INFLUENCE OF KRAFT PAPER QUALITY ON THE PERFORMANCE OF AN INDUSTRIAL PAPER IMPREGNATION PROCESS

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Resumo

Num processo industrial de impregnação de papel foi realizado um estudo para avaliar a variabilidade de uma das suas matérias-primas (papel Kraft) e o seu efeito sobre o desempenho do processo. Determinadas propriedades do papel (porosidade, espessura, densidade, humidade) foram medidas e comparadas para avaliar a variabilidade entre fornecedores e entre lotes. Verificou-se uma diferença significativa na qualidade do papel entre fornecedores, nomeadamente na densidade, espessura e porosidade.

Numa segunda fase, os dados históricos do processo foram analisados utilizando uma técnicas multivariadas de análise de dados. Verificou-se que o processo tem diferentes desempenhos de acordo com a combinação do formato de papel e tipo de resina. A qualidade do papel revelou-se crítica para o desempenho, tendo-se identificado correlações entre duas propriedades do papel (porosidade e humidade) e o desempenho do processo.

Com base no trabalho realizado, foram recomendados ajustes às especificações do papel para porosidade e humidade (aplicável a ambos os fornecedores). Isto pode conduzir a uma melhoria do desempenho do processo, com potencial para poupar até 15% no consumo de gás e aumentar até 5% a produção de folhas de papel impregnado.

Palavras-chaves: papel Kraft, impregnação de papel, MVDA, conhecimento e compreensão do processo, porosidade do papel

Por motivos confidenciais, o nome dos fornecedores do papel Kraft foram omitidos assim como, os valores do processo e as especificações do papel Kraft foram normalizados.

Abstract

At an industrial paper impregnation process a study was performed to assess the variability of one of its raw materials (Kraft paper) and its effect on the process performance. Therefore Kraft paper from two different suppliers was measured for different quality properties (porosity, thickness, density, moisture). It was observed that one of the paper suppliers when compared to the other provides paper which has higher density and lower thickness and porosity.

In a second stage, historical process data was analysed using multivariate data analysis techniques. It was found that the process has different performances according to the combination of the paper format and the different resin types. Evident correlations between two paper quality properties (porosity and moisture) and the process performance could be noticed.

Based on the observed facts, adjustments to the paper specifications for porosity and moisture (applicable to both suppliers) are recommended. This can lead to an improved process performance, where a saving in the gas consumption up to 15% can be achieved, as well as an increase up to 5% in the output (impregnated paper sheets.)

Keywords: Kraft paper, paper impregnation, MVDA, process knowledge and understanding, paper porosity

For confidentiality reasons, the names of the paper suppliers have been omitted, as well as process values, and the paper specifications have been normalised.

Contents

List of Figures

List of Tables

Abbreviation

HPL - High Pressure Laminate

EN - European Norm

ISO - International Organisation for Standardisation

USA - Unit States of America

UV - Ultraviolet

EBC - Electron Bean Curing

PPA - Papier-Prüf-Automat

TAPPI - Technical Association of the Pulp and Paper Industry

IST - Instituto Superior Técnico

BSEL- BioSystems Engineering Lab

MVDA- Multivariate Data Analysis

PCA - Principal Components Analysis

S_k - Standard Deviation

BSPC - Batch Statistical Process Control

LEL - Low Explosive Level

Chapter 1

1.1. Introduction

Trespa International B.V. is a Dutch company founded in 1960 that manufactures High Pressure Laminate (HPL) panels for decorative façades, according to the European norm EN 438 and International Organisation for Standardisation ISO 4586, and produces four distinct product lines (Athlon, Meteon, Toplab^{Plus}, Virtuon) by using two distinct technologies, paper impregnation and dry forming.

The headquarter of the company is located in Weert (The Netherlands), with approximately 650 employees, manufacturing more than 5 million m^2 of panels *per annum*, and earning a turnover of approximately 125 million Euros.

The company has three design centres located in New York (USA), Barcelona (Spain) and Santiago (Chile), twelve local offices and a worldwide distribution network. [1]

Figure 1.1. Trespa world map.

1.2. Processes and products at Trespa

In general a Trespa HPL panel is composed by three layers:

- A top layer that has the function of protecting the panel against e.g. UV radiation;
- A decorative layer to provide colour to the panel;
- A core layer that is composed by Kraft paper sheets impregnated with resin or resinated wood fibre boards.

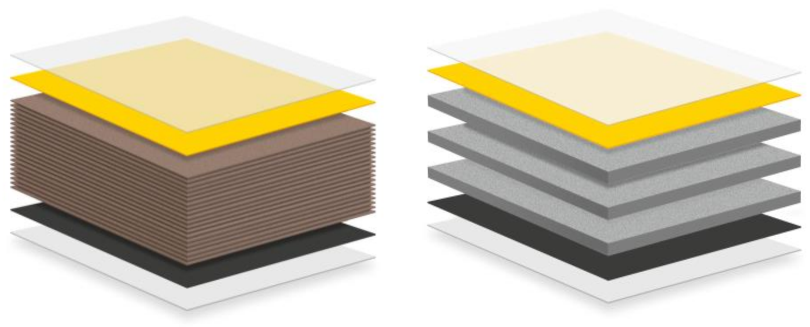

Figure 1.2. Panel layer composition with Kraft (on the left) and wood fibre board (on the right) core.

The fabrication of a Trespa HPL panel can be divided into different independent stages:

Production of the resin – Trespa manufactures all types of resin used at its facilities. These are phenolic resins, obtained through an exothermic polymerisation reaction between a phenol and an aldehyde.

Production of core material - Core material consists of layers of Kraft paper sheets impregnated with a thermosetting resin (paper core), or of resinated wood fibre boards (wood core), in both cases the material being bonded by means of heat and pressure.

Production of decor material – The decor layer consists of a resin-impregnated Kraft paper surface coated on both sides with chemical additives (against e.g. UV radiation) and processed by Electron Beam Curing (EBC).

Assembly and finishing – Semi finished products for both core and decorative surface are layered-up in packages. Each package goes under high pressure and temperature in a multi-opening press.

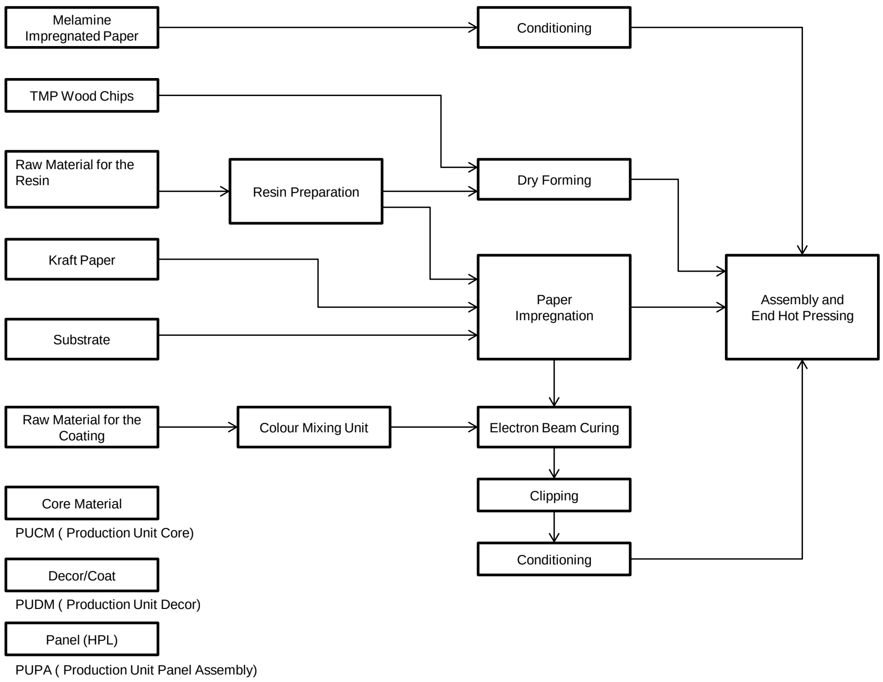

Figure 1.3. Trespa production process flow sheet.

1.3. Cooperation between IST and Trespa

In the end of 2014 a new equipment to test Kraft paper, the Emco Papier-Prüf-Automat (PPA), was purchased and implemented by Trespa. So far the quality of the supplied Kraft paper had never been tested internally. This purchase brought the opportunity to increase the understanding of the paper impregnation process, by linking the quality of the Kraft paper to the process performance. To accomplish this purpose, a project was internally defined in the beginning of 2015 and carried out by an M.Sc. student from Instituto Superior Técnico (IST).

IST is known to nest internationally recognized groups in the field of Chemical Processes and Systems Engineering, being BSEL (BioSystems Engineering Lab) one of them. This cooperation is an example of a successful one, where a practical problem at a chemical company could be solved by an M.Sc. student, by applying the state-of-the-art techniques in the Process Engineering field.

1.4. Thesis objectives

The main goals of this thesis are a) to assess the variability of the Kraft paper batch-to-batch and by supplier, by analysing the paper properties measured with the PPA, b) to increase the understanding on the paper impregnation process by analysing historical process data with multivariate data analysis (MVDA) techniques, and c) to determine if there is a correlation between the Kraft paper quality and the process performance. Based on the results fact-based adjustments to the Kraft paper specifications can be recommended, to further improve the impregnation process performance.

1.5. Thesis Structure

This thesis is divided into seven chapters. Chapter 1 provides an introduction about the context of this thesis, whereas the second chapter is an introduction to the Kraft paper and the paper properties measurements as well as to the impregnation process.

Chapter 3 contains a brief résumé to Chemometrics and the multivariate data analysis techniques.

An analysis to the Kraft paper measurements data applying multivariate data analysis (MVDA) techniques is made in chapter 4.

In Chapter 5 the historical process data regarding the impregnation process is analysed with MVDA, to identify patterns and correlations. In Chapter 6 correlations between the paper quality and the process performance are investigated.

Finally, Chapter 7 presents the thesis conclusions and makes suggestions of future work, indicating where there is still room for further improvement.

Chapter 2

This chapter is an introduction to one of the raw materials used in the paper impregnation process, the Kraft paper, how the paper properties measurements were performed and a brief explanation about the process at Trespa International B.V.

2.1. Kraft paper

Paper is a thin layer of mostly cellulosic plant fibres, produced on a screen by dewatering slurry of fibres in water. The slurry is called pulp. This pulp can be achieved by separating cellulose fibres from wood, fibres crops or waste paper. There several separations methods like the mechanical separation, chemical separation or using both separations [2].

To ensure that the different paper applications are successful, paper characteristics must be controlled. These characteristic are strength, thickness, porosity and absorption, among others that are not relevant for this work. Paper strength is obtained by using strong, long fibres pulp, and sometimes combined with a certain amount of shorter fibres for an improved structure and uniformity avoiding weak spots. Wet strength is increased by adding a wet strength chemical to the pulp.

The figure below shows the different types of pulp and corresponding quantities used in the production of paper. Different types of paper will have different percentages of mixed pulps.

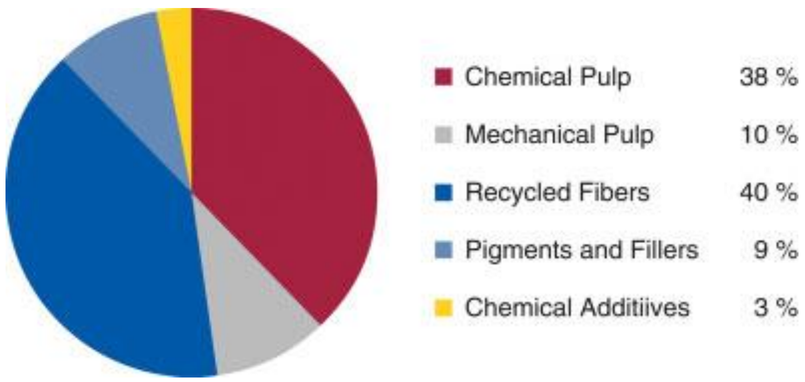

Figure 2.1. Components used in paper and board worldwide (mass percentages) [2].

A schematic diagram shows below the main steps of the paper production process.

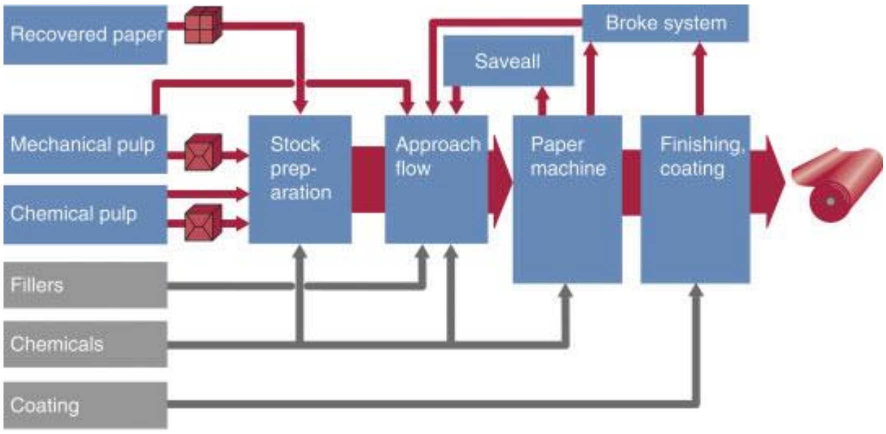

Figure 2.2. Overview of the paper making process [2].

