LAPPEENRANTA-LAHTI UNIVERSITY OF TECHNOLOGY LUT
School of Engineering Science
Chemical Engineering

Master’s thesis

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Quality optimisation of the overall paperboard manufacturing process for a rotogravure printing

Examiners: Professor Tuomas Koiranen
Assistant Professor Kristian Melin

ABSTRACT

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Quality optimisation of the overall paperboard manufacturing process for a rotogravure printing

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111 pages, 30 figures, 25 tables and 1 appendix
Examiners: Professor Tuomas Koiranen and Assistant Professor Kristian Melin
Supervisor: MSc Matti Viitala

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Thesis has been done for Metsä Board Tako board mill as part of the project to study the possibilities of an artificial intelligence analytics in quality optimisation of the overall paperboard manufacturing process towards a rotogravure printing machine. Purpose of the project was to find high-quality correlations between controlled variables of the overall paperboard production process and register stability measured at the rotogravure printing machine. Register stability refers to the alignment between printing units. The overall process includes also transportation and warehousing conditions of the paperboard reels.

In the experimental part, data collected from the board machine, winder, transportation and warehousing, and rotogravure printing machine were analysed by an artificial intelligence analytics supplier Valmet. Correlations between the controlled variables of the overall paperboard manufacturing process and register stability measured at the rotogravure printing machine were researched from the trial order and additionally from certain normal customer orders. Data analysis found correlations between the overall paperboard manufacturing process controlled variables and register stability measured at the rotogravure printing machine but due to the amount and quality of the data, results were evaluated to be approximate. Paperboard manufacturing process, rotogravure printing process, and paperboard warehousing and transportation were discussed in the literature review. Based on the gained knowledge in the literature review, findings of the data analysis were examined. In conclusion plan for the future work was established.

As result of the data analysis, correlations were found between the controlled variables of the overall paperboard manufacturing process and register stability measured at the rotogravure printing machine. Correlations were found from the board machine and winder process parameters, and from the transportation and warehousing conditions.

TIIVISTELMÄ

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Kemiantekniikka

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Kartonginvalmistuksen kokonaisprosessin laadunoptimointi syväpainokoneelle

Diplomityö
2022
111 sivua, 30 kuvaa, 25 taulukkoa ja 1 liite
Tarkastajat: Professori Tuomas Koiranen ja Apulaisprofessori Kristian Melin
Ohjaaja: DI Matti Viitala

Hakusanat: taivekartonki, syväpaino, laadunoptimointi, tekoäly

Diplomityö on tehty Metsä Board Takon kartonkitehtaalle osana projektia, jossa tutkittiin tekoälyn mahdollisuuksia kartonginvalmistuksen kokonaisprosessin laadunoptimoinnissa asiakkaan syväpainokoneelle. Projektin tavoitteena oli löytää laadukkaita korrelaatioita kartonginvalmistuksen kokonaisprosessin säätösuureiden ja painokoneella mitattavan rekisterivakauden välillä. Rekisterivakaudella viitataan painoyksiköiden väliseen kohdistukseen. Kokonaisprosessiin sisällytettiin myös kartonkirullien kuljetuksen ja varastoinnin aikaiset olosuhteet.

Kokeellisessa osassa analysoitiin kartonkikoneelta, pituusleikkurilta, kuljetusketjusta ja painokoneelta kerättyä dataa tekoälyanalytiikan toimittajan Valmetin toimesta. Korrelaatioita kartonginvalmistuksen kokonaisprosessin säätösuureiden ja painokoneella mitattavan rekisterivakauden välillä etsittiin erillisestä koeajosta ja lisäksi tietyistä normaaleista asiakastilauksista. Data-analyysin perusteella löytyi korrelaatioita kartonginvalmistuksen kokonaisprosessin säätösuureiden ja syväpainokoneella mitatun rekisterivakauden välillä, mutta datan määrän ja laadun vuoksi tulokset arvioitiin suuntaa antaviksi. Kirjallisuusosassa käsiteltiin kartongin valmistusprosessia, syväpainoprosessia sekä kartongin varastointia ja kuljetusta. Data-analyysin tulokset käytiin läpi kirjallisuusosassa tehtyihin havaintoihin verraten. Lopuksi tehtiin suunnitelma, miten tutkimusta kannattaisi jatkaa tulevaisuudessa.

Data-analyysin tuloksena löydettiin korrelaatioita kartonginvalmistuksen kokonaisprosessin säätösuureiden ja painokoneella mitatun rekisterivakauden välillä. Korrelaatioita löydettiin kartonkikoneen ja pituusleikkurin prosessiparametreista sekä kuljetuksen ja varastoinnin aikaisista olosuhteista.

LIST OF ABBREVIATIONS

BCTMP	Bleached chemi-thermomechanical pulp
CMYK	Cyan, magenta, yellow, black
CTMP	Chemi-thermomechanical pulp
DCS	Distributed control system
ERP	Enterprise resource planning
ESA	Electrostatic assist
FBB	Folding boxboard
GW	Ground wood
HW	Hard wood
IQR	Interquartile range
LDPE	Low density polyethylene
LNP	Long nip press
MES	Manufacturing execution system
MG	Machine-glazing (cylinder)
mMPC	Multivariate model prediction control
MSP	Metered size press
PA	Polyamide
PET	Polyethylene terephthalate
PGW	Pressure ground wood
QCS	Quality control system
SW	Soft wood
TMP	Thermomechanical pulp
WIS	Web inspection system
WMS	Web monitoring system

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1. INTRODUCTION

The overall manufacturing process of the folding boxboard includes multiple controlled variables, which are controlled for achieving the wanted quality properties for each purpose. Traditionally feedback to quality and process controlling has come from the folding boxboard machine on-line and off-line quality measurements. (Fadum, 2009) New way of improved quality and process control, and optimisation can include data also outside a board mill. Data for the quality and process controlling can be collected for example from transport chain and customer's process as well. Data collected from the overall manufacturing process can be utilised in the quality optimisation of the paperboard manufacturing process. Artificial intelligence analytics and methods enables new way of analysing enormous amounts of data and for finding interesting correlations between production batches, which have been behaving differentially in customer's process for example in quality or runnability wise. Utilising this kind of modern technology and analytics, it is possible to optimise product quality and production process more efficient than earlier.

1.1. Aim and scope of the study

Aim of the study was to explore the possibilities of an artificial intelligence analytics in quality optimisation of the overall folding boxboard manufacturing process, that register stability at a rotogravure printing can be improved. Study was done for Metsä Board Tako mill in close cooperation with paperboard converting customer, which is afterwards called in this thesis as the converter. Artificial intelligence analytics was supplied by a technology company Valmet, which is afterwards called in thesis as Valmet.

Data were collected from the board machine, winder, transport chain and rotogravure printing machine. Transport chain refers to conditions during the transportation and warehousing of the paperboard reels. From the board machine and winder, all the process data were available for the data analysis. Data logger devices were installed inside the paperboard reel packages to collect information from supply chain conditions. Moisture and temperature measurement sensors were installed in the rotogravure printing machine before and after the printing units for collecting both cross and machine direction data. Also, other process parameters like for example speed and tension were available from the rotogravure printing machine.

Data collection part was taking place in October-November 2021, and after the planned data amount was collected, it was analysed with an artificial intelligence analytics and methods. Data analysis was done by Valmet. As result of the data analysis, Valmet reported correlations found between the register stability at the rotogravure printing machine and the controlled variables of the overall paperboard manufacturing process. Results of the data analysis were evaluated based on the findings in the literature review section. Based on the evaluation of the data analysis results, plan for the future work was established.

