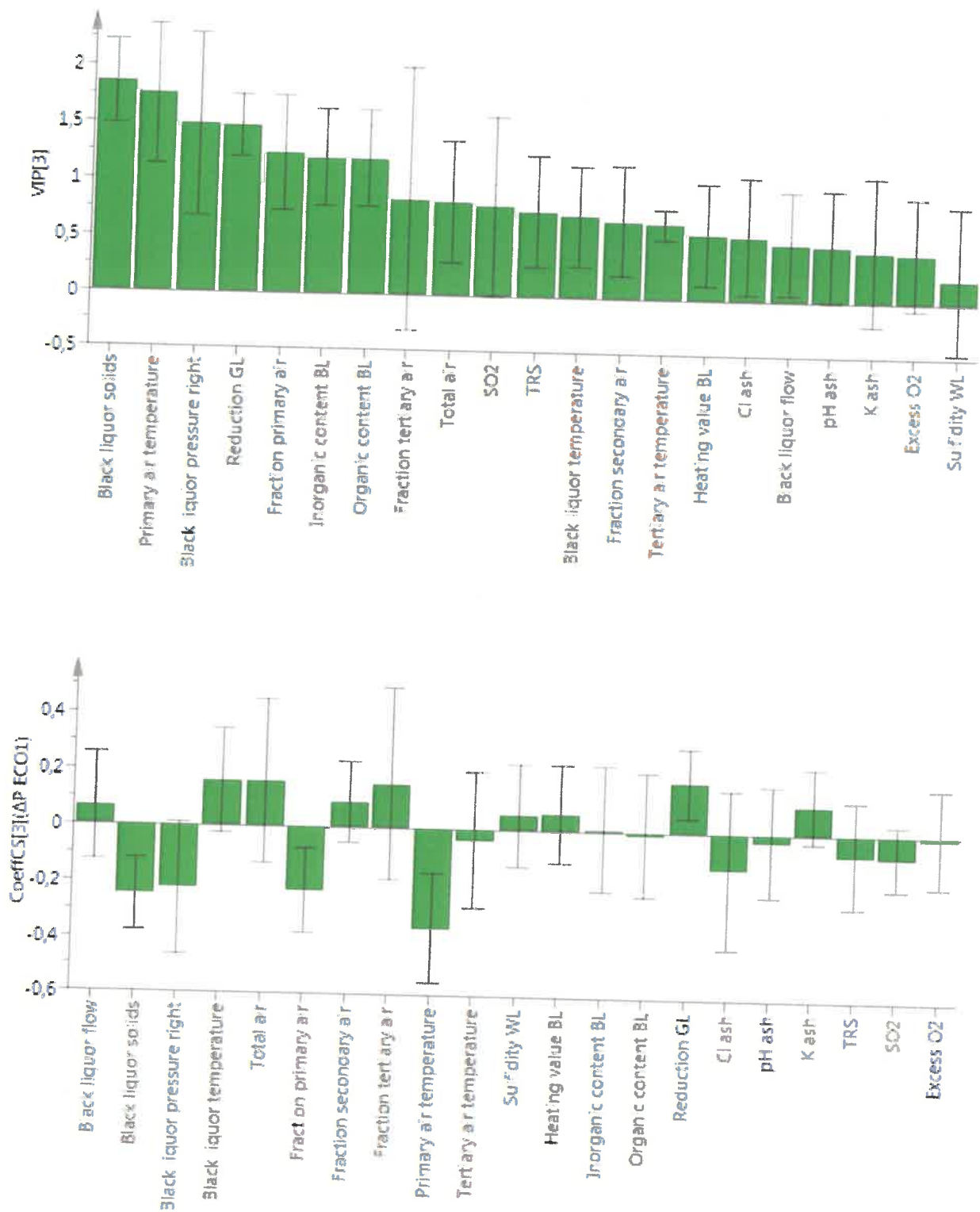
8.2.2 AP ECO2

Y parameter in the model	PCs in PLS	R2X(cum)	R2Y(cum)	Q2(cum)
AP ECO2	2	0.353	0.763	0.626