Trespa uses Kraft paper in the impregnation process (from the German word *Kraft* , which means *strength*), because of the high strength and porosity compared to other types of paper. Kraft paper is produced from Kraft, mechanical and chemical pulps and recycled fibres. It is used predominantly for packaging purposes. Kraft paper has low resin impregnation ability. Therefore a special more absorbent Kraft paper is used instead at Trespa, which has the same properties but a higher porosity leading to a better resin impregnation.

For the paper impregnation process there are three different paper suppliers:

- A.
- B.
- C.

Kraft paper from C was not used during the timeline of this project. For that reason this study was only performed with A and B paper.

2.2. Kraft Paper Properties Measurements

The Kraft paper properties were measured using the Emco PPA Decor Climate supplied by Emco (Leipzig, Germany).

Emco PPA Decor Climate is an automatic testing machine designed for commitment in labs of paper industry and paper converting industry for determination of quality properties of decor paper in a grammage range from 50 g/m^2 to 400 g/m^2.

Figure 2.3. Emco PPA Decor Climate.

The Emco PPA Decor Climate measures the following Kraft paper properties (see Table 2.1) in standard humidity conditions (50 ± 3 % relative humidity) and each paper sample has 310 ± 5 mm of length.

Table 2.1. Kraft paper properties.

Properties	Unit	Technical data
Grammage	g/m^2	50 - 400 ± 0,2 g/m^2
Thickness	mm	± 1 mm
Porosity*	s	Tappi T 460, ISO 5636/5
Moisture	%	-
Temperature	ºC	-

* according to Gurley [4].

Chamber temperature and relative humidity are controlled during the measurements. A paper band is measured at fifteen different spots, which enables one to plot the spatial profiles of each measured properties as well as to calculate the average and standard deviation of that properties for each sample. The measurements made to the Kraft paper band are in the width direction.

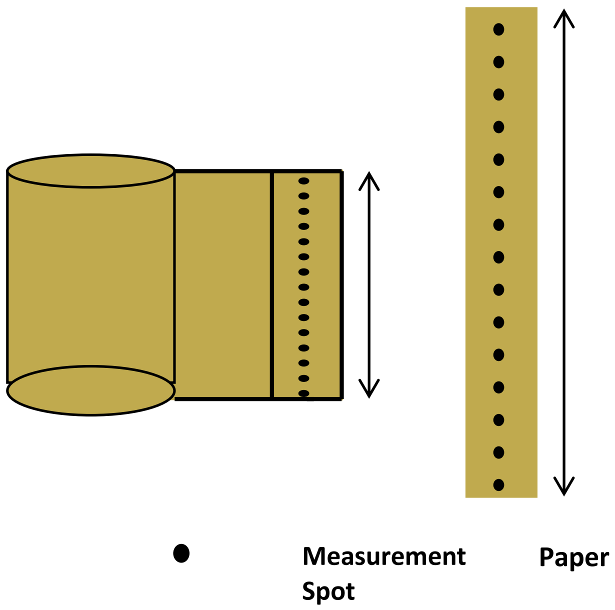

Figure 2.4. Spatial direction of Kraft paper measurements.

2.3. Resin

For the impregnation process four different types of resin are mainly used: B13, B21, F30 and F33. Trespa resins are phenolic, obtained through an exothermic polymerisation reaction between a phenol and an aldehyde, as previously mentioned. Phenolic resins are thermosets, i.e. once hardened they cannot be reheated and melted to be shaped differently [5].

At Trespa resins are produced batch-wise. After a batch is completed the resin is stored in containers, most of the time being mixed with previous batches, until used within 1 or 2 days.

2.4. Impregnation process

The impregnation process is a continuous process, in which a Kraft paper band is impregnated with resin. The band is then cut in at a given length that depends on the product specifications. The impregnated paper sheets are a semi-finished used as core material for the final Trespa product, the panel.

The impregnation process has different main steps, as shown in Figure 2.5 below.

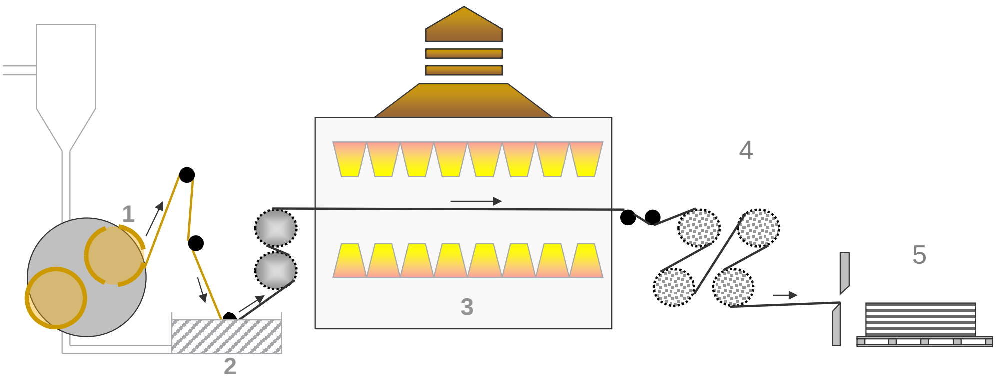

Figure 2.5. Schematic representation of the paper impregnation process: 1 - roll unwinding, 2 – resin bath, 3 – oven, 4 – cooling cylinders, 5 – stacking station.

The process starts by unwinding the paper roll. Here there are two unwinding cylinders, smaller cylinders to create tension on the line and a larger warming roller. The objective of the two unwinding cylinders is to ensure that when one roll is being unwound another one is getting prepared to start immediately and without any break after the first is finished. This happens in less than one second, by means of tape to make the connection between the two rolls. The larger warming roller is meant to warm up the Kraft paper, leading to a better impregnation of the resin into the paper.

After warming up the paper band goes into the resin bath. This is an isolated zone for safety purposes due to the toxic vapours released from the resin, which are extracted and burned off in a gas burner. The wet paper will further on pass between two cylinders to remove the resin excess. These cylinders (known as the dosing cylinders) play a very important role, as they are part of the loop control for the amount of impregnated resin, which is a specification of the semi-finished.

The squeezed resinated paper band enters then the set of sequential ovens. There are eight ovens with the function of drying the resin in the Kraft paper. Each oven has its own temperature setting, which increases from oven one to three, then the temperature is kept constant in ovens 4 and 5 and finally decreases from oven 6 to 8. The ovens are isolated zones and each one has a gas extractor to remove the volatiles released from the resin to the off-gas burner.

After leaving the oven the impregnated Kraft paper band is cooled down to room temperature. There are four cooling cylinders that remove the exceeding heat by means of a cold air flow. Furthermore there are three smaller cylinders to create tension on the paper band together with the ones located right after unwinding section.

Next to the cooling cylinders, there is a contactless mass sensor. This measures the specific weight (or grammage) of the impregnated paper. Considering that the raw Kraft paper has a fixed grammage, using the following formula the amount of impregnated resin can be calculated and compared to the specification (set-point).

$$Impregnated\ resin\ (\%) = \frac{Grammage\ impregnated\ paper - Grammage\ raw\ kraft\ paper}{Grammage\ raw\ kraft\ paper} \times 100 \qquad \textbf{Eq. 1}$$

Linked to the weight sensor, the controller will send a signal to the dosing cylinders, whose gap will be adjusted if needed to regulate the amount of impregnated resin.

Finally the impregnated paper band is cut and the paper sheets are stacked, wrapped up with a foil and stored in an acclimatised room.

Chapter 3

Industrial processes are nowadays highly automated, having multiple instruments collecting data at a high frequency. This generates massive amounts of data, containing potentially valuable information about the processes. Nevertheless, to extract the information from such large datasets is no easy task, if the right methods are not used. In the common situation of having 50 parameters and variables being measured at high frequency, plotting each at a time and doing a univariate analysis is no longer efficient. Furthermore, the sampling times for the different parameters and variables can be different and/or at different frequencies. To deal with such large and complex datasets multivariate data analysis (MVDA) techniques were developed. This chapter deals with the different issues that should be addressed when facing complex process datasets and introduces the multivariate data analysis tools throughout this work.

3.1. Chemometrics

Multivariate data analysis techniques have a very important contribution from Chemometrics, which is a chemical discipline that uses mathematical and statistical methods to design or select optimal measurement procedures and experiments, and to provide maximum chemical information by analysing chemical data. Chemometrics was introduced in 1972 by the Swede Svante Wold and the American Bruce R. Kowalski. One of the strongest points in Chemometrics is the possibility to identify groups or classes within data without using any prior knowledge on those groups.

Chemometrics uses multivariate statistics, which involves observation and analysis of more than one statistical outcome at a time. Other important contributions come from applied mathematics and computer science. Pattern identification, data classification and regression are some of chemometric application fields [6].

3.1.1. Principal component analysis

Principal component analysis (PCA) is one of the Chemometrics techniques with widest application. It is usually used for exploratory data analysis, very powerful in pattern identification and data grouping (clustering).

PCA searches for correlations among the variables and observations (samples) to reduce the dimension of the dataset. It extracts what is characteristic from that dataset and keeps noise or not significant information away. The algorithm involves an abstract mathematical transformation of the original data matrix, which, can be represented by the equation:

$$X = TP + E \qquad \textbf{Eq. 2}$$

Where:

- X is the original data matrix of dimensions $I \times J$, being I the number of observations and J the number of variables;

- T is the scores matrix of dimensions $I \times A$, being A the number of principal components in the PCA model; the scores are a representation of the observations in the new dimension;

- P is the loadings matrix of dimensions $A \times J$; the loadings describe the variables in the new dimension;

- E is the residuals matrix of dimensions $I \times J$; it represents the information in the dataset that is not explained by the model.

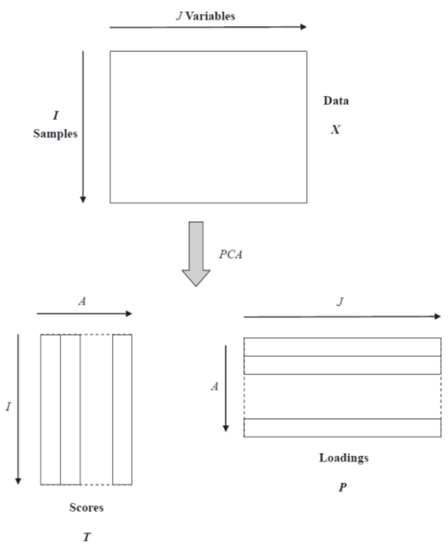

Figure 3.1. Matrix representation of a PCA.

By applying a PCA model to a dataset with *J* variables, the dimension of the dataset will be reduced from *J* to *A*, where *A* is the number of principal components of the model ($J \leq A$). Principal components are linear combinations of the original variables with no particular physical meaning, being orthogonal to each other. The first principal component will describe the most of the variation in the dataset, the second principal component will describe the second largest variation and so on.
From the PCA, two plots are the most important ones in analysing the data: the scores plot and the loadings plot. The scores plot shows how the samples relate to each other, and the loadings plot shows the correlations within the variables and which ones contribute the most for the variability in the dataset [7].

3.1.2. Data Pre-treatment

Data are often pre-treated in order to enhance the signal towards the noise, as well to normalize the variables if their values have different magnitudes. Scaling and mean-centring were pre-processing tools used in this work and are described below.

Scaling

PCA is a maximum variance projection method, it follows that a variable with a large variance is more likely to be expressed in the modelling than a low variance variable, therefore the data need to be normalize for both variables make the same contribution to the model. One of the methods is the unit variance. For each variable (column) one calculates the standard deviation (s_k) and obtains the scaling weight as the inverse standard deviation ($1/s_k$). Subsequently, each column of X is multiplied by its corresponding scaling weight. In this way, each variable has equal (unit) variance [8].

Mean-centring

By mean-centring the data, to each sample of a variable the average value of that variable is subtracted. This is applied to all variables in the dataset. In the end, the data is transformed in such a way that all variables will have average zero. This improves the interpretability of the model [8]
These two techniques are often applied together, being the data *autoscaled*.

3.1.3. Batch Modelling

Although the paper impregnation process is continuous, batch modelling techniques were used in this work as well. Therefore a short description of batch statistical process control (BPSC) is here presented.

By opposition to continuous processes, a batch process has a finite duration, from start-up to completion, which means the data from a batch process is time dependent. For that reason, measured data from batches are handled as three-way matrices.

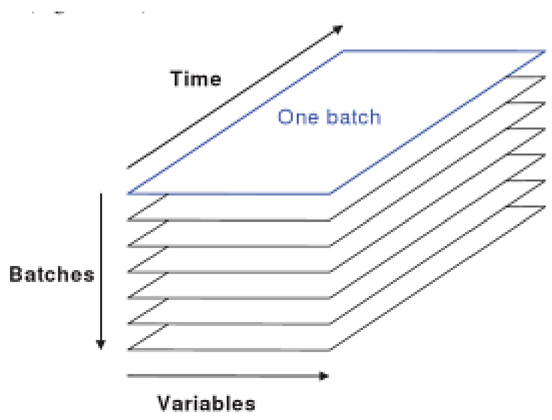

Figure 3.2. A three-way matrix of batch process data. The data comprises *I* batches, *J* variables and *K* time points.