LITERATURE REVIEW

2. PAPERBOARD MANUFACTURING PROCESS AND THE MAIN CONTROLLED VARIABLES

Folding boxboard (FBB) is a paperboard which is classified into packaging boards. Folding boxboard is used for packing food, alcohol, cosmetics, drugs and cigarettes. Folding boxboard is typically consisted of multiple layers as shown in Figure 1, which are meant to give wanted properties with as little costs as possible for the folding boxboard. Middle layer is typically made from mechanical or bleached chemi-thermomechanical pulp (BCTMP) and a mill broke. Broke pulp is refined from a folding boxboard, which is not suitable for converting and thus have been rejected. Some amount of broke pulp is constantly formed for example by trim waste and during a paperboard web breaks at the board machine. Top layers are typically made from bleached chemical pulps. Fillers can be used in all the layers of folding boxboard to replace fibre raw materials. Folding boxboard is typically coated on another or both sides. Grammage varies from 160 to over 600 g/m2. (Emblem & Emblem, 2012, Paulapuro, 2000, Münch & Holik, 2006)

In this section are presented folding boxboard manufacturing process starting from a stock preparation ending to a reel packaging. The main controlled variables and their functions are presented in each described process.

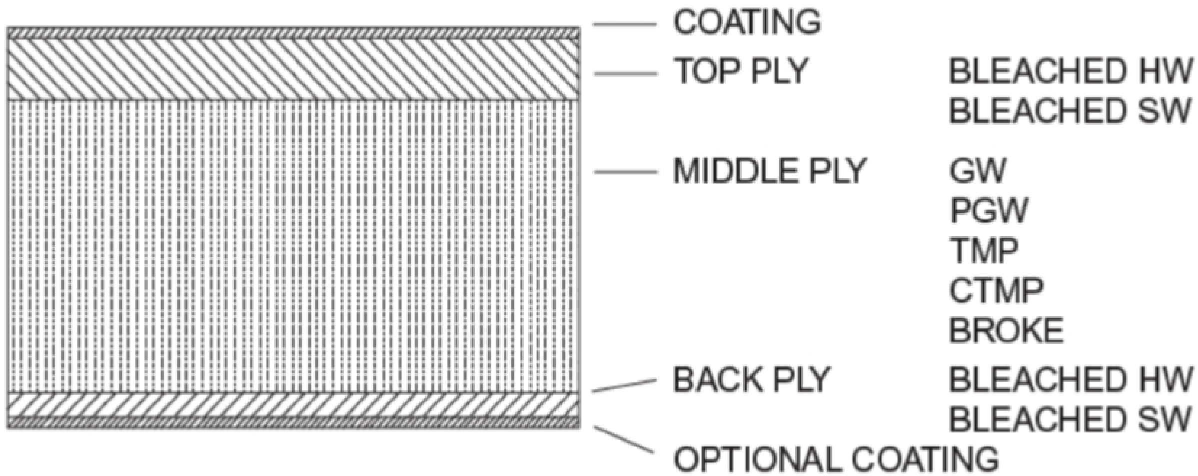

Figure 1 Typical structure of the folding boxboard (Paulapuro, 2000)

2.1. Paperboard making in short

Board machine can have length of 350 meters if on-line coating and final calendering are included and machine width can be up to 10 meters. Board machine is divided into different sections like a wire section, press section, drying, surface sizing, coating, calendering and reeling. (Münch & Holik, 2006) Visible paperboard making starts from wet end, more precisely from a headbox. Main task of the headbox is spreading a fibre pulp suspension as evenly as possible across the machine width on the wire. Water content at this stage is around 99 %. Water is removed from the fibre pulp suspension on the wire section mostly by draining. Typically, all the layers of paperboard are produced with separate wires as shown in Figure 2. After the wire section water content in a paperboard web is approximately 80 %. (Paulapuro, 2008) Next unit process is a press section, where a paperboard web is led through the press nips. Main tasks of the press section are water removal, surface smoothening and increasing of the wet strength before a drying section. After the press section water content in paperboard web is around 50 %. (Paulapuro, 2008) Drying section starts after the press section. Main task of the drying section is to remove enough water from a paperboard web with as little energy consumption as possible. Some of the folding boxboard machines has machine-glazing cylinder (MG), which is large drying cylinder typically located after the first drying groups. Main purpose of the MG cylinder is drying, but it is also improving paperboard gloss and smoothness. (Karlsson, 2010)

Surface sizing unit is typically located before a coating section, because it closes the paperboard surface and therefore coating penetration into the paperboard web can be controlled. Surface sizing improves surface strength, stiffness and Z-directional strength. (Paltakari, 2009) After the surface sizing a paperboard web is coated to achieve better printability and visual appearance. Coating can be done also off-line with a separate coating machine. (Paltakari, 2009) Typically the folding boxboard machine has two calenders, a pre-calender before the coating section and a final calendering before reeling. Purpose of the pre-calendering is to control a cross-machine directional thickness profile before a paperboard web enters to coating section. Final calendering is also used for the cross-machine directional thickness control and it improves gloss as well. (Rautiainen, 2010) Reeling is the last process in the board machine. Main purpose of the reeling is to form uniform machine reels for the coming finishing processes like winding or sheet cutting. This part of the folding boxboard machine is typically called as dry end. Moisture content of the finished product is typically between 5-8 %. (Rautiainen, 2010) Above mentioned processes are described more deeply in the following sections. Typical folding boxboard machine layout is shown in Figure 2.

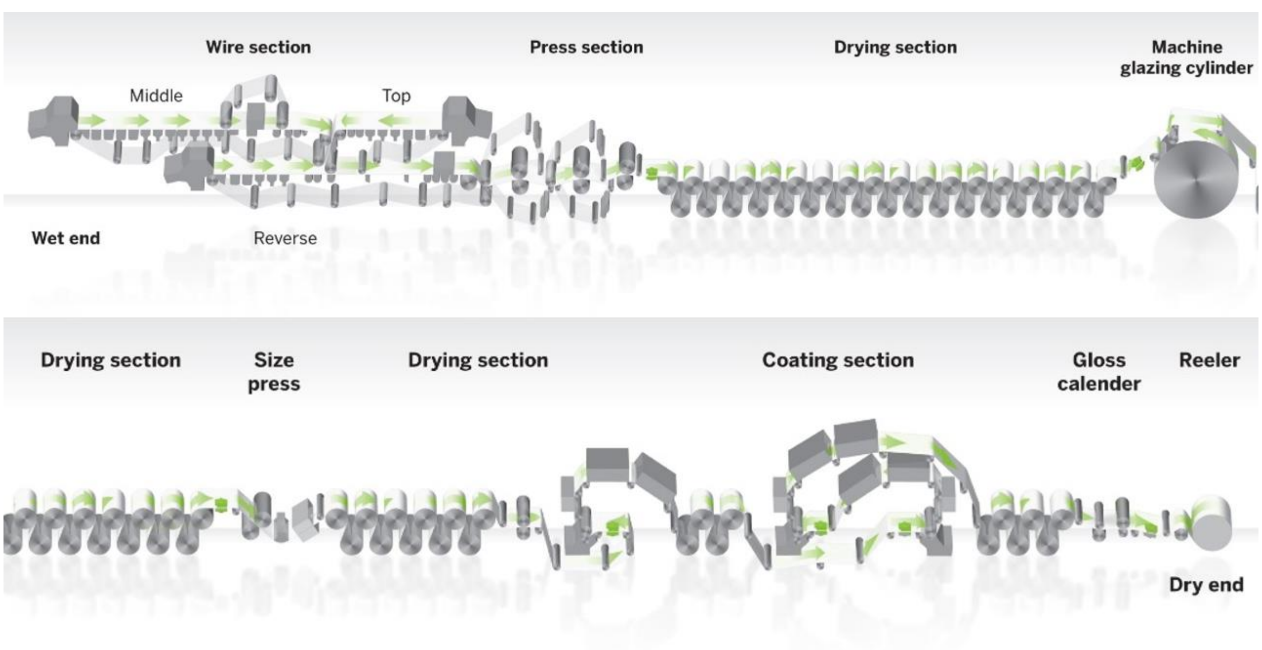

Figure 2 Layout of the typical folding boxboard machine (Metsä Board, 2021b)