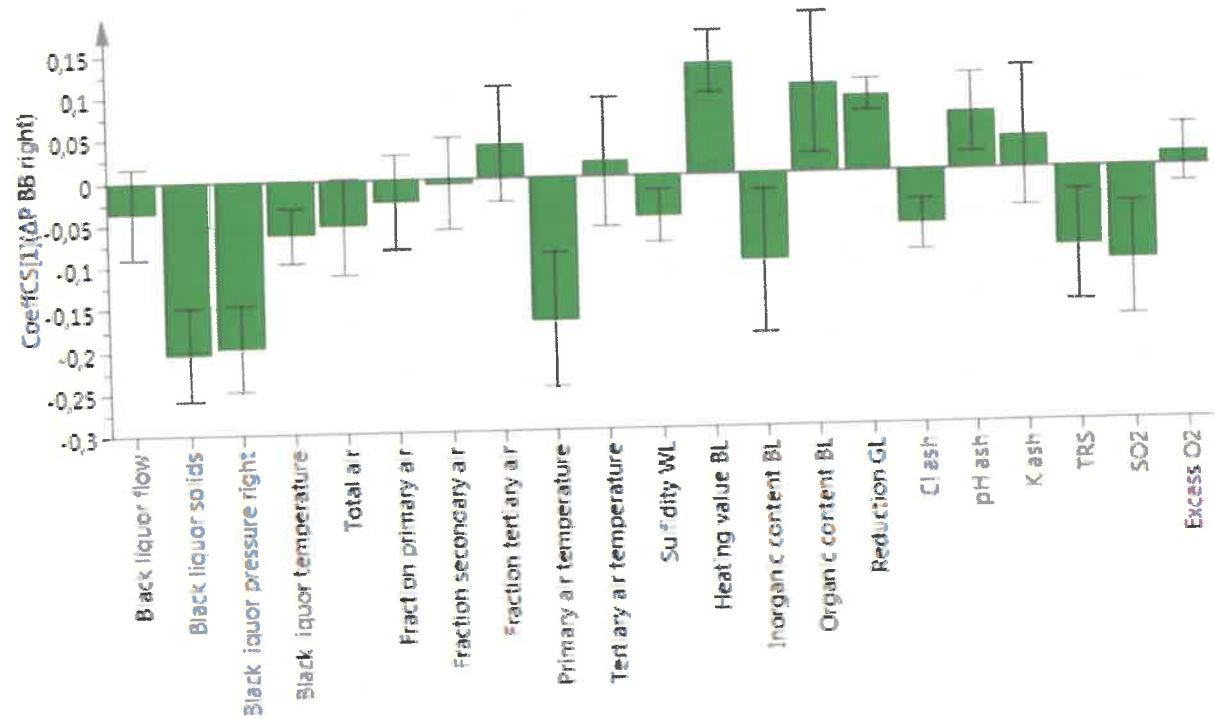
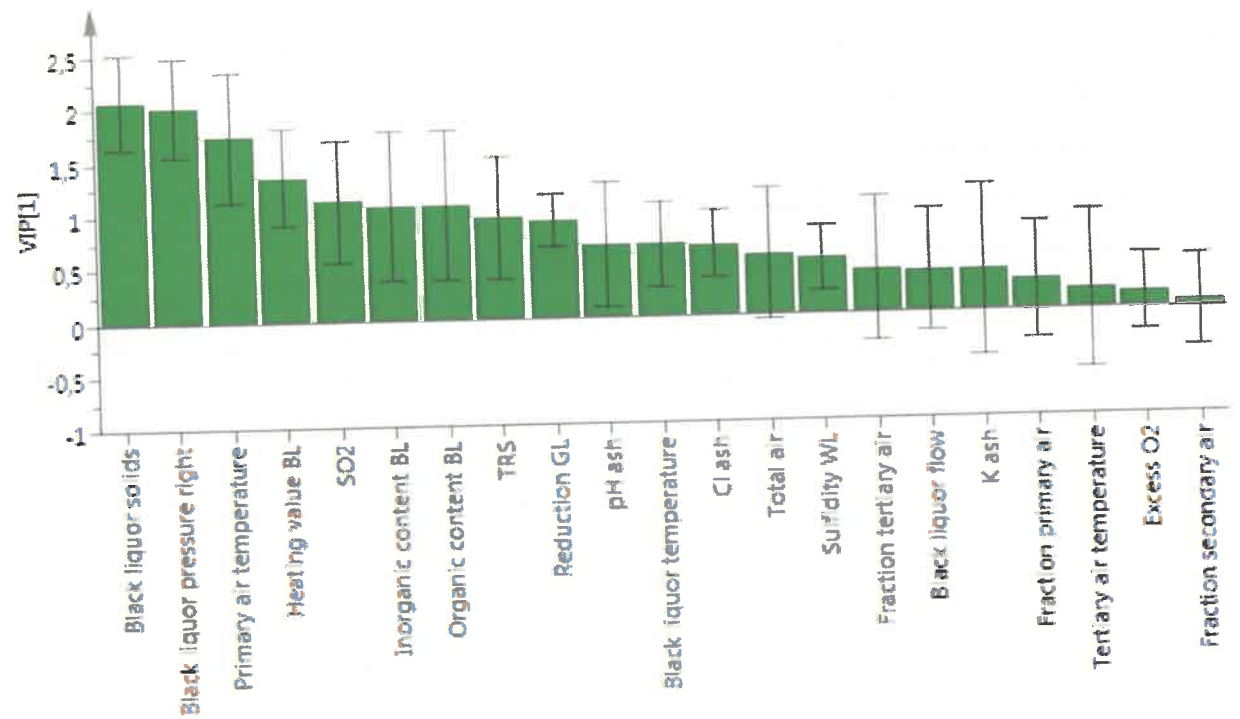
### 8.2.3 $\Delta P$ ECO1