For batch modelling, one way of handling the three-way matrix is by stacking all *I* matrices one below the others. Therefore a big bi-dimensional matrix will be built, with *J* columns containing the variables and (*K* x *I*) rows containing all the time points. With such a matrix a regular PCA can be applied to analyse and interpret easily the batch process data [9] [10].

Batch data can often involve two more distinct blocks of data, besides the one described above: one containing initial conditions (e.g. raw material measurements) and another with quality characteristics, as a result of the batch process. Each one can be analysed independently and related to each other by PCA or by regression methods.

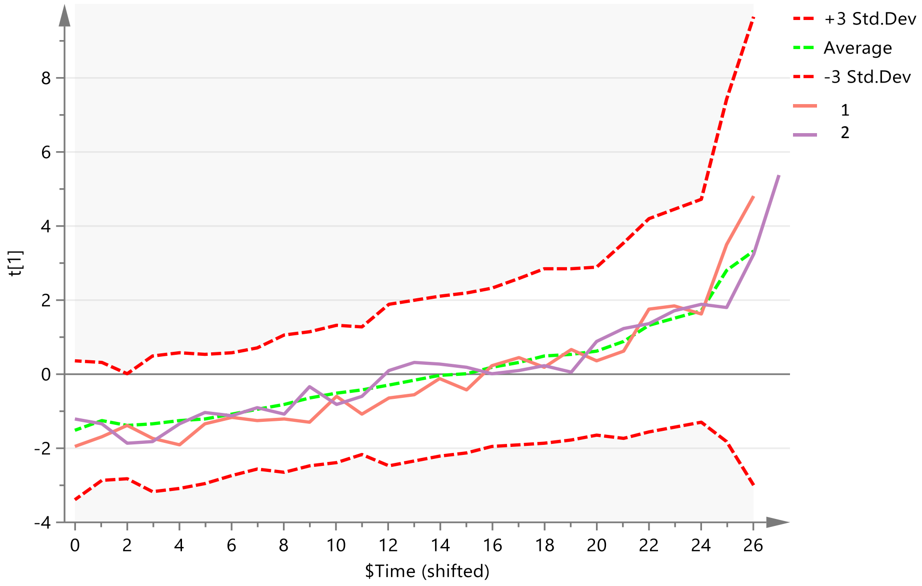

Figure 3.3. Example of a batch control chart with 2 batches.

Chapter 4

In this chapter the results of the measurements performed by the PPA on the Kraft paper are presented. The variability roll-to-roll and between suppliers is analysed, using both univariate and multivariate approaches.

4.1. Kraft paper quality measurements: univariate approach

Kraft paper rolls are delivered at Trespa depending on the stock and needs. As they arrive at the plant they are stored in a non-acclimatised room. Just before the rolls are going to be processed, they are brought from the storage to the production line, unwrapped, aligned to the unwinding cylinder and prepared with the tape to make the connection to the previous roll during the process. In the meanwhile a stripe of paper along the width of the roll is cut off for analysis at the PPA.

Figure 4.1. Forklifts with special claws for paper rolls handling and transportation.

Table 4.1. Kraft paper specifications per supplier.

Suppliers	Specifications	Density	Grammage	Porosity*	Moisture
A	minimum	0	0	0	0
	maximum	1	1	1	1
	nominal	0,5	0,5	0,5	0,5
B	minimum	0	0	0	0
	maximum	1	1	1	1
	nominal	0,5	0,5	0,5	0,5

*measured according to Gurley [4]

During the time line of this study 4105 rolls were processed by the impregnation line. From these 521 B rolls and 414 A rolls were analysed by the PPA, which represents 23 % of the total rolls.

The PPA measures grammage, thickness, porosity and moisture of the paper. A fifth property is density, which is not directly measured but calculated instead according to equation 3.

$$\text{Density} = \frac{\text{Grammage}}{\text{Thickness}} \quad (g/m^3) \qquad \textbf{Eq. 3}$$

Although there is no specification agreed with the suppliers for thickness, this is implicit within the specifications for grammage and density.

After removing existing measurements that were not done properly, the measurements on Kraft paper from both suppliers were compared. Each figure below illustrates the difference between each supplier and the off-specification measurements for each measured property.

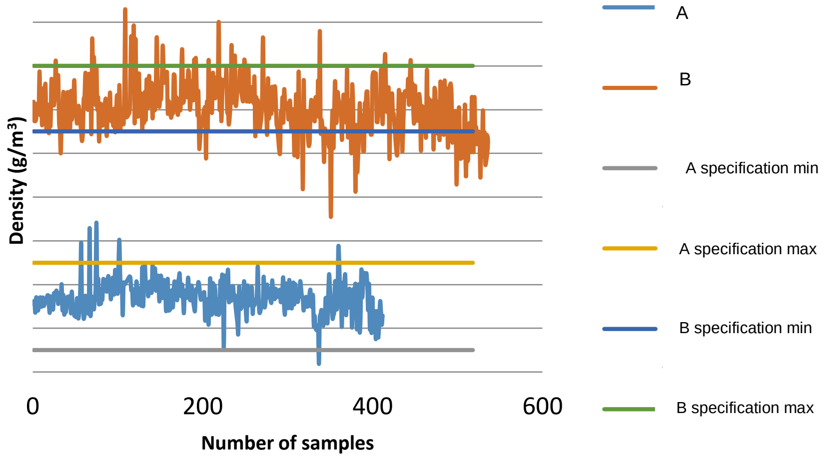

Figure 4.2. PPA density measurements on Kraft paper.

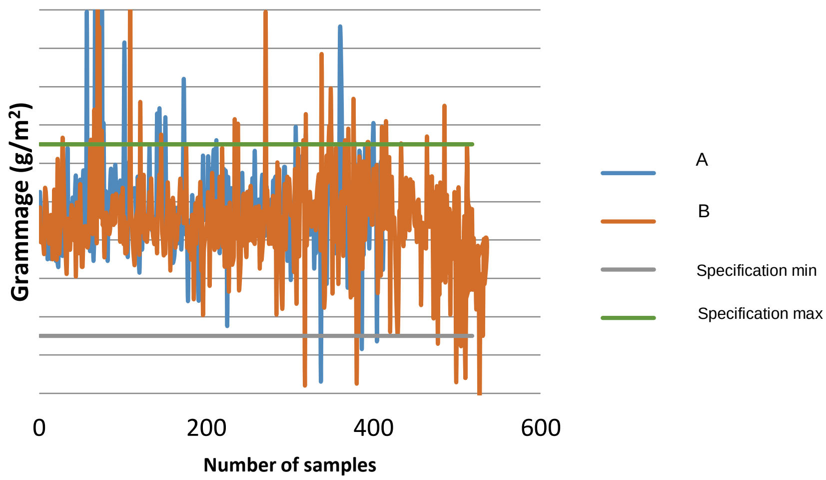

Figure 4.3. PPA grammage measurements on Kraft paper.

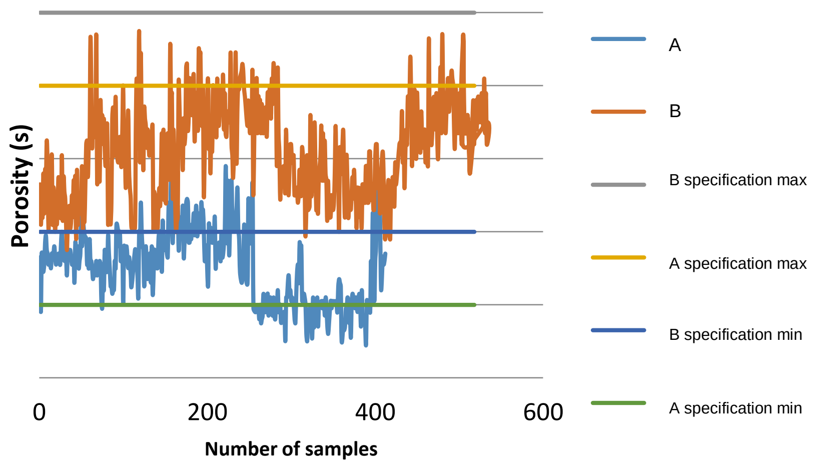

Figure 4.4. PPA porosity measurements on Kraft paper.

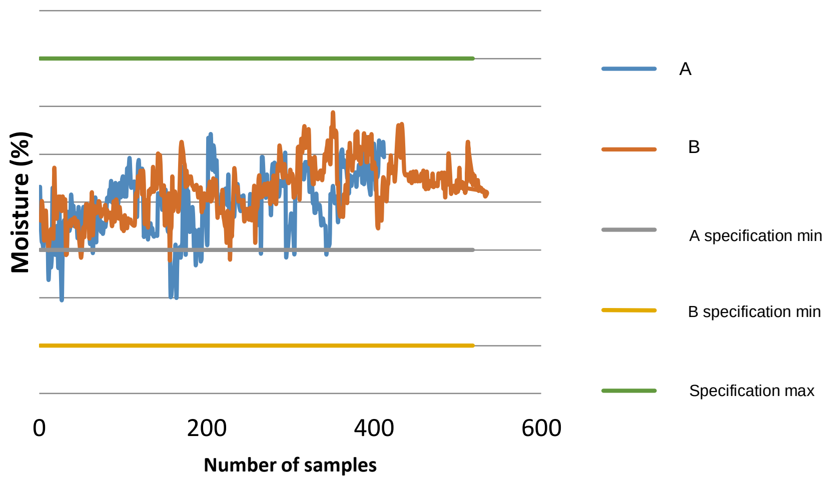

Figure 4.5. PPA moisture measurements on Kraft paper.

In total 25 % of A samples were out of specifications, being the porosity the main reason (ca. 17 %). For B in total 17 % of the samples were out of specifications being the main cause the grammage (ca. 8,3%).

The differences observed between the two suppliers were already expected, as each supplier has a different Kraft paper production process and even uses different Kraft pulp as raw material.

The B compared to A has:

- Higher density;
- Lower thickness;

- Lower porosity (because porosity is measured according to Gurley, higher values for the measurement will correspond to lower porosity of the paper).

Measurements over the width of the paper samples were performed as well. The spatial profiles show that moisture and porosity have variations around 22% and 5-8%, respectively. Density, grammage and thickness are more stable over the width with variations around 1-2%.(see Table 4.4 and Figure 4.6).

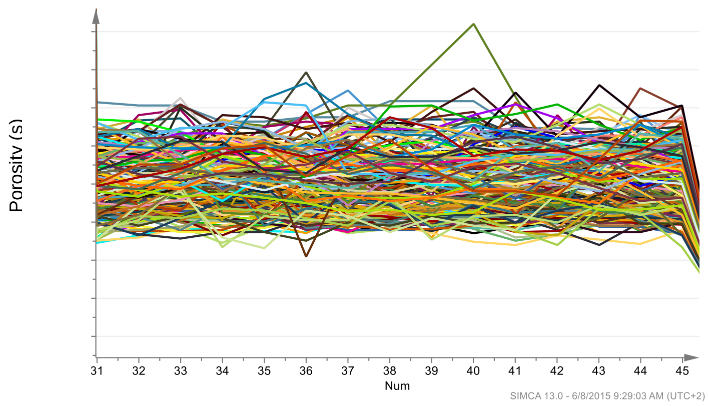

Figure 4.6. Porosity spatial profile for B paper.

4.2. Kraft paper quality measurements: multivariate approach

Multivariate data analysis was applied to the quality measurements performed on the Kraft paper to assess the variability roll-to-roll and between the two suppliers. A specific software was used for this analysis: SIMCA v.13 (MKS Umetrics, Umeå, Sweden). The dataset was scaled and mean-centred and fault measurements were removed to reduce noise.
In a first approach a PCA was developed using the data from both suppliers. The model explains 95% of the variance in the dataset in 3 principal components. The scores plot (see Figure 4.2) shows that the scores are clearly clustered according to the supplier. This is in accordance to what has been previously said in section 4.1, as each supplier produces paper with particular characteristics.

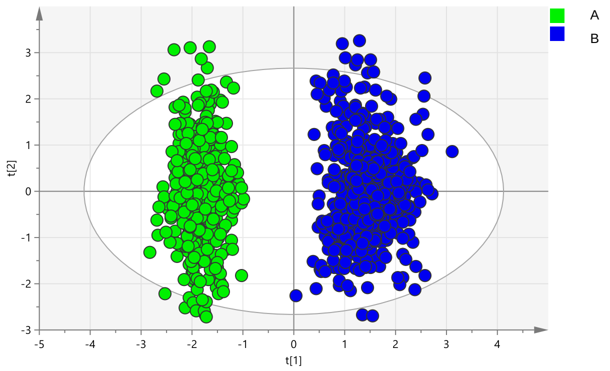

Figure 4.7. PCA to Kraft paper quality measurements: scores plot.

The loadings plot (see Figure 4.3) shows that porosity, thickness and density are the qualities that make the distinction between the suppliers so clear, confirming again what has been previously seen. The scattering in each cluster in the second principal component direction is due to variations in moisture and grammage: the higher the second principal component scores are the higher the values of moisture and grammage are. The higher the first principal component scores are the lower the thickness and the porosity (according to Gurley) are and the higher the density is.