2.2 Stock preparation

Process starts with a slushing of pulp bales in a pulper. The pulp bales are exposed to mechanical forces in a hot water, and they start to break up. Main purpose of the slushing is to fully separate, wet and to make fibres flexible before moving forward in the process. After the slushing the pulp slurry should not have visible flakes or pulp bundles. When talking about an integrated mill, the slushing is no needed, because the pulp slurry comes directly from a pulp mill via pipe. At this point the pulps fibre consistency is approximately 3-5 %. In this study by the consistency is described the relative amount of fibres per gram of fibre-water suspension. (Bajpai, 2018, Mujumdar, 2014, Ek, Gellerstedt & Henriksson, 2009)

2.2.1 Refining

After the pulp slurry is created by the pulping, next process stage is a refining. Refiners can be divided into two types, conical and disc type. Example layouts of the above-mentioned refiners are shown in Figure 3. There are different mechanical solutions inside the category available depending for example on the refined volumes and pulp types. In the refining wood fibres are exposed to mechanical stress. Mechanical stress is created in a refiner between a stationary and rotating disc. Main targets in the refining are improving strength properties and formation. Strength properties can be improved by fibrillating refining, which means treating the fibres so that they are fibrillating and becoming more flexible. Wood fibres are also forming new surfaces by fibrillation. (Bajpai, 2018) Fibrillating refining can be achieved, when the bars in a refiner plate are as wide as grooves. Better formation is achieved by cutting the fibres. Formation improving refining can be achieved, when the bars in a refiner plate are clearly narrower than the grooves. Refining process is basically controlled by increasing or decreasing the gap between the stator and rotor discs. Also pulp concentration has an effect to refining result. Higher the consistency is more fibres are between the refiner bars resulting in more gentle refining. Refining is one of the most important single factors affecting on stock quality and the paperboard properties. Typically, different pulp fractions are refined differentially to achieve optimal fibre properties for each purpose. (Ek, Gellerstedt & Henriksson, 2009). Precise control of the fibre pulp suspension consistencies and flows in a stock preparation and further in a short circulation are one of the most crucial factors for the folding boxboard quality. In practice it means minimizing or preventing any slow or fast variations coming from the mentioned processes. Complexity of the uniform production can be illustrated, when thinking that uniformity needs to be achieved in machine and cross-machine direction starting from a millimeter scale to several kilometers. In Table 1 are shown an example of different frequencies of machine direction variations. In Table 2 are shown the main controlled variables in the stock preparation. (Leiviskä, 2009)

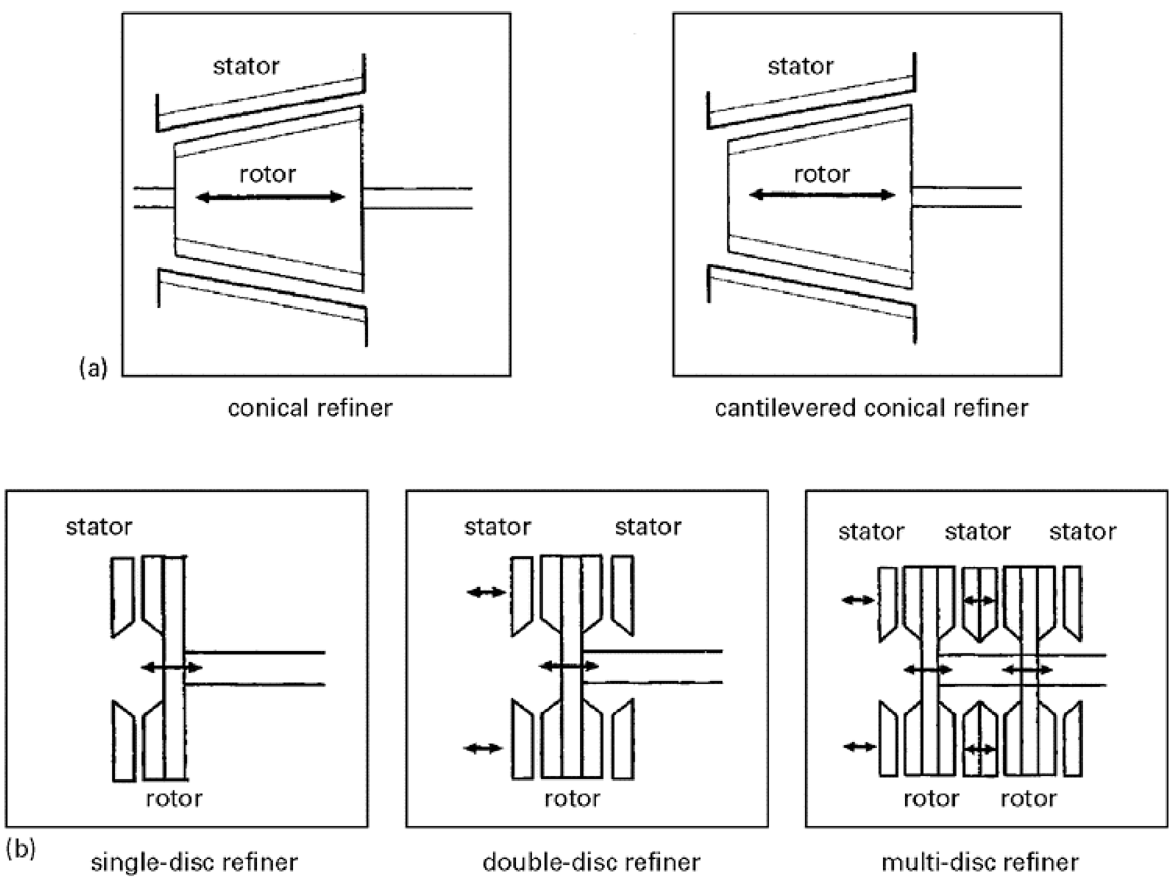

Figure 3 The conical (a) and disc type (b) refiner illustrated with different mechanical layouts (Ek, Gellerstedt & Henriksson, 2009)

Table 1 Different frequencies of the machine direction variations (Ek, Gellerstedt & Karlsson, 2009)

Frequency 1/s	Wavelength m	Random Variations	Periodic Variations	Equalizing Measures
0.001	10,000	Stock Variations		Control of Thick Stock Dosage
0.01	1,000			
0.1	100		Pressure Pulsa-tions	
1	10	Instability in Head-box		Equalization in Machine Chest
10	1			
100	0,1			
1,000	0.01	Fibre Flocculation	Wire Mark	
10,000	0.001			

Table 2 The main controlled variables in the stock preparation (Ek, Gellerstedt & Henriksson, 2009, Leiviskä, 2009)

Process	Controlled variable	Main impact	Definition	Unit
Stock preparation	Stock consistency	Number of fibres carried, runnability	Dry solid content of a fibre pulp suspension	w-%
	Thick stock flow	Number of fibres carried, runnability	From slushing to a short circulation	l/s
Refining	Power	Degree of refining	Typically controlled by specific energy consumption per ton	kWh/t
	Stock consistency	Degree of refining	Dry solid content of a fibre pulp suspension	w-%
	Gap between the refiner discs	Degree of refining	Effects on the degree of refining	mm
	Freeness	Measurement	Measurement for the degree of refining	ml