Y parameter in the model	PCs in PLS	R <sup>2</sup> X(cum)	R <sup>2</sup> Y(cum)	Q <sup>2</sup> (cum)
$\Delta P$ ECO1	3	0.465	0.857	0.719



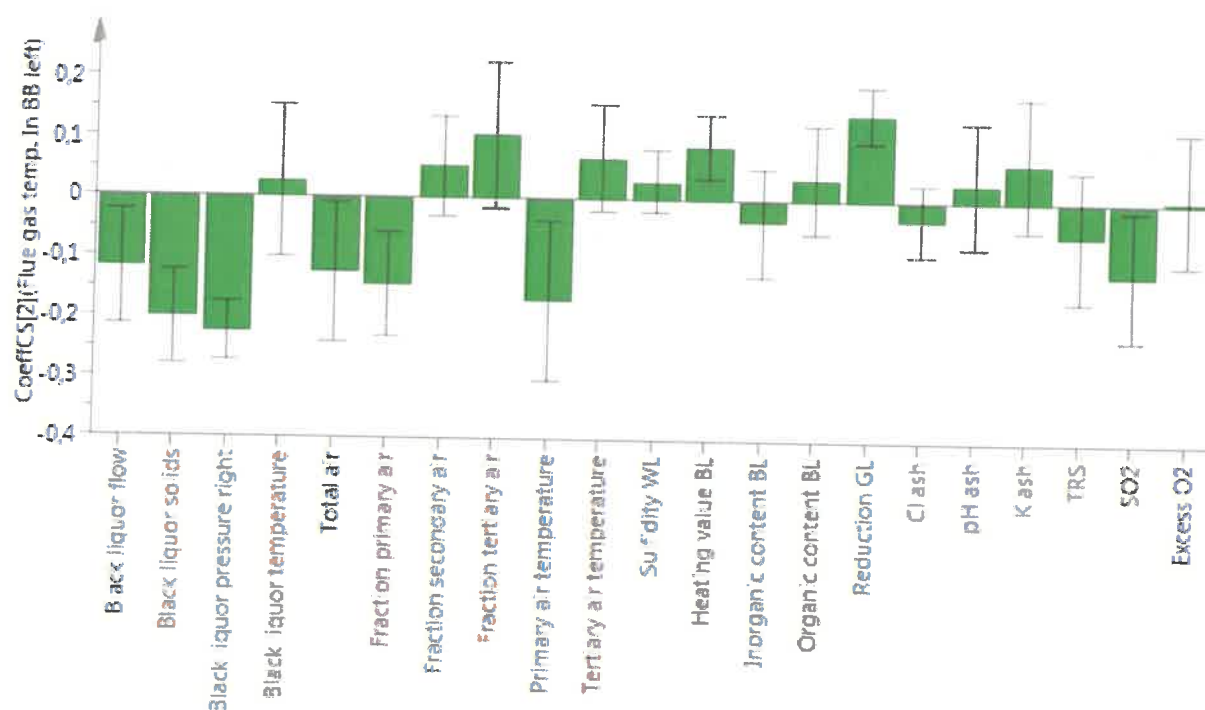
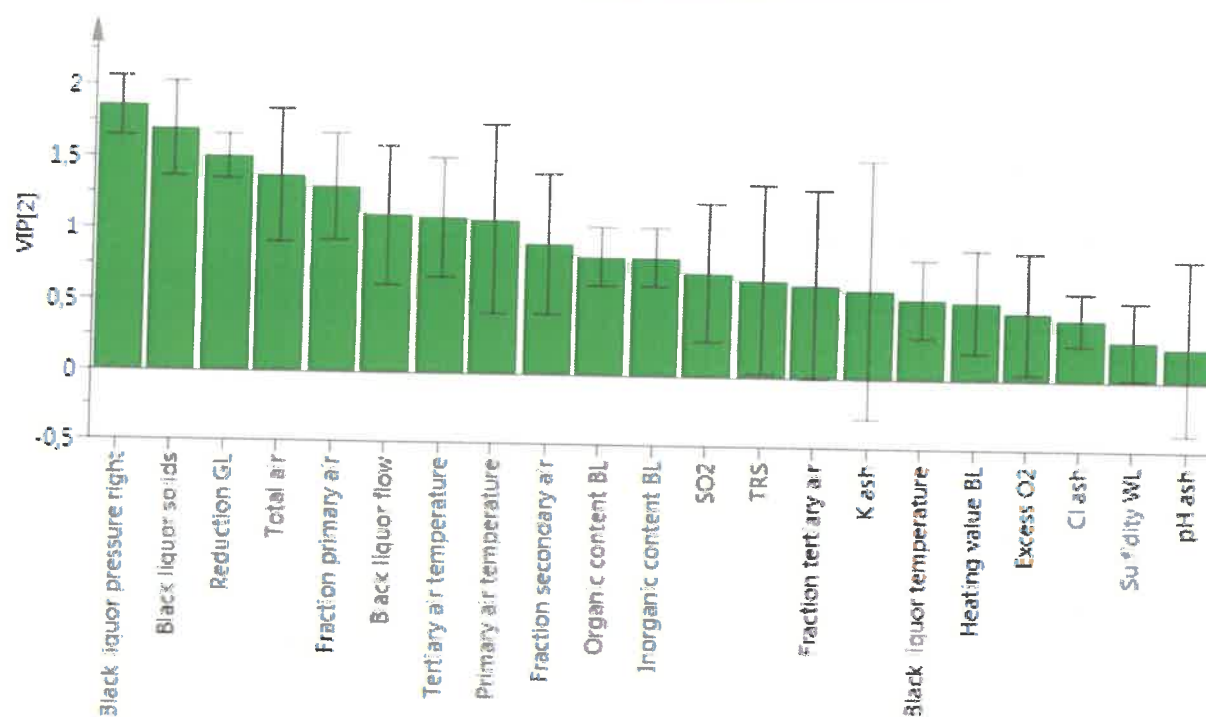
8.2.4 AP BB right

Y parameter in the model	PCs in PLS	R2X(cum)	R2Y(cum)	Q2(cum)
AP BB right	1	0.179	0.720	0.676



## 8.2.5 Temp. BB left

Y parameter in the model	PCs in PLS	R2X(cum)	R2Y(cum)	Q2(cum)
Temp. BB left	2	0.362	0.806	0.733





## 8.2.6 Temp BB right

Y parameter in the model	PCs in PLS	R2X(cum)	R2Y(cum)	Q2(cum)
Temp. BB right	2	0.356	0.876	0.803