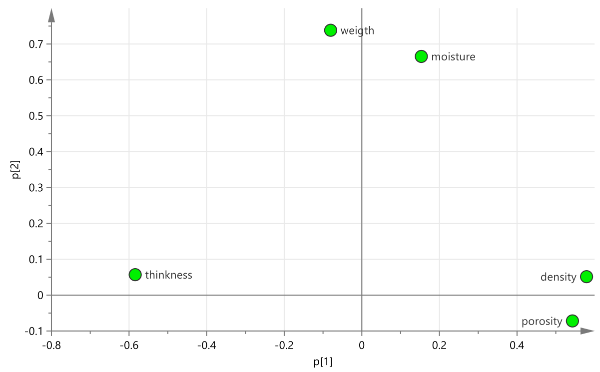

Figure 4.8. PCA to Kraft paper quality measurements: loadings plot.

To increase the resolution in each cluster, a PCA was applied to the data of each supplier in separate. For A paper a model with 4 principal components was developed, explaining 99% of the data variance. For B paper a model with 4 principal components was developed, explaining 99% of the data variance.

The scores plots (see Figure 4.9) shows that the scores are randomly scattered with no evident outliers.

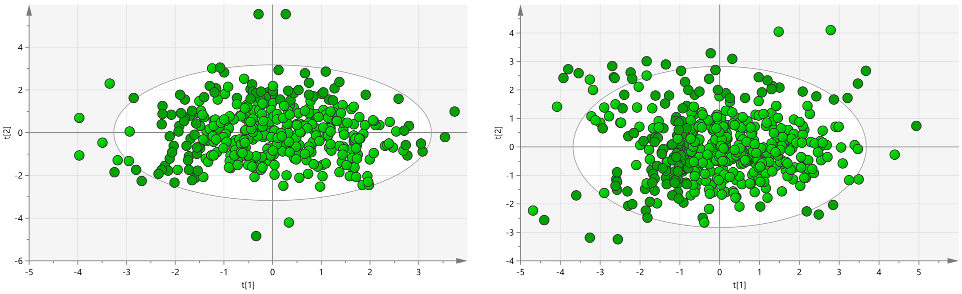

Figure 4.9. PCA to Kraft paper measurements: scores plots. A paper data on the left and B paper data on the right.

In the loadings plots (see Figure 4.10) it is possible to see that density and thickness are inversely correlated, which was already expected as a result of equation 3. The paper porosity is increasing with the thickness as well. In general there are no other strong correlations among the properties.

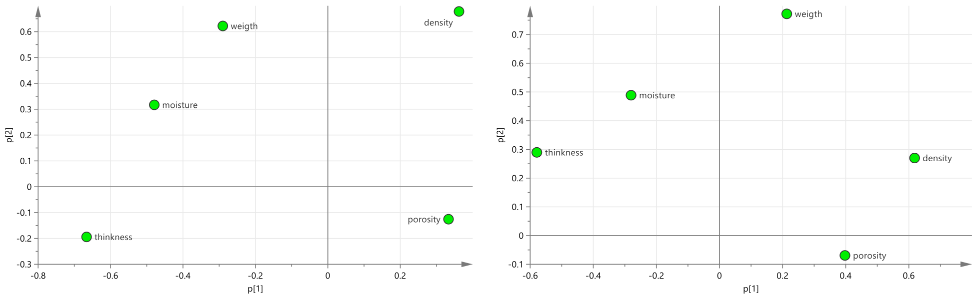

Figure 4.10. PCA to Kraft paper measurements: loadings plots. A paper data on the left and B paper data on the right.

4.3. Conclusions

The paper of each supplier has its own characteristics regarding the properties measured. Being moisture and grammage qualities with very similar values for both suppliers, density, porosity and thickness are the qualities making the difference. This could be made very evident using the multivariate approach, where the paper samples are clearly clustered according to the supplier, having no overlapping. However, the univariate approach is easier for analysing each property at a time and see if there are trends in the measurements or the amount of samples that lay out of the specifications.

Two correlations between the properties could be identified: thickness is inversely correlated to density and directly correlated with porosity. This is valid for both suppliers.

The *intra*-roll measurements (spatial profiles) didn't show significant variations of the properties over the width, with exception of moisture (variations greater than 20%).

Chapter 5

In this chapter historical process data of the paper impregnation process is analysed using multivariate data analysis. Patterns in the process performance are searched, as well as variations in the process parameters/variables.

5.1. Exploratory analysis to the impregnation process

When studying a process one of the first things to check is knowing what are the parameters, which variables are measured and from these which are automatically (or manually) controlled and which are not. In the historical data from the paper impregnation process there are 108 variables/parameters recorded. From these, the following are set at the beginning of the process:

- Line speed,
- Product format (paper sheets length),
- Ovens temperatures,
- Paper band tension,
- Amount of resin in the paper.

These parameters are defined according to the type of product running in the line, depending on which paper (supplier) and resin type is used. However, during the continuous process several sources of disturbances can lead to adjustments in those parameters. For that reason the border between a parameter and a process variable is very thin. The two main disturbances, according to the line operators, are variations in the quality of the resin and of the paper, although this is not more than qualitative empirical knowledge.

For the exploratory analysis, performed using multivariate techniques, historical data from the process was used corresponding to the same time frame of the paper quality measurements. Thus, only process data from March until July and corresponding to the rolls analysed by the PPA were used, in a total of 935 rolls (line runs).

As previously mentioned, the impregnation process is continuous. However, it can be seen as a batch as well. The duration of a roll in the line is the duration of the batch: every time that a roll starts being processed, a new batch starts. For that reason and because this makes easier the comparison of the process performance for different rolls a batch modelling approach was used.

In a first step, a PCA was applied to all process data available. Possible reasons were searched, that could be a cause for a clustering in the scores, e.g. seasonality, resin type, paper supplier, product format or some process parameter/variable. An important pattern could be observed, where the line speed is dominating the distribution of the scores.

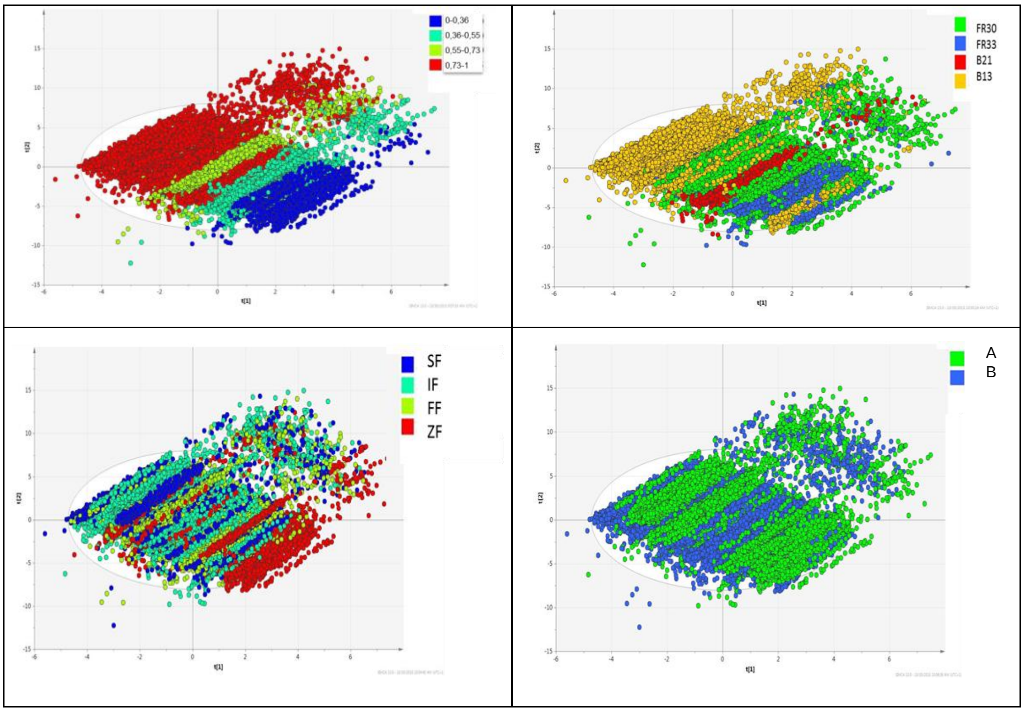

Figure 5.1. PCA to impregnation process data: scores plot. Top left plot - the scores are coloured using a colour gradient for line speed, where blue is the lowest speed and red the highest; Top right plot – the scores are coloured by resin types; Bottom left – the score is coloured by format product; Bottom right – the scores are coloured by suppliers.

The most evident pattern in the process data is with the line speed. Also the resin type looks to have some influence on the process performance. The product format and the paper suppliers do not show a significant impact on the process, as the scores are mixed.

To help in the interpretation of the data, a batch modelling approach was used (although the process is continuous). It is interesting to see in figure 5.2 that the first principal component scores increase notoriously with the line speed. Within the batch the scores remain constant, which is an indication that there are no changes during the batch as the process is continuous.

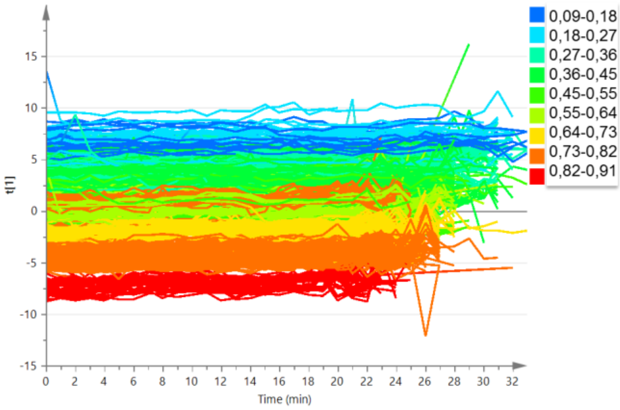

Figure 5.2. Batch control chart for first principal component of the batch model coloured by line speed.

A more detailed analysis to the process follows in the next sections.

5.2. Process parameters analysis

As said before the line speed is one of the process parameters and it depends on the type of resin used. The table below shows the target speed for each resin type.

Table 5.1. Line speed targets for the different resin types.

Resin Type	B13	B21	F30	F33
Target Line Speed (m/min)	1	1	0,7	0

A more careful analysis to this process parameter was done. Figure 5.2 (top left) shows the histogram of the line speed. Although only three different targets are defined, at least six peaks can be identified in the data distribution (four of them matching the defined targets), besides an evident scattering.

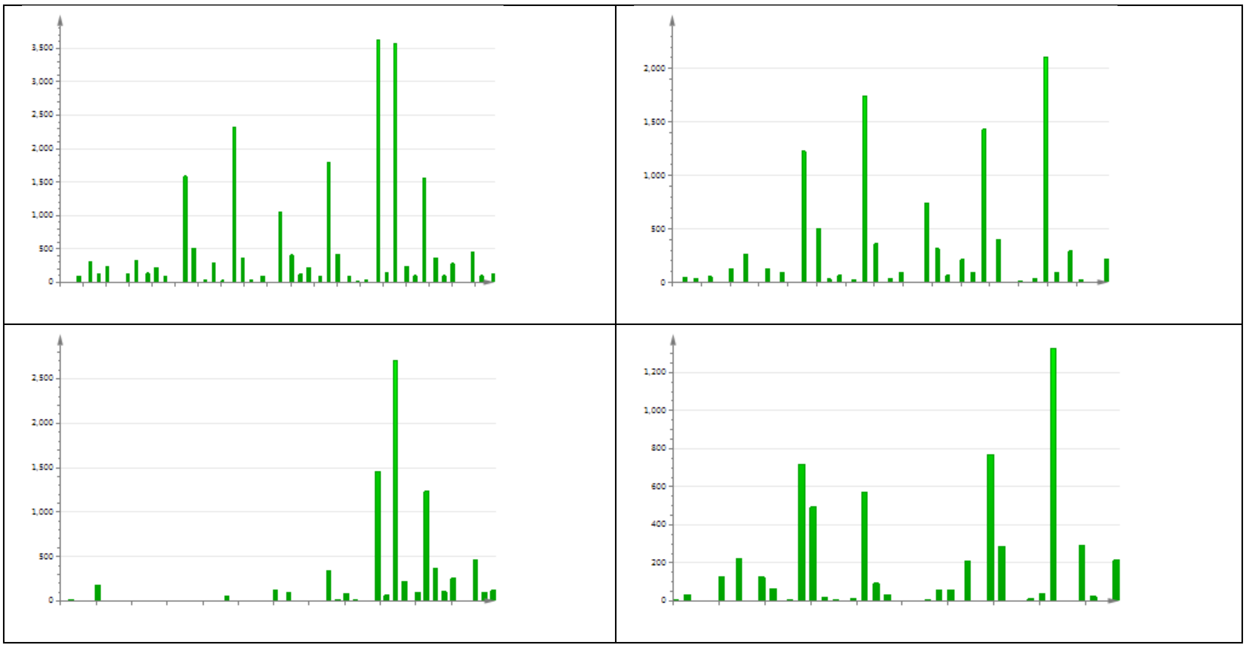

Figure 5.3. Line speed histograms. Top left - all process data; top right – with F30 resin; bottom left – with B13 resin; bottom right – with F30 resin combined with B paper.

Splitting the data per resin type, still there is reasonable scattering in the line speed (Figure 5.2 top right and bottom left). This could be due to the different paper suppliers (as the paper characteristics are distinct), but Figure 5.2 bottom right does not show that.

The variations in the line speed, even for a fixed combination of resin type and paper supplier, can be explained as follows. When the process is running, the optimal situation is reaching the defined line speed or even higher (to maximise the line output), as long as the semi-finished stays within specifications (ensuring the minimal required quality). These specifications are:

- Volatiles content,
- Resin content, and
- Resin penetration into paper (visual check).