2.3 Short circulation

After the refining section a pulp slurry is pumped through mixing and machine chests to a short circulation. All the paperboard layers have typically a separate short circulations and process equipment may vary. After the machine chest is located a basis weight valve, which is adjusting the right amount of pulp slurry according to a grammage of the paperboard produced. This thick stock is pumped into a wire pit at consistency of 3 – 4 %. In the wire pit thick stock will be mixed with a white water which is circulating back from the wire section. After a dilution, headbox consistency at 0.1 - 1.5 % can be achieved. (Paulapuro, 2008) The need of a dilution is connected to strength requirements of the final product. Lower consistency allows better strength properties by improved forming of the fibres. Diluted stock is pumped with a fan pump forward towards to the headbox. Pulp is led through to several cleaning stages before entering to the headbox. Typically, in the short circulation of a middle layer is a centrifugal cleaning plant, where the stock is cleaned by vortex forces. At this stage are removed all the unwanted particles like sand, hard fibre flocs, metal particles, stickies and pitch. (Ek, Gellerstedt & Henriksson, 2009) After the centrifugal cleaning, the stock is pumped through a deaeration system, which is removing air from the stock. Before reaching the headbox, stock is pumped through a machine screen. Machine screen is a pressure screen, and its slot size is typically 1.2 – 2.5 mm. Function is to remove rest of the foreign particles from the stock, which might harm the headbox or other machine components. Machine screening also gives de-flocculating effect to the stock before entering to headbox. It is important to keep the stock flow through the machine screen as even as possible to prevent unnecessary pressure variations forming in the headbox. The main controlled variables in the short circulation are shown in Table 3. Principle of the short circulation is shown in Figure 4. (Ek, Gellerstedt & Henriksson, 2009)

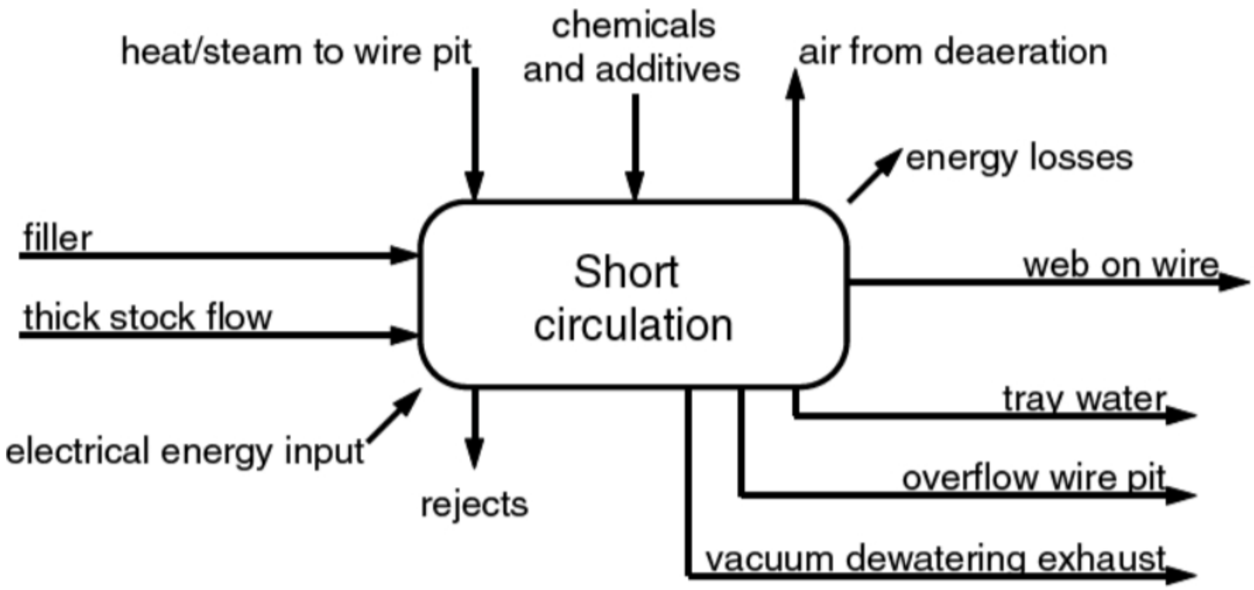

Figure 4 Principle of the short circulation (Paulapuro, 2008)

Table 3 The main controlled variables in the short circulation (Paulapuro, 2008, Ek, Gellerstedt & Henriksson, 2009)

Process	**Controlled variable**	**Main impact**	**Definition**	**Unit**
Short circulation	Stock consistency	Number of fibres carried, runnability	Dry solid content of a fibre pulp suspension	w-%
	Stock pump power	Thick stock flow, grammage	Located between a machine chest and wire pit	% of max power
	Basis weight valve opening	Thick stock flow, grammage	Located between a machine chest and wire pit	%
	Fan pump power	Diluted stock flow	Diluted stock flow from a wire pit to headbox	% of max power

2.4 Headbox and wire section

Headbox is one of the main single process components in the board machine. Example of a headbox is shown in Figure 5. In addition to a fibre pulp suspension consistency in a headbox, floc breaking by generated turbulence is an essential process effecting on the paperboard web formation. Floc breaking in the vastly used hydraulic headboxes are based on the convergent flow tubes, which are creating the turbulence based on a fibre pulp suspension acceleration. Some slow paperboard machines are still equipped with rectifier roll headboxes, which are based on the mechanically created turbulence. (Biermann, 1996) In the case of hydraulic headboxes adjustments on the floc breaking efficiency are mainly made by changing the flow tube geometry. In the rectifier roll headboxes, for example the number, size, speed and geometry of the rolls are affecting on the floc breaking power.

Main task of the headbox is spreading the stock as evenly as possible on a wire across the machine width. It means, that in the headbox should be the same supplying pressure from a drive side to operating side. At the same time pulp suspension is accelerated to the wire speed as approximately 10-15 mm high jet. With the headbox are controlling a fibre orientation and cross-machine directional dry weight profile. With the fibre orientation is described how the fibres are aligned in forming paperboard web. When the pulp suspension flows from the headbox in direction of the moving wires, fibres tend to align themselves in the flow direction. Because of this phenomenon, approximately twice as many fibres are aligned into the machine direction than into the cross-machine direction. Fibre alignment has an influence on the paperboard behavior to changes in surrounding conditions like temperature or relative humidity. When the paperboard is exposed to changing surrounding conditions, wood fibres will expand or shrink 3-4 times more compared in their thickness than in length, which has a strong effect for example on the paperboard cross-machine directional curl. (Paulapuro, 2008, Järvinen, 2016) Paperboard can curl also diagonally and it is called as twist. Twisting can appear for example when between the paperboard layers has remarkable differences in the fibre orientation. (Bortolin, Gutman & Nilsson, 2006)

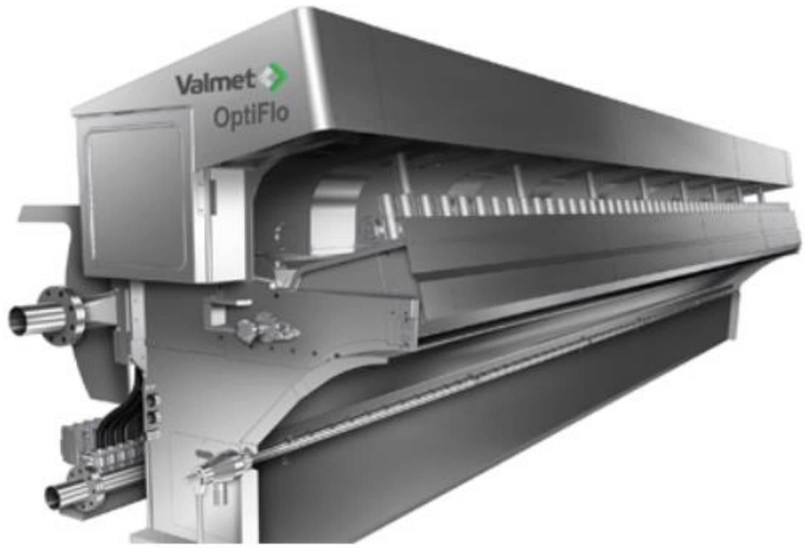

Figure 5 Valmet OptiFlo headbox (Valmet, 2021b)