However there are 3 bottlenecks in the process:

- Technical speed,
- Lower explosive limit (LEL) in the ovens, and
- Temperature in the ovens.

For safety reasons, in the ovens there are 4 sensors measuring the volatiles concentration in the hot air. These vapors released by the resins are extremely flammable. Therefore there is a maximum value for these volatiles concentration, defined by the LEL and that cannot exceed 25 %. When this concentration has reached 20 %, the safety procedure is to decrease the line speed, as the resin flow entering the ovens will decrease.

The volatiles content in the semi-finished is measured manually at a regular frequency. When the result is out of spec, the operator can decide whether he adjusts the temperature of the ovens or the speed of the line. Usually the second choice is taken, because the result is faster to achieve. Nevertheless, if the first option is taken, it will be limited by the ovens maximum temperature. This is a similar situation also for when the resin penetration into the paper is not optimal. To increase the resin penetration, the paper should have a higher residence time in the resin bath and therefore the line speed is decreased and the temperature of the Kraft paper needs to be increased. A possible reason for variations in the volatiles content of the impregnated paper and in the resin penetration can be related to variations in the raw materials (paper and resin).

The width of the paper band as well has an impact on the speed of the line. There are four different formats (see Table 5.2). For each the target line speed will be distinct. In general, smaller formats will lead to higher line speeds (as shown in Figure 5.2).

Table 5.2. Paper formats.

Format	SF	IF	FF	ZF
Paper Width (mm)	0	0,3	06	1

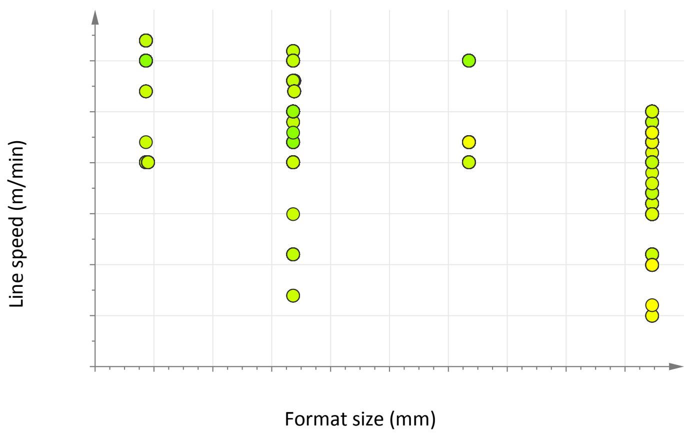

Figure 5.4. Line speed vs. paper format.

All these situations will lead to variations in the line speed, which are seen in the histograms in Figure 5.2. As this parameter changes, others have to be adjusted as well, to keep the semi-finished within specifications. That is the case of the temperatures in the ovens. As the line speed changes, the residence time of the wet paper in the ovens changes. To keep the same evaporation rate, the temperatures have to be adjusted accordingly: the higher the speed (the less the residence time), the higher the temperature. These adjustments are manual, made by the operators. Figure 5.5 shows the correlation between these two parameters for ovens. This correlation gets stronger if the model is made with just one supplier and one type of resin. Both suppliers have a similar correlation between speed and ovens temperature and all ovens have the same tendency.

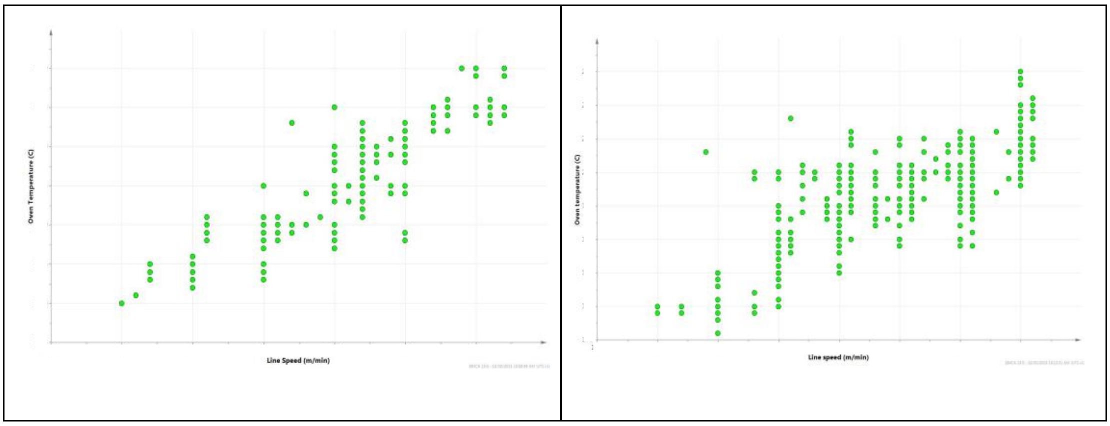

Figure 5.5. Impact of line speed on temperature of oven 4. Left – data referring to A supplier combined with resin B13; right - data referring to A supplier combined with resin F30.

5.3. Process variables analysis

The resin types are already known to have impact in the impregnation process. Each resin has different line speed target, due to the different volatiles concentrations arising in the ovens. Each resin has different quantity of solvent used to adjust the viscosity. In general, the more viscous the resin is the lower the solvent concentration in the resin (and consequently the lower the volatiles that arise in the ovens). The table below shows the viscosity of each resin.

Table 5.3. Viscosity ranges for the different resin types.

Resin Type	B13	B21	F30	F33
Viscosity (cP)	1	0,45	0,4	0

There are four sensors for volatiles concentration in the ovens, located at different places. Sensor number 3 placed in oven number 4 is the one reaching the highest values.

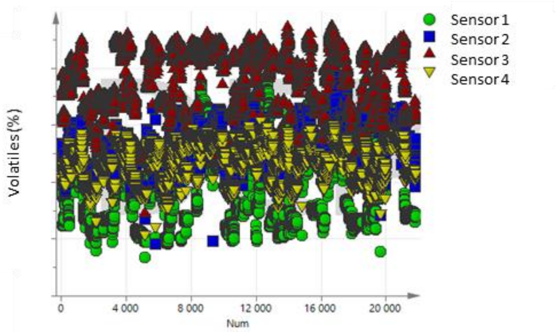

Figure 5.6. Volatiles concentrations in the ovens measured by the four sensors (1-4).

Because sensor 3 is the one reaching the highest values (close to the LEL values), it is this one where the operators focus during the process.

The figure below shows that resin F30 and F33 normally reach higher volatiles contents compared to B13 and B21.

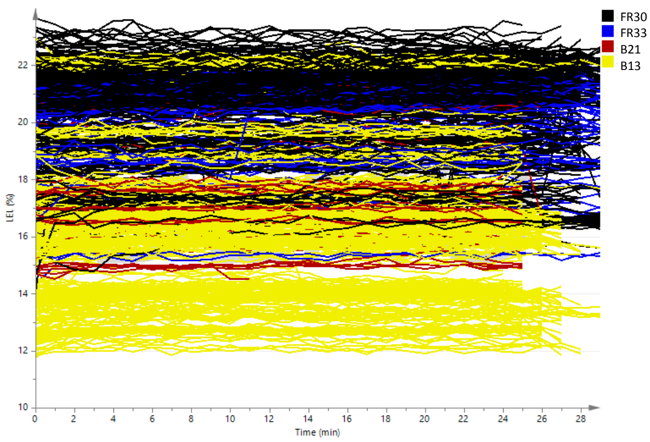

Figure 5.7. Volatiles contents measured by sensor 3 for the different resins.

As just seen, the performance of the paper impregnation process will be affected at least by the type of resin, the format of the paper and by the process parameters. Other sources of variance will be blurred by these. For this reason, to make easier identifying patterns and correlations among the variables/parameters, noise must be kept away. The entire process dataset needs to be refined and spit into smaller ones. The diagram below explains the approach used. Each smaller dataset will contain data regarding only one paper supplier, in combination with one resin type and one paper format. In the end several smaller datasets regarding specific combinations of these three factors will be built and analysed independently.

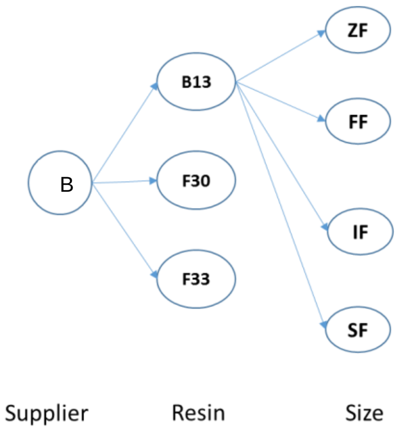

Figure 5.8. Approach to refine the process datasets and develop better process models. Possible combinations for paper rolls from B supplier (the same was applied to paper from A).

After refining the datasets, another important correlation was found that was not evident using all the process data at once. Depending on the line speed the gas consumption in the ovens is changing.

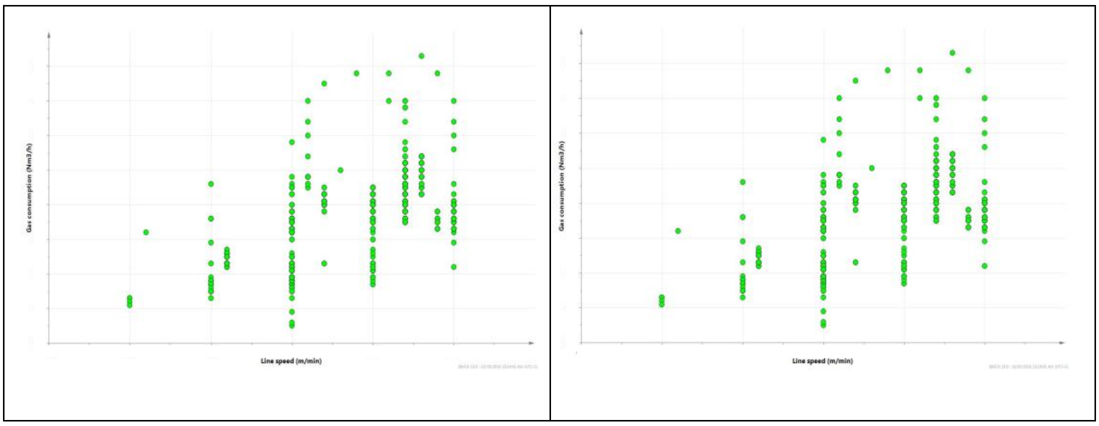

Figure 5.9. Impact of line speed on oven gas consumption. Left – data related to A paper in SF format combined with resin F30 ; right - data related to A paper in ZF format combined with resin B13.

This observation is expected, since the semi-finished needs to meet the specification for volatiles content. As the line speed increases the retention time of the paper in the ovens decrease and if the ovens temperatures do not increase, the volatiles in the semi-finished would increase and be out of

spec. Therefore the temperature in the ovens need to be increased to keep the same volatiles release rate and keep constant the remaining content in the impregnated paper. As a consequence, the gas consumption increases due to the increased temperature.
Other correlations between parameters and variables have been identified, but they are not relevant for this project. Therefore focus will be given on the ones that have a relation with the Kraft paper quality, which will be presented in the following chapter.

5.5. Conclusions

The performance of the impregnation process is highly dependent on the combination of resin type and format. Depending on these two, different targets for the line speed are defined. The line speed is then dominating the process performance, with an evident impact on the ovens temperatures, gas consumption and volatiles concentration in the ovens. Still there are variations that cannot be explained only by these two factors (resin type and format). One of the source of disturbances could be the quality of the Kraft paper, and that is the subject of the next chapter.

Chapter 6

In this chapter the impact of the Kraft paper properties in the impregnation process is studied and presented. The critical properties are identified and the impact on several key process performance indicators are quantified. Adjustments in the Kraft paper specifications are proposed in order to improve the impregnation process performance.

6.1. Kraft paper quality and process performance: exploratory analysis

As the Kraft paper quality is different for each of the two suppliers, as seen previously in Chapter 4, the process dataset was split only according to the paper supplier as a starting point.

A batch modelling PCA was applied to all process data available when B paper was used. The model explains 70% of the variance in the dataset in 4 principal components and the scores plot is shown below.