Main task of a wire section is removing water from the stock by draining. At the wire section are produced relatively high hydrodynamic forces on the paperboard web for improving the water removal. Wire is a permeable filter fabric, which is in a key role when discussing about the dewatering. (Carlsson, Söderberg & Lundell, 2010) In the past the wires were made from a metal like for example bronze, but nowadays they are usually made from polyethylene terephthalate (PET) or polyamide (PA). (Biermann, 1996)

In terms of dewatering more efficient wire type compared to the Fourdrinier wire is a twin wire, in which the paperboard web goes through two wires, which are located above and below of the paperboard web. Dewatering is more efficient, when it happens in two directions. It enables also better formation mainly because of the faster dewatering. So called former wire can be installed on above the Fourdrinier wire, which is then called a hybrid former. This is a typical construction in three-layer folding boxboard machines for the middle layer. (Paulapuro, 2008) Hybrid former improves the formation compared to the Fourdrinier wire alone. In addition, there are different types of wire section types available for paper and board machines. Roll former is based on the twin-former design. In the roll former there are two wires applied on a one rotating roll, and the headbox is usually located relatively close to a forming section. (Ek, Gellerstedt & Henriksson,

2009) One invention is so called blade forming application, which has been further developed from the roll forming. With the blade forming it is possible to achieve better formation based on the vibrating dewatering pressure. (Ek, Gellerstedt & Henriksson, 2009) Roll blade former can be seen as third development stage after the roll former and blade former. Even better formation can be achieved with this type of forming, and it is based on multiple forming blades located below the wire. With these forming blades it is possible to create even more varying and vibrating dewatering pressure on the formed paperboard web. (Ek, Gellerstedt & Henriksson, 2009) Formation number F can be used for describing the formation. Formation number represents the factor of small scale grammage variation and it is shown by Equation 1. (Ek, Gellerstedt & Henriksson, 2009):

$$F = \sigma(W)/W_m \tag{1}$$

where $\sigma(W)$ standard deviation, g/m^2,
W_m average grammage, g/m^2.

Main controlled variables at the wire section, like for example vacuum of a suction box, are related to the water removal to achieve a wanted retention level and sufficient dry content level before a press section. High and stable retention level has many benefits. High and stable retention level leads to lower white-water consistency, which can be seen as better board machine runnability. Stable runnability leads to better paperboard quality as well. After the wire section when all the paperboard layers are formed together water content in the paperboard web is approximately 80 %. (Paulapuro, 2008). The main controlled variables of the headbox and wire section are shown in Table 4. The short circulation retention RS can be calculated by Equation 2. (Ek, Gellerstedt & Henriksson, 2009):

$$R_S = \frac{Q_0 c_0}{Q_1 c_1} = \frac{Q_1 c_1 - Q_2 c_2}{Q_1 c_1} = 1 - \frac{Q_2 c_2}{Q_1 c_1} \quad (2)$$

where Q flow rate, l/s,

c component concentration, g/l.

0 material flow into short circulation

1 material flow into headbox

2 white water flow

Table 4 The main controlled variables of the headbox and wire section (Paulapuro, 2008, Ek, Gellerstedt & Henriksson, 2009)

Process	Controlled variable	Main impact	Definition	Unit
Headbox	Jet speed	Jet to wire ratio, fibre orientation	Jet speed divided by a wire speed	#
	Pressure	Jet speed	Pressure inside the headbox	mbar
	Stock consistency	Formation	Dry solid content of a fibre pulp suspension	w-%
	Slice opening	Stock consistency, CD flow profile	Position of a top slice and apron plate	mm
Wire section	Vacuum	Water removal, formation	Foil boxes, suction boxes, couch rolls	mbar
	Wire speed	Jet to wire ratio, fibre orientation		m/min

2.5 Press section

Paperboard web comes to a press section after the wire section. At the press section water is removed from the paperboard web by pressing it between press rollers. Press rollers are typically covered with press felts, which main function are to transfer water away from the paperboard web. Typically, board machines have 1 to 4 nips through the press section. (Paulapuro, 2008) Nips are usually double felted, which means that both press rollers are covered with a felt. In addition to conventional hard press rollers, there are also so-called shoe press rollers used. With the shoe press it is possible to create longer nip and therefore more efficient water removal. Main tasks of the press section are water removal, surface smoothening and increasing of the wet strength before a drying section. (Paulapuro, 2008) The main controlled variable during the production is the nip load. Higher nip load means better water removal to a certain point, but too high nip load can create remoistening phenomenon. Also nip dwell time is a remarkable process variable. Dwell time means how long the paperboard web is under nip pressure. Press impulse I can be described by Equation 3 in the case of varying pressure during pressing (Ek, Gellerstedt & Henriksson, 2009):

$$I = \int_0^{tpress} p(t)dt \tag{3}$$

where tpress press time, s,

p pressure, kN/m^2.

Other significant process variables are temperature, ingoing moisture content of the paperboard web and sheet properties. More the wet pressing is used, less drying energy is needed at drying section. On the other hand, more the wet pressing is used, less bulky the paperboard will be. In folding boxboard, top layer of the paperboard is wanted to be as smooth as possible. For this purpose, last nip in the press section has typically only below roller is covered with felt, but an above roller is without the felt. With this kind of a nip, top layer of the paperboard web will be smooth but not so compacted as the felt side. After the press section, water content in the paperboard web has decreased from 80 % to 50 %. (Paulapuro, 2008, Ek, Gellerstedt & Henriksson, 2009). The main controlled variables in the press section are shown in Table 5.

Typical press section of the folding boxboard machine is shown in Figure 6. First nip is a long nip press (LNP), second nip is a shoe press and third one is a smoothening press.

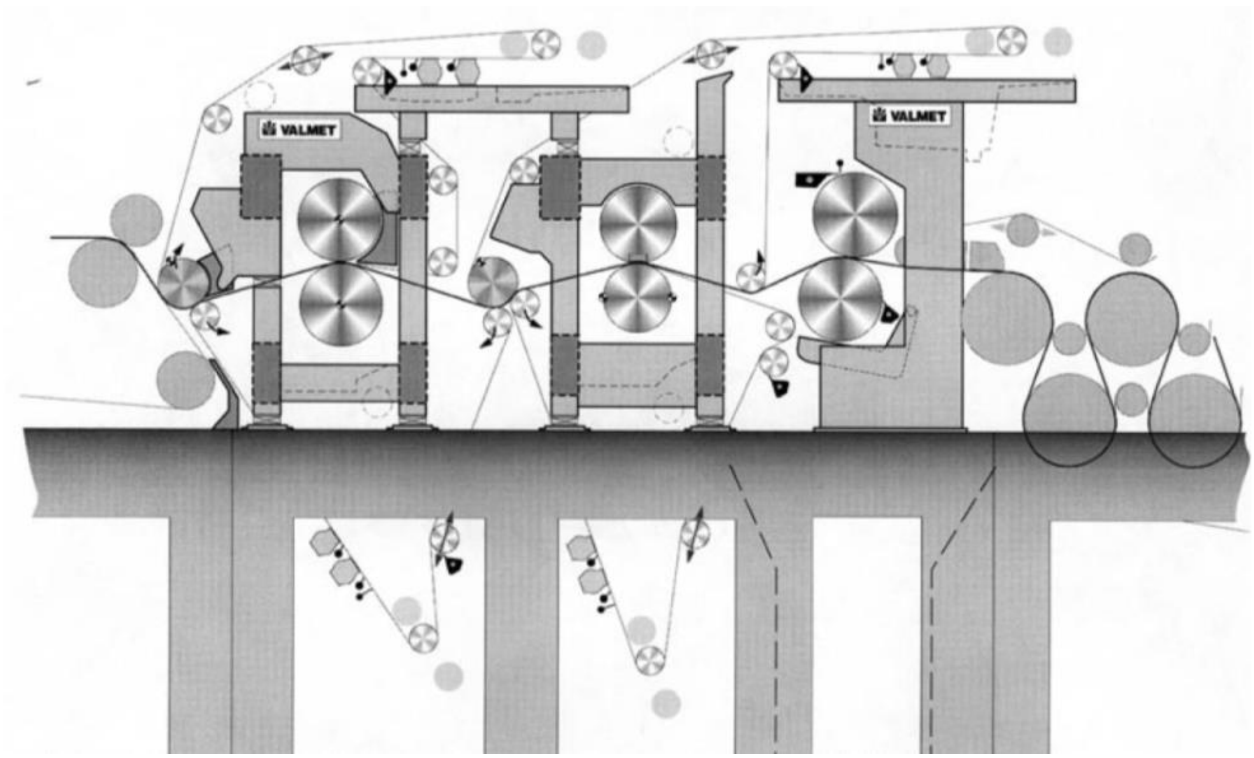

Figure 6 Typical press section of folding boxboard machine (Paulapuro, 2008)