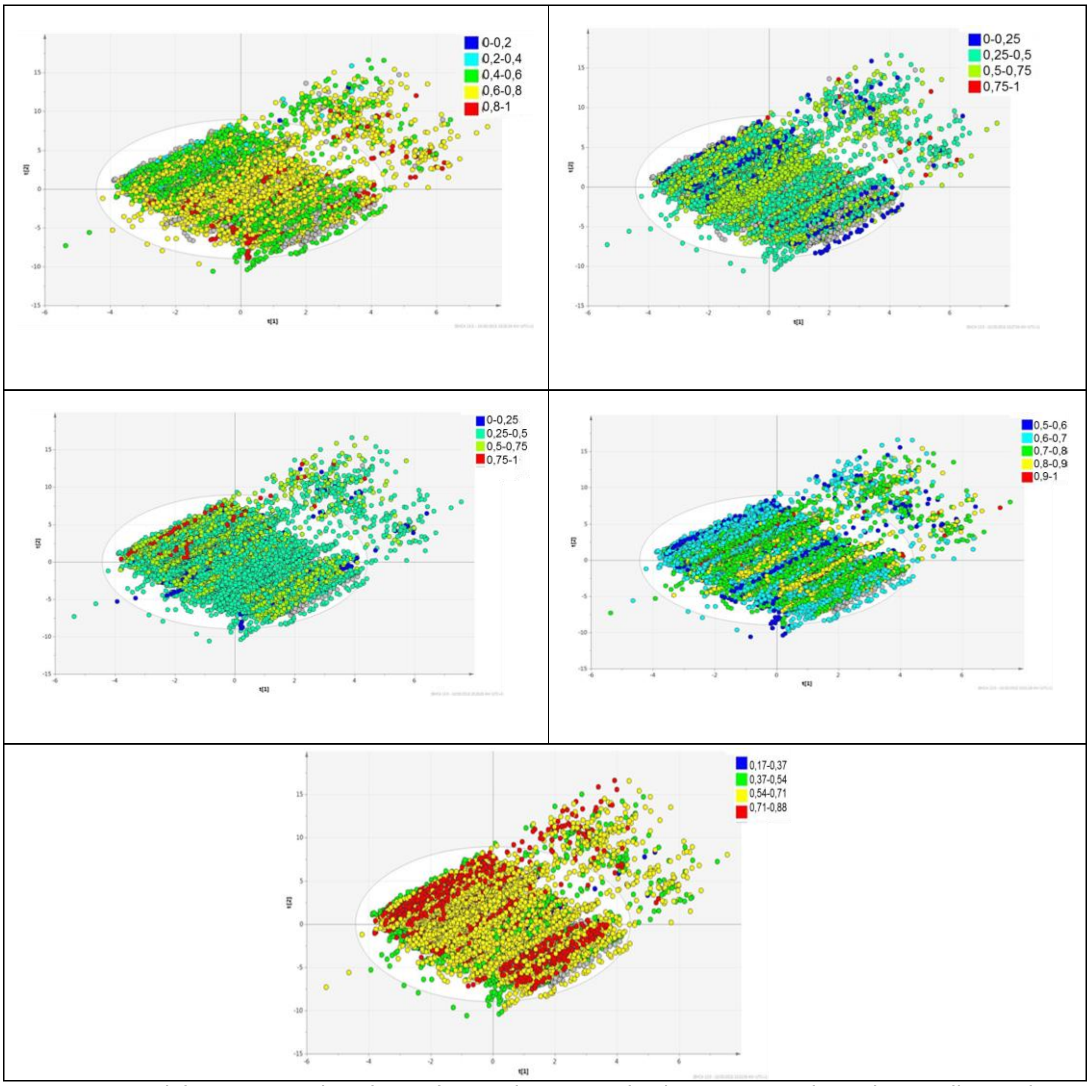

Figure 6.1. PCA model to process data (B Kraft paper): scores plot (scores are coloured according to the paper properties). Top left – scores coloured by density; Top right – scores coloured by grammage; Middle left – scores coloured by thickness; Middle right – scores coloured by porosity; Bottom – scores coloured by moisture. Where blue is the lowest paper properties and red the highest.

No visible patterns in the process performance linked to the Kraft paper properties could be observed for any of the suppliers.

From the previous chapter, it has been observed that the resin type and the paper format play an important role on the process performance. Looking at Figure 6.1 it may be that the paper quality impact is blurred by these two factors. For that reason, their impact on the process must be isolated and kept apart. On the other hand it has also been seen that the speed of the line is a critical parameter for this process. Depending on this, all other parameters will have to be adjusted, such as the ovens temperatures, and some variables will also respond to these changes (e.g. gas consumption and volatiles concentration in the ovens). Therefore, taking all this into consideration, a similar approach like the one in Figure 6.2 was used, although this time an additional restriction for line speed was taken. The reason behind is that if the target line speed is reached or even overcome, it is considered that the process is running properly and there are no constraints regarding mechanical failures or safety (e.g. LEL) or unknown disturbances.

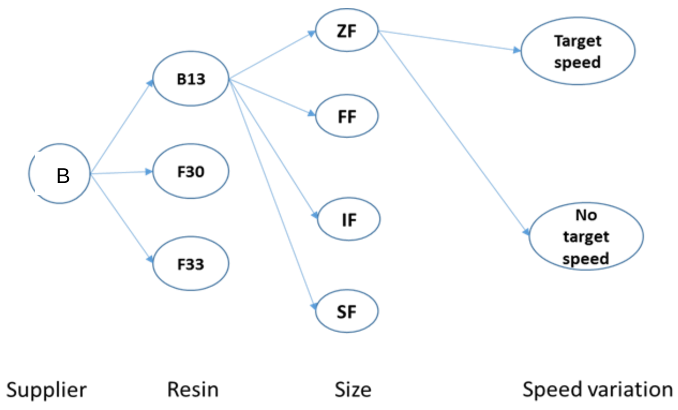

Figure 6.2. Approach to refine the process datasets and develop better process models (only process data with target speed or higher was used for modelling). Possible combinations for paper rolls from B supplier (the same was applied to paper from A).

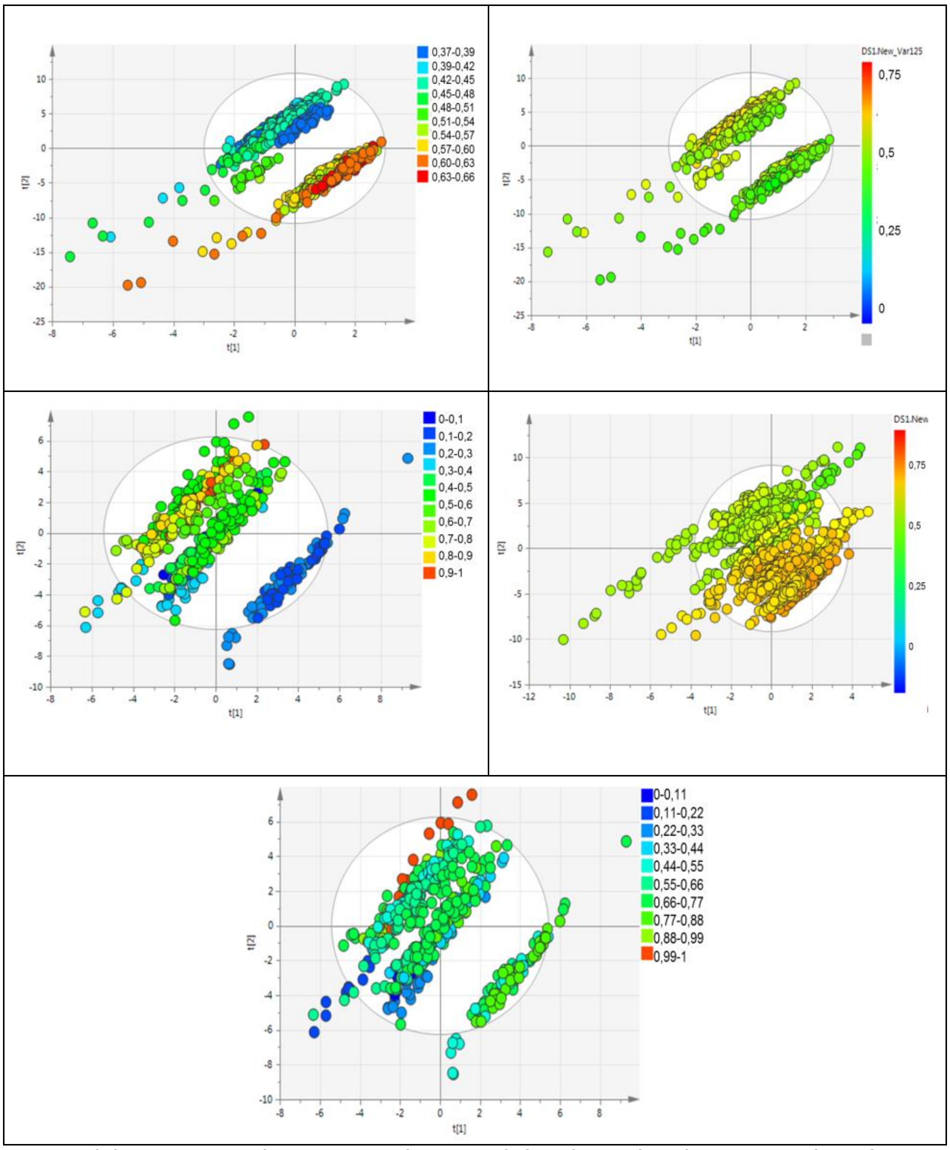

Figure 6.3. PCA models to process data: scores plots. Top left – data related to A paper in IF format combined with resin B13, scores are coloured by paper porosity; Top right plot – data related to A paper in IF format combined with resin B13, scores are coloured by paper moisture; Middle left – data related to A paper in IF format combined with resin B13, scores are coloured by paper porosity; Top right plot – data related to A paper in FF format combined with resin F30, scores are coloured by paper moisture; Middle right – data related to B paper in IF format combined with resin B13, scores are coloured by paper moisture; Bottom – data related to A paper in FF format combined with resin F30, scores are coloured by paper density.

After analysing all the possible combinations of paper supplier, resin type and paper format at line speeds equal or higher than the respective targets, a general pattern could be found related to paper porosity and moisture. For density, thickness and grammage no influence on the process performance could be seen.

In the next section of this chapter a more detailed analysis will follow, in order to understand the impact of paper porosity and moisture on the paper impregnation process.

6.2 Kraft paper quality and process performance: impact of critical paper properties

Previously it has been shown that there is a relation between the process performance and the paper porosity and moisture. A deeper look is now taken in each of these properties and their effect on the process. For that the dataset was limited to resin types B13 and F30. Both are used in combination with the two paper suppliers. For the other resin types there was not data enough for this more detailed study.

6.2.1. Paper moisture

According to what has been observed in Chapter 4, both suppliers provide paper within the same moisture range. The theory says that a very dry paper will have a bad impregnation ability. Some moisture is needed as a drive to enable the resin to penetrate the paper pores by capillarity [10].

One of the quality checks performed by the operators on the impregnated paper is the resin impregnation (as previously mentioned in Chapter 5.2). If the resin doesn't reach the paper core one of the actions that the operators can take is to increase the temperature of the warming cylinder (just before the resin batch). It is interesting to observe that this temperature is influenced by the paper moisture (see Fig. 6.6). The temperature of the cylinder increases with increasing paper moisture. This could be an indication that the resin impregnation to the paper core ability has to be increased when the moisture content of the paper is higher (within the moisture range in the data).

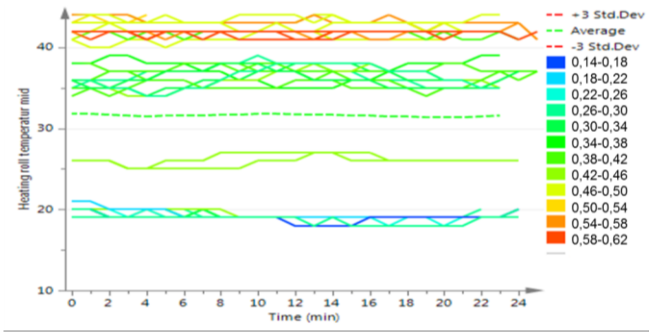

Figure 6.4. Variable batch plot for the temperature of the warming cylinder. The batch curves are coloured according to the paper moisture. Data referring to A paper in combination with IF format and resin B13. Where blue is the lowest speed and red the highest

The influence of the paper moisture can be seen as well on other parameters/ variables of the process. It seems that the speed of the line tends to decrease with increasing paper moisture, although this may be blurred by some scattering of the data. As a consequence, the temperatures in the ovens are decreasing as well as the gas consumption with the decrease of the line speed.

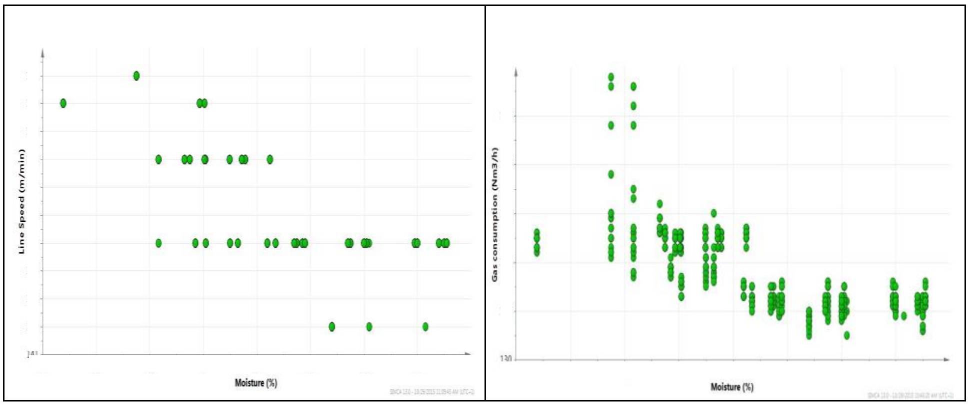

Figure 6.5. Influence of paper moisture on line speed (left) and gas consumption (right). Data referring to A paper in combination with IF format and resin B13.

For paper supplied by B the situation is similar. The same type of trends is observed.

Regarding the volatiles concentration in the ovens, also an influence of the paper moisture is to be observed, but only for B paper: the higher the paper moisture, the higher the volatiles concentration. For A paper this effect was not observed.