Table 5 The main controlled variables in the press section (Paulapuro, 2008, Ek, Gellerstedt & Henriksson, 2009)

Process	Controlled variable	Main impact	Definition	Unit
Press section	Nip load	Water removal, smoothness, thickness	Press force between press rollers	kN/m
	Vacuum on press felts	Water removal	Water removal from press felts	mbar

2.6 Drying

Main task of a drying section is to remove enough water from the paperboard web with as little energy consumption as possible. Drying section can have several condensing steam drying cylinders made from steel and typically these cylinders are divided into different drying groups according to a steam pressure. (Ek, Gellerstedt & Henriksson, 2009) Typically the paperboard machine has 30 – 60 cylinders with a diameter of 1.2 – 1.8 m. Cylinder wall thickness typically varies according to the cylinder diameter but is generally around 2.54 cm or more. (Mujumdar, 2014) Paperboard web goes through the drying groups supported by drying fabrics made from plastic. Drying cylinders are heated by a hot steam, which is produced in a power plant. Large amount of energy is required during the drying process. Steam can be supplied excessively from the boilers, or it can be directed first through a backpressure turbine. Electricity can be produced with the backpressure turbine. Most of the incoming steam does condensate inside the drying cylinder. Condensate is carried out from the cylinder by the steam which is not condensing. Amount of the not condensing steam is approximately 10-15 % of the ingoing steam. (Ek, Gellerstedt & Henriksson, 2009) Drying cylinder surface temperatures are varying between 80 and 130 °C. Drying section is typically covered by a hood, which is beneficial for creating an optimal drying environment for the paperboard web. When heat is transferred from the drying cylinders to the paperboard web by contact, water starts to evaporate. Formed evaporate needs to be transferred away from the drying section hood. At the same time, fresh air is supplied into the drying hood. Ventilation system of the drying section includes also heat recovery systems and exhaust and supply air systems. With these systems, it is possible to recovery heat from the evaporated water and therefore improve energy efficiency. (Heo, Cho & Yeo, 2011)

Drying section is a critical unit process for controlling especially the cross-machine directional curl and moisture profile. (Karlsson, 2010) Paperboard curl exists mainly because of an unsymmetrical residual stress in a thickness (Z) direction. One of the main factors for this is unsymmetrical drying of the paperboard web during the drying section. Effect gets stronger down the drying process. Paperboards are typically produced to have a certain pre-curl (negative curl) level. It is needed in printing and converting because the paperboard tends to curl to the side which is printed or similarly processed and then dried. Pre-curl helps printers and converters to produce flat cartons, which may be otherwise curling up without having any pre-curl. Cross-machine directional curling can be controlled by applying different amount of a drying power on the top and reverse layer of the paperboard. Typically, last adjustments for the curling level can be done during the last drying groups. Curl can be also controlled with a special apparatuses like moistening or additional drying devices. (Münch & Holik, 2006)

Some board machines are equipped with a machine-glazing cylinder (MG), which is large drying cylinder typically located after the first drying groups. Maximum diameter of the MG cylinder is approximately 7 m, and it can weight more than 100 tons. MG cylinder has own press roller, which is covered with a felt. Main purpose of the MG cylinder is drying, but it is also improving gloss and smoothness. MG cylinders main controlled variables are steam pressure and press rollers pressure. After the drying section, the paperboard web moisture content is approximately 5-10 %. (Karlsson, 2010) The main controlled variables in the drying section are shown in Table 6. Typical drying section of the folding boxboard machine with the MG cylinder is shown in Figure 7.

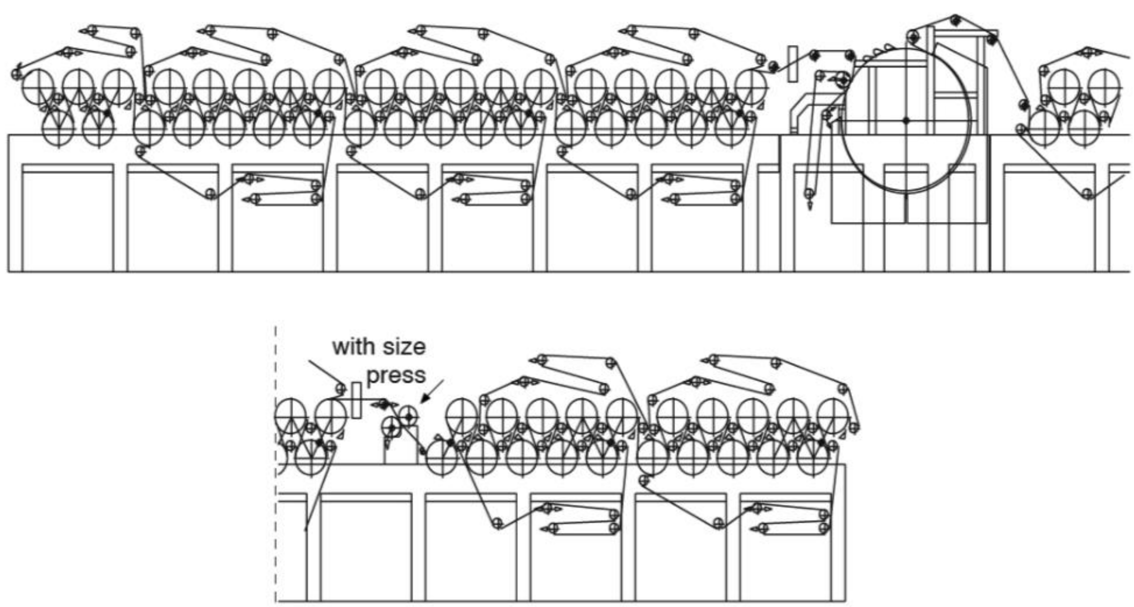

Figure 7 Drying section of the folding boxboard machine with the MG cylinder (Karlsson, 2010)

Table 6 The main controlled variables in the drying (Karlsson, 2010, Ek, Gellerstedt & Henriksson, 2009)

Process	Controlled variable	Main impact	Definition	Unit
Drying	Steam pressure	Drying power	Steam pressure for drying cylinders by drying group + MG cylinder	bar
	Press roller pressure at MG cylinder	Drying power, runnability, smoothness	Press force between MG cylinder and a press roller	kN/m

2.7 Surface sizing

There are two different kind of surface sizing units, modern film-type size press or conventional pond size press. In the film size presses or metered size presses (MSP) surface size is applied by a roll surface and in the conventional pond size presses surface size is forming a pond in a nip of two rollers. With the metered size presses size amount is controlled by rods, which are attached into a rod bed. (Ek, Gellerstedt & Henriksson, 2009) Most commonly used strength additive in surface sizes is starch, whose typical raw materials are wheat, corn, tapioca, potato or barley. Some functional additives are also used for example to improve the stability of a sizing process. Typically used functional additives are for example anti-foaming and dispersing agents. Dry solid content of the surface size is usually 6-15 %. In both surface sizing units, size is penetrated into the paperboard web by a nip pressure. (Paltakari, 2009) Surface sizing improves surface strength, stiffness and Z-directional strength. Z direction is one of the three main directions in paper and paperboard, and it stands for the thickness direction, also known as ZD. Other main directions are machine direction (MD) and cross-machine direction (CD). (Stenberg & Fellers, 2002) Surface strength is a crucial property especially in an offset printing, where is used relatively tacky inks. (Ek, Gellerstedt & Henriksson, 2009) Other remarkable benefits achieved by the surface sizing are decreased linting and dusting, decreased porosity and improved dimensional stability. Surface sizing is typically located before a coating section, because it also closes the paperboard surface and therefore coating penetration can be controlled. If the base paperboard surface is porous, the formed film of starch may decrease the porosity of the paperboard surface which effects on the water or coating absorption rate. Temperature has an effect on the viscosity of the surface sizing thus higher temperature leads into lower viscosity. Viscosity is a crucial variable how the surface size penetrates into the porous material. Drying temperature has also an effect on the forming result of the film. It results in more rapid water transit through the paperboard web and thus influences on the film forming. (Iselau et al., 2018, Ek, Gellerstedt & Henriksson, 2009) The main controlled variables in the surface sizing are shown in Table 7. Surface sizing amounts used on folding boxboard are typically 0.6-2.5 g/m2 per side. Paperboard web moisture content in the surface sizing section varies between 4-11 %. (Paltakari, 2009)

Table 7 The main controlled variables in the surface sizing (Paltakari, 2009, Ek, Gellerstedt & Henriksson, 2009)

Process	Controlled variable	Main impact	Definition	Unit
Surface sizing	Size amount	Strength and surface properties	Typically varies between 0.6 – 2.5 g/m^2	g/m^2
	Nip pressure	Runnability, size penetration	Press force between size press rollers	kN/m
	Applicator rod pressure	Film forming	Size amount is controlled by applicator rods	bar

2.8 Coating

Paperboard is coated to achieve better printability and visual appearance. Coating colour is a mixture of pigments, binders and additives. Pigments are the main raw material as they represent approximately 80 – 95 % of the coating colour by weight. Typically used pigments are calcium carbonates and kaolin. Coating process includes two main steps: coating application onto the paperboard web and controlling the coating amount to a wanted level. (Bajpai, 2015, Kogler et al., 2006) There are three different main types of coating units divided by how the coating layer is formed. Most typical ones are blade coating, film transfer coating and curtain or spray coating. In the blade coating applications, coating colour may be applied onto the paperboard web by an applicator roll or with a jet applicator. After the coating colour is applied, coater blade scrapes coating colour surplus from the moving paperboard web and returns it to a coating colour circulation. Folding boxboard is typically coated with a bent blade method, which means that the coating blade is adjusted in relatively low angle, 3°-12°. In the film coating applications coating colour is transferred as a film on a roller like in surface sizing units. In third coating type the coating colour is applied as a curtain or sprayed onto the paperboard web. After coating units, the coating colour is dried typically with an infrared dryers, hot air and drying cylinders. Infrared dryers can be heated by an electricity or gas. Hot air blowers enable also a stabilizing effect on the paperboard web and therefore prevents creasing. (Kogler et al., 2006) The main controlled variables in the coating section are shown in Table 8. The applicator roll coating unit is shown in Figure 8. (Paltakari, 2009)

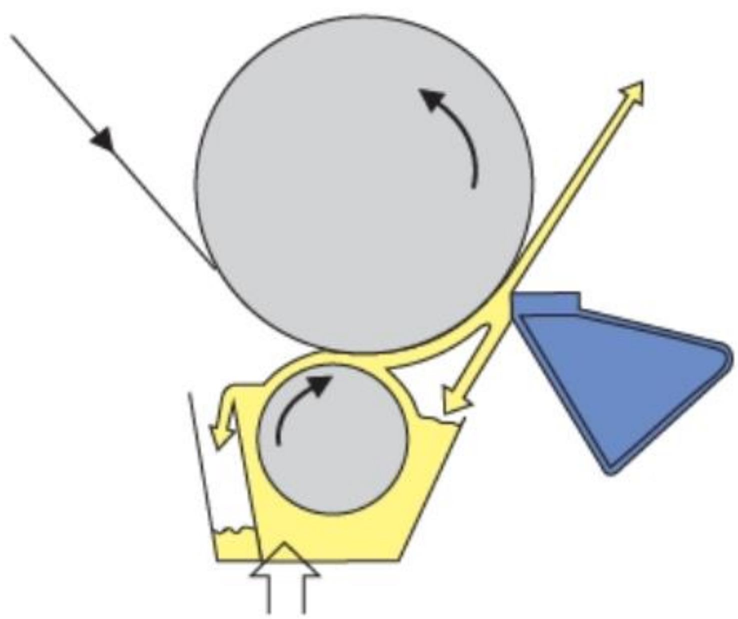

Figure 8 Applicator roll coating unit (Paltakari, 2009)

Table 8 The main controlled variables in the coating section (Paltakari, 2009, Kogler et al., 2006)

Process	Controlled variable	Main impact	Definition	Unit
Coating	Coating colour amount	Visual appearance, printability	Typically varies between 5-15 g/m²	g/m²
	Blade angle	Coating colour amount	Coating layer formation	Degree (°)
	Blade pressure	Coating colour amount	Coating layer formation	bar
	Applicator roll speed	Application of the coating colour, runnability	Typically, around 20 % of a web speed	m/min
	IR drying power	Drying of the coating	Natural gas feeding pressure	mbar
	Air drying power	Drying of the coating	Located after IR dryers	°C

2.9 Calendering

Typically, a board machine has two calenders, pre-calender before a coating section and a final calendering before reeling. There can be either hard or soft rollers in a calender. Hard nip calender results to uniform thickness and varying density, when soft nip results to varying thickness and uniform density. (Rautiainen, 2010) Comparison of these two calendering effects are shown in Figure 9. Purpose of the pre-calendering is to control cross-machine directional thickness profile before the paperboard web enters to a coating section. Typically, in this part, linear loads are relatively low, between 10-30 kN/m. This applies for folding boxboard machines equipped with a MG cylinder. Low calendering effect is sufficient, because the surface is relatively smooth already after the MG cylinder. Cross-machine directional controlling is possible by heating the roller on sector by sector or with an induction. Final calendering can be done with a hard-nip or soft-nip. Linear load in this part varies between 10-150 kN/m, where the requirements for a folding boxboard are on the lower end. (Rautiainen, 2010) Final calendering is also used for a cross-machine directional thickness control and it can also improve gloss. Gloss is mainly created by replication of the smooth cylinder surface but also some shear deformation happens during the calendering process. Improvement in gloss can be seen as decrease of a small-scale surface roughness so in general achieving a good surface for printing is major task of the final calendering. (Ek, Gellerstedt & Henriksson, 2009, Rautiainen, 2010)

Calendering reduces the paperboard surface roughness on both micro and macro wavelength length scales. (Vernhes, Dube & Bloch, 2010)