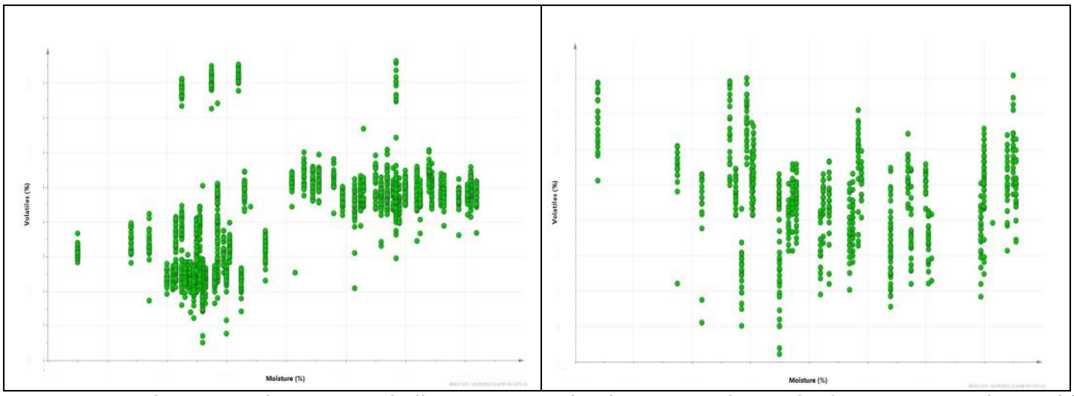

Figure 6.6. Impact of paper moisture on volatiles concentration in oven 4; data referring to B paper in combination with IF format and resin B13 (left). Impact of paper moisture on volatiles concentration in oven 4, data referring to A paper in combination with FF format and resin B13 (right).

For resin F30, in general the trends are the same as described for B13. However for resin F30 an additional impact of the paper moisture can be seen on the gap between the dosing cylinders. This is not visible for resin B13. This may be due to the resin properties, such as viscosity. B13 is less fluid than F30, which can have an impact on the amount of resin that adheres on the paper surface, dominating the paper moisture effect.

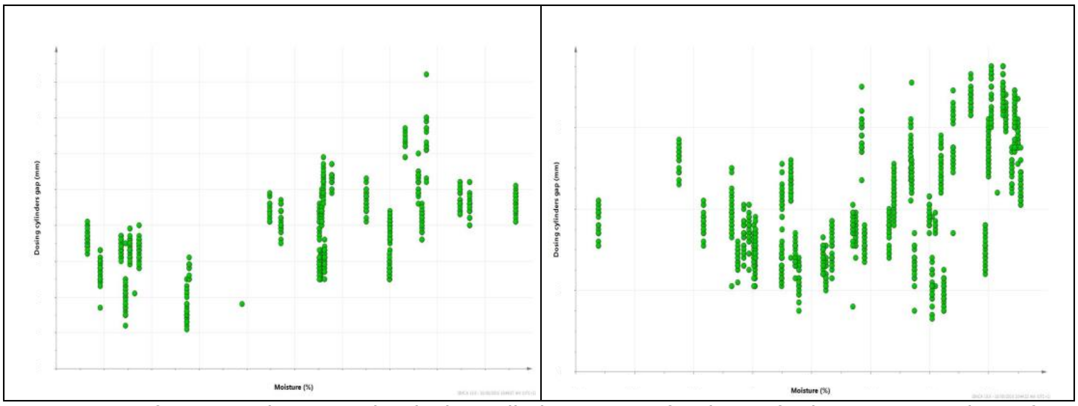

Figure 6.7. Impact of paper moisture on the dosing cylinders gap. Left - data referring to A paper in FF format in combination with resin B13; right - data referring to A paper in FF format in combination with resin F30.

In general, the line speed and consequently the ovens temperature and the gas consumption decrease with the increase of the paper moisture. This can happen because the impregnation of the paper is so effective as the paper moisture increases that the volatiles content specification is exceeded as well as the volatiles content in the ovens reaches easily the LEL. As a consequence the process has to slow down. Nevertheless, some deviations to this trend could be found for A paper and resin B13.

6.2.2. Paper porosity

A and B have different ranges of porosity, being A paper within 0,35 to 0,56 and B within 0,56 to 1. The differences in porosity are related to the paper specific area. Theoretically higher porosity will lead to higher specific area, which facilitates the resin impregnation of the paper [2].

Looking at the data referring to A paper combined with resin B13, the influence of the paper porosity on the temperature of the warming cylinders can be noticed. As the porosity increases (the values for porosity measured according to Gurley are decreasing), the temperatures are higher, which can be explained in the same way as for the paper moisture. As the paper porosity increases, the impregnation of the resin onto the paper is so much favored that the process has to slow down due to the increasing levels of volatiles in the ovens and/or the semi-finished.

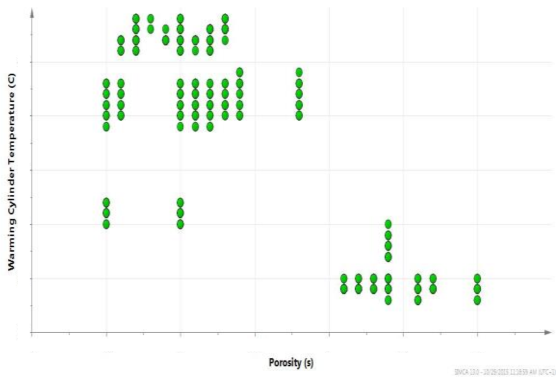

Figure 6.8. Impact of paper porosity on the temperature of the warming cylinders. Data referring to A paper in combination with IF format and resin B13. Porosity according to Gurley.

Just like already observed for paper moisture, also paper porosity is influencing the line speed, and consequently the temperatures in the ovens and the gas consumption, as seen in Figures 6.9 and 6.10. As the paper porosity increases, the line speed decreases, as well as the ovens temperatures and the gas consumption.

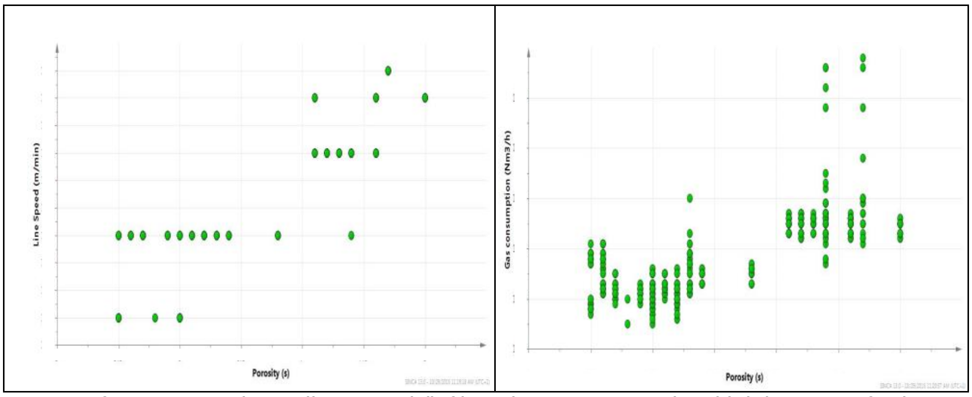

Figure 6.9. Impact of paper porosity on line speed (left) and gas consumption (right). Data referring to A paper in combination with IF format and resin B13.

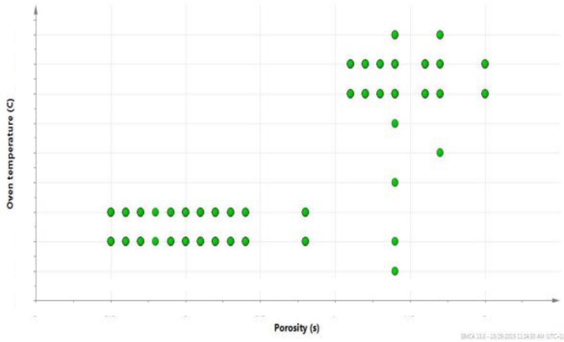

Figure 6.10. Impact of paper porosity on temperature of ovens 3.Data referring to A paper in combination with IF format and resin B13.

B paper porosity will have almost no impact on the line speed, gas consumption and ovens temperatures, as well as on volatiles in the ovens (see Figure 6.11). The situation observed for A, in which an increase of the paper porosity is leading to an excessive impregnation and a consecutive slow down of the process, seems not to occur for Kotkamills. B paper is less porous than A, and therefore not so favorable to the resin impregnation for both resins.

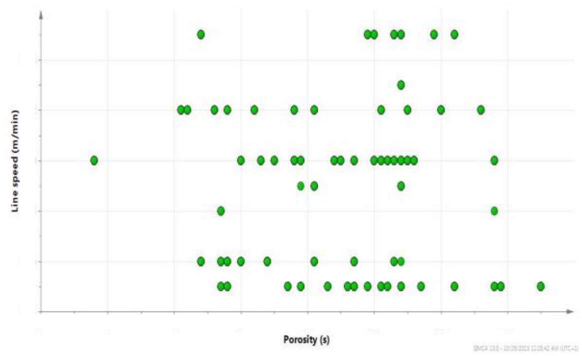

Figure 6.11. Impact of paper porosity on line speed. Data referring to B paper in combination with IF format and resin F30.

As already observed for the paper moisture, also the dosing cylinders gap has a correlation to the A paper porosity in combination with F30 resin. The lower the paper porosity, the lower the gap. However for resin B13 there is no evident impact from the paper porosity. This was also happening for the paper moisture. Apparently, the reason would be the same: B13 is much more viscous than F30 and the adherence of the resin onto the paper is dominating over the paper porosity effect.

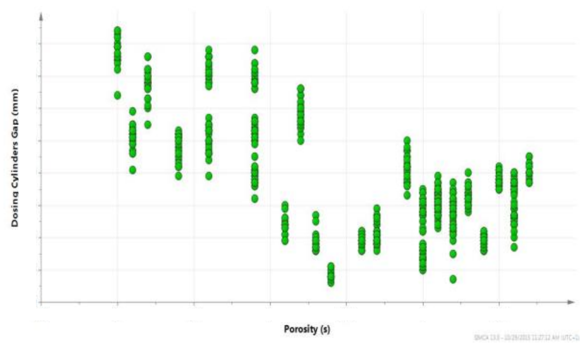

Figure 6.12. Impact of paper porosity on the gap between the dosing cylinders. Data referring to A paper in combination with SF format and resin F30.

From the presented data, an impact of the paper porosity on the process performance could be noticed but only for A paper. This has a porosity range which is so favourable to the resin impregnation, that the process needs to be slowed down. For B paper, it looks the situation is different. The porosity range is never that favourable, and the impact of the paper porosity is not noticed on the process performance.

Furthermore the effect of the resin type cannot be neglected. The influence of the paper porosity is stronger when resin B13 is being, compared to F30.

6.3. Impact of critical Kraft paper properties on key process performance indicators

The impact of the critical paper properties, moisture and porosity, was quantified for two important process performance indicators, the line speed and the gas consumption. The first is related to the process output (amount of semi-finished produced per time unit) and the second is related to energy consumption. This was done by calculating per batch the average line speed and gas consumption and then plotting against the paper properties of the roll used for that batch. As for most industrial processes, the target is to increase the output while decreasing the costs (e.g. by increasing the energetic efficiency). To simplify, due to the complexity of combinations of resin type, paper format and suppliers, the combinations with reasonably enough amount of data are shown.

For resin B13 and A paper, the output can be increased until 5% (above the target line speed) by keeping the moisture and the porosity on the low level (see Figures 6.13 until 6.20). This is also beneficial for the gas consumption.

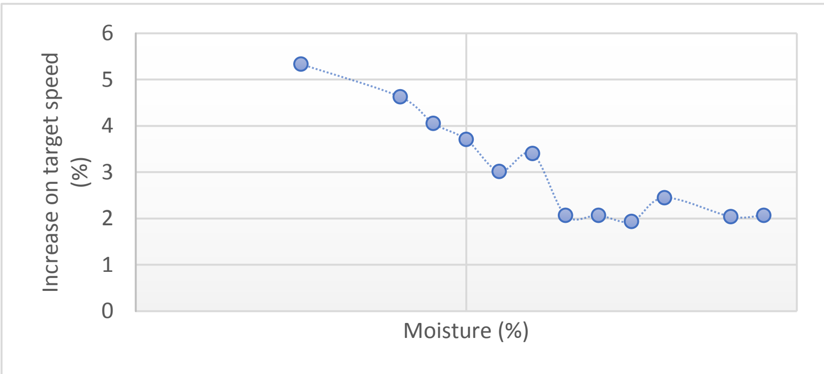

Figure 6.13. Impact of the paper moisture on the line speed. Data is referring to A paper in combination with IF format and resin B13. Plot based on 35 paper rolls.

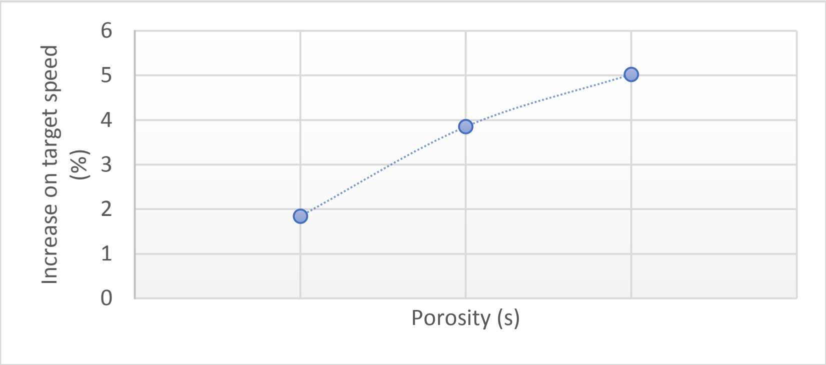

Figure 6.14. Impact of the paper porosity on the line speed. Data is referring to A paper in combination with IF format and resin B13. Plot based on 35 paper rolls.

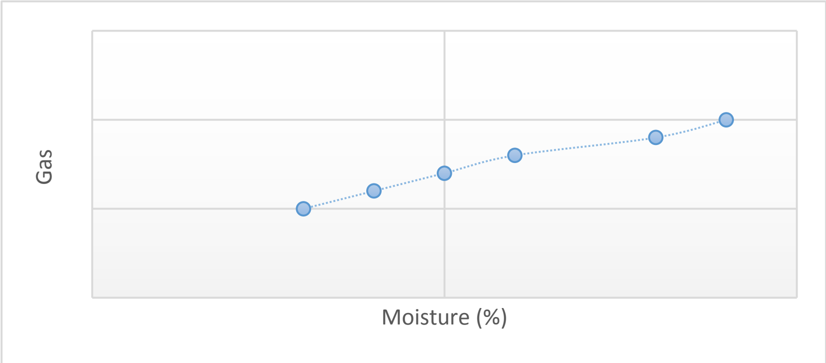

Figure 6.15. Impact of the paper moisture on the gas consumption. Data is referring to A paper in combination with IF format and resin B13. Plot based on 20 paper rolls; Fixed Line speed.

For resin B13 in combination with B paper, the best results for the gas consumption are achieved when the paper has lower moisture and porosity.

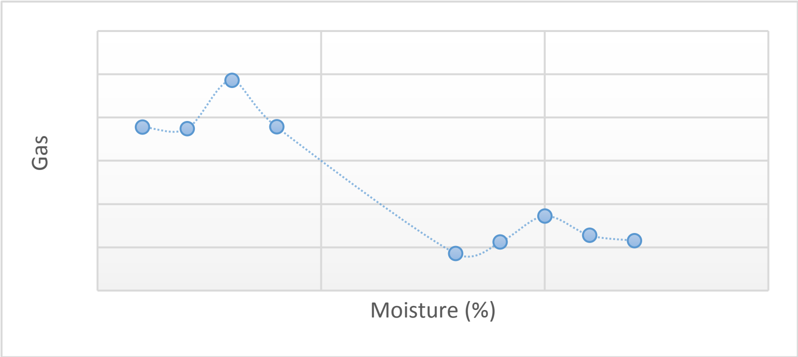

Figure 6.16. Impact of the paper moisture on gas consumption. Data is referring to B paper in combination with IF format and resin B13. Plot based on 28 paper rolls; Fixed Line speed.

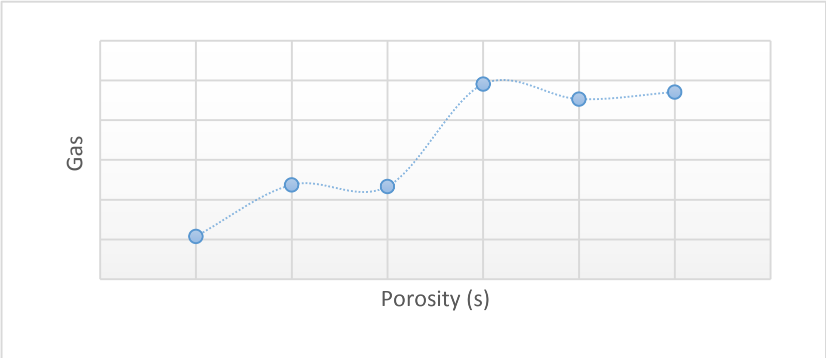

Figure 6.17. Impact of the paper porosity on gas consumption. Data is referring to B paper in combination with IF format and resin B13. Plot based on 28 paper rolls; Fixed Line speed.

For resin F30 the same is observed. By keeping the paper moisture and porosity on the lower level, increases in the output together with less gas consumption can be achieved, no matter which paper supplier is used.

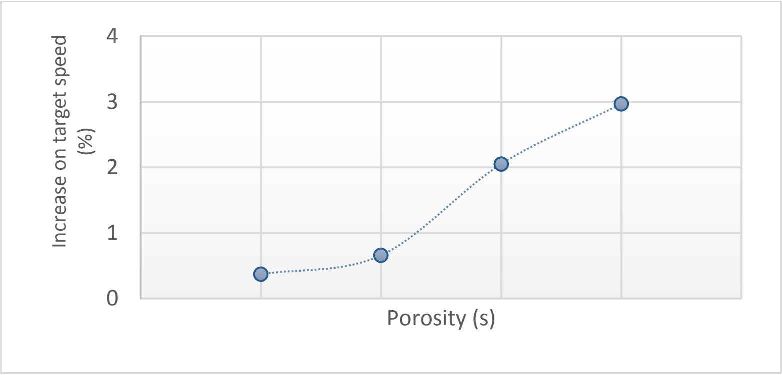

Figure 6.18. Impact of the paper porosity on line speed. Data is referring to A paper in combination with SF format and resin F30. Plot based on 31 paper rolls.

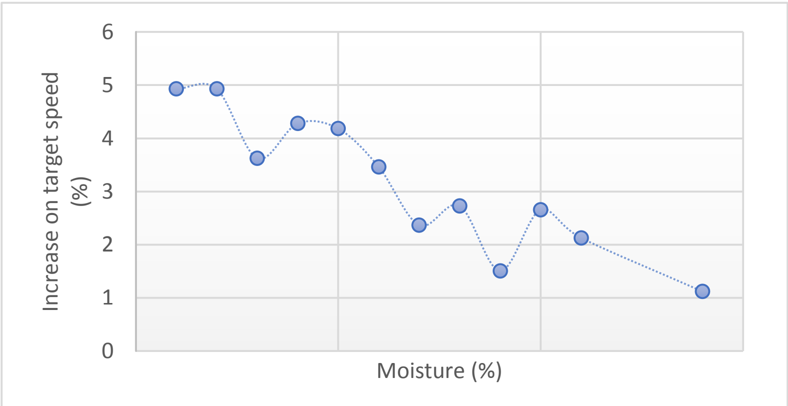

Figure 6.19. Impact of the paper moisture on line speed. Data is referring to B paper in combination with IF format and resin F30. Plot based on 31 paper rolls.

6.4. Proposal for adjustments in the Kraft paper specifications

Based on the information from the previous section, a proposal to adjust the Kraft paper specifications is presented. By monitoring the paper critical properties and reacting accordingly, two key process performance indicators can be improved, i.e. output and gas consumption. No extra investments in equipment are needed. Eventually a different way on how raw material inspection is done would have to be adopted. Currently the paper rolls are checked just before being used. That does not allow enough reaction time in case some critical property is out of spec.

The following tables give an indication of the potential increase in the selected key process performance indicators (it is a comparison between the worst case scenario and the best one). Only data for line speeds equal or higher than the target was considered and the results were averaged for all formats. In total the data contained 116 rolls of B paper with resin F30 and 128 with B13, and 97 rolls of A with resin B13 and 67 with F30.

If the paper control is applied and only A paper with porosity ranging from 0,42 to 0,56 is used, the potential increase in the process output can be as shown in the table below.

Table 6.1. Example of the increase in output by controlling A paper porosity (worst case: porosity is 0,35).

	B13		**F30**	
Porosity (s)	0,42	0,56	0,42	0,56
Output increase (%)	1,3	3,6	1,7	2,9
Rejects (%)	4,0		6,1	

For A paper an increase of ca. 4% in the output can be achieved by optimising the porosity, and a maximum of 6% of rolls will be outside this new specification range. For B paper, the rolls that are not optimal in porosity for one resin type can be used for the other type. This decreases the number of potentially rejected rolls if the specification is adjusted to the new range.

Table 6.2. Example of the increase in output by controlling B Kraft paper porosity. (worst cases: for resin B13 - porosity is 1; for resin F30 - porosity is 0,56).

	B13		**F30**	
Porosity (s)	0,56	0,7	0,7	0,91
Output increase (%)	1,4	1,1	2,9	3,3
Rejects (%)		3,9		

Table 6.3. Example of the increase in output by controlling Kraft paper moisture.

	A + resin B13		**B+ resin F30**	
Moisture (%)	0	0,6	0	0,6
Output increase (%)	5,3	1,8	4,8	2,5
Rejects (%)	4,1		2,1	

By controlling the moisture within a tighter range (from 0 until 0,6), increases up to 5% can be achieved when combining A paper with resin B13 and B paper with resin F30. There would be no more than 4% of rejected rolls.

For calculating the gas consumption savings, a fixed line speed was used. The cost saving related to the gas consumption is the difference between the lowest gas values observed in the data for the property at the minimum and maximum limits of the corresponding proposed specification. For B paper the results were inconclusive for both paper properties. For A paper no significant saving due to moisture could be found, but for porosity the results were positive and shown in the table below.

Table 6.4. Example of energy saving by controlling A kraft paper porosity. For resin B13 - line speed fixed (24 rolls); for resin F30 – line speed fixed (32 rolls) .

Resins	**B13**		**F30**	
Porosity	0,42	0,56	0,42	0,56
Cost saving (%)	15,3	0	12,5	0,6

6.5. Conclusions

The process performance has variations caused by changes in the paper porosity and moisture, whereas changes in the other measured paper properties (thickness, density, grammage) didn´t show to have a significant influence on the process. The impact of the critical properties (porosity and moisture) depends somehow on the paper supplier and on the impregnated resin type, but in general the best performance of the process can be achieved as the paper has lower moisture content and porosity.

Controlling the critical paper properties will give the opportunity to increase the process output up to 5%. For A paper, there is still the chance to decrease up to 15% the gas consumption by controlling the paper porosity with both studied resin types (B13 and F30).Therefore, adjustments in the current paper specifications for porosity and moisture were proposed

Chapter 7

In this final chapter the main conclusions of this thesis are presented as well as suggestions for future work.

7.1. Conclusions

The main objective of this thesis was to access the variability of one of the raw materials of an industrial paper impregnation process, i.e. the Kraft paper, and find out if the quality variations would affect the process performance.

The Kraft paper is supplied by two different paper manufacturers, A and B. It was observed that paper delivered by B has higher density and lower thickness and porosity, compared to A paper. The variability found in the paper quality measurements is responsible for 25% of the A rolls to be out of specification (mainly related to porosity variations), whereas for B only 17% fail the specification (mainly due to grammage variations).

The process performance was analysed with multivariate data analysis and it could be seen that two major factors are dominating: paper format and resin type. Only by isolating these factors the influence of the paper quality on the process performance could be seen and two critical quality properties of the paper identified: moisture and porosity. These have a significant impact on the ability of the paper to get impregnated with resin. In general the best performance of the process can be achieved as the paper has lower moisture content and porosity. The process performance was evaluated by selecting two key process performance indicators: output and gas consumption. The first should be maximised and the second minimised.

Based on the found correlations between the paper properties and the process performance, a proposal to adjust the current specifications for paper moisture and porosity was presented. Depending on the paper supplier and the resin type, an increase of up to 5% in the output and a decrease of up to 15% in the gas consumption can be achieved if the supplied paper falls into the new specifications.

7.2. Future work

The schedule of this study was very tight. Only data from 3 months was analysed. During this time it was not possible to gather enough data regarding two of the four resin types (B21 and F33), as well as the third paper supplier (C). A complete study would need to include this missing information as well.

The impact of the resin quality variations has never been so far quantified. It is known from a qualitative perspective that the performance of the process is dominated by the resin type, but within each type the impact of the variations remains unknown.

The suggested changes in the specifications ranges need to be discussed with the paper manufacturers, first to evaluate their capability in supplying the paper according to the new ranges and second to verify if that would have an impact on the costs. Afterwards, the logistics around the paper delivery and quality inspection would have to be modified. The paper rolls would have to be inspected right after delivery in order to assure that only material within the new specification ranges is used in the most optimal way (i.e. in combination with the favourable resin type). This may request extra resources, such as operators, time and eventually storage room.

References

[1] http://www.trespa.com/us/history (consulted in 15/08/2015)

[2] Holik, H. (2006). *Handbook of Paper and Board.* WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

[3] http://www.emco-leipzig.com/viomatrix/imgs/emcoppadecor_e.pdf (consulted in 21/08/2015)

[4] http://www.tappi.org/content/SARG/T460.pdf (consulted in 21/09/2015)

[5] Gardziella, A., Pilato, L. & Knop, A. (2000). *Phenolic Resins: Chemistry, Applications, Standardization, Safety and Ecology*. Christiane Messerschmidt: Rheinau.

[6] Otto, M. (1999). *Statistical and Computer Applications in Analytical Chemistry*. Wiley – VCH: Weinheim.

[7] Eriksson, L., Johansson, E., Kettameh-Wold, N., Trygg, J., Vikström, C. & Wold, S. (2006). *Multi- and Megavariate Data Analysis.* Umetrics Academy: Sweden.

[8] Beebe, R. & Pell, R. (1998). *Chemometrics: A practical Guide*. John Wiley & Sons. Inc.

[9] Santorius (2013). *User Guide to BioPat®Simca.* RKS Umetrics AB.

[10] http://www.paperonweb.com/paperpro.htm (consulted in 25/09/2015).