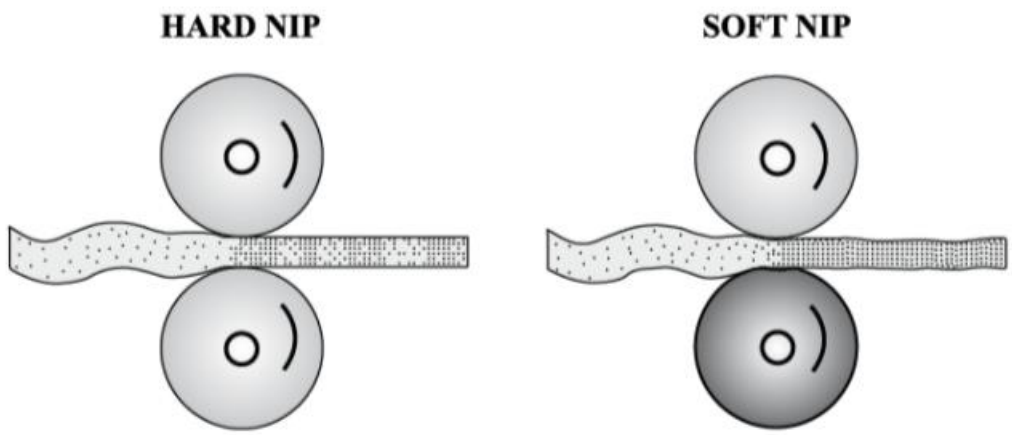

Figure 9 Comparison of the hard nip and soft nip calendering (Rautiainen, 2010)

2.10 Reeling

Reeling is the last process of the board machine. Main purpose of the reeling is to form uniform machine reels. Reeling unit includes a reel drum, primary and secondary arms and reeling rails. The paperboard web is reeled around a spool. When machine reel is starting to come full, an empty spool is accelerated to the paperboard web speed. Then a set change equipment is cutting and at the same time attaching the paperboard web onto an empty spool. Ready full machine reel is transferred further from the reeling on the reeling rails. New spool is locked to the primary arms, which are rotating down placing the spool on the reeling rails. Secondary arms are now locked on the spool and primary arms rotating up for the next spool coming. Reeling is a continuous process when the board machine is running. (Rautiainen, 2010) Secondary arms are building up the required pressure (nip load) against the reel drum as long as the machine reel is ready. Typical so called pope reeler is shown in Figure 10. The main controlled variables in the reeling are tension of the paperboard web and reeling pressure against the reel drum. Nip load effects the most on the tightness of the machine reel. The main controlled variables are shown in Table 9. Moisture content of the finished folding boxboard is typically between 5-8 %. (Rautiainen, 2010)

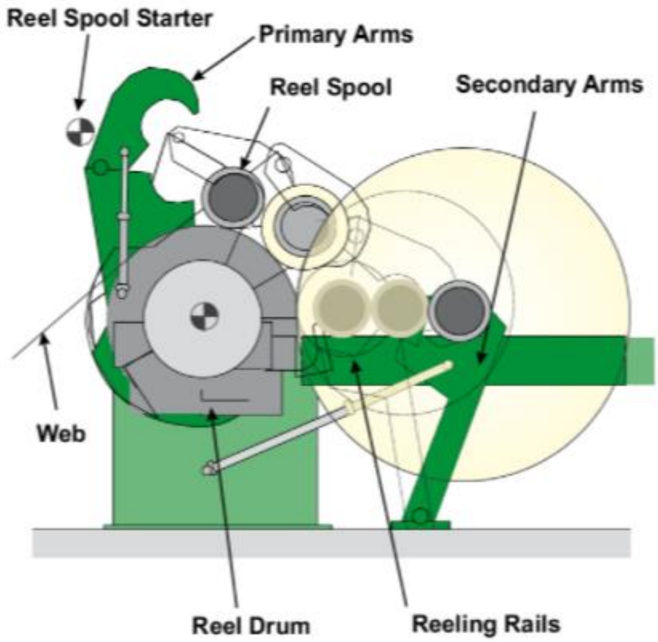

Figure 10 Pope reeler (Rautiainen, 2010)

Table 9 The main controlled variables in the calendering and reeling (Rautiainen, 2010)

Process	Controlled variable	Main impact	Definition	Unit
Calendering (pre- and final)	Nip pressure	Thickness, gloss	Press force between the calender rollers	kN/m
Reeling	Web tension	Machine reel forming, runnability	Paperboard web tension at a reeler	N/m
	Reeling pressure	Machine reel forming, runnability	Press force against a reel drum made by secondary arms	kN/m
	Speed	Web tension	Machine speed	m/min

2.11 Winding

Machine reels will be cut to customer reels in a winder. Winding process is a process where stresses and tensions in a reel are formed incrementally. (Ärölä & von Hertzen, 2007) Two-drum winders are typically used in the folding boxboard manufacturing as the two-drum winder is robust choice for relatively heavy reels. (Rautiainen, 2010) In the two-drum winder, formed customer reels lies on two winding drums. Winder includes three main sections, which can be divided to unwinding, slitting and winding. At first, paperboard web is led through the winder from unwinding. Unwinding section is equipped with a brake generator or a mechanical brake, which is controlling the required paperboard web tension between the unwinding and reel forming stages. Problems in paperboard web tension control may lead to winding defects or even variations in a reel diameter. (Carrasco & Valenzuela, 2006) Slitting section includes several pairs of shear-cut rotating blades, which are slitting the paperboard web on the wanted width. In modern winders, positioning of the slitting blades are fully automatic. After the slitting section, slit paperboard webs are separated by sectional spreader rolls, bowed rolls or D-bars. Purpose of the paperboard web separation is to prevent the customer rolls stick to each other on the drum rollers. It is important to achieve as evenly wound customer reels as possible. Reels should achieve required amount of hardness, that they are able to stand the forces applied during transportation, handling and warehousing. Reel hardness is a crucial factor for a runnability in printing machines and in other converting stages. Reel hardness should be created so, that it is uniform or slightly decreasing from the core towards to outside layers of the reel. (Rautiainen, 2010) Customer reel tightness control is fully automated in the modern winders. The main controlled variables are shown in Table 10. Two-drum winder is shown in Figure 11. (Rautiainen, 2010)

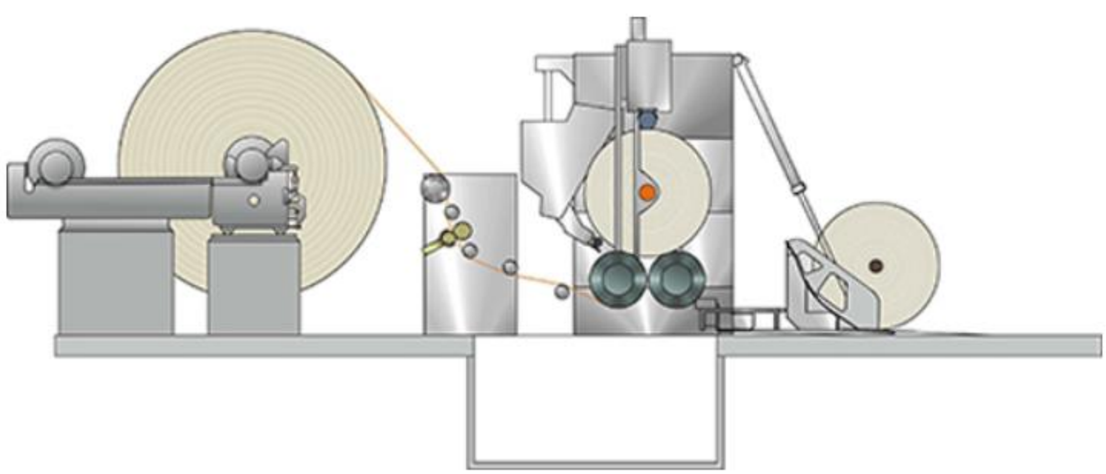

Figure 11 Two-drum winder (Valmet, 2021e)

Table 10 The main controlled variables in the winding and packaging (Rautiainen, 2010, Carrasco & Valenzuela, 2006)

Process	Controlled variable	Main impact	Definition	Unit
Winding	Web tension	Reel forming	Important especially for a slitting process	N/m
	Speed	Runnability, efficiency	Machine speed	m/min
	Rider roll pressure	Reel forming and hardness	Press force against forming customer reels	N/m
	Drum roll torque ratio	Reel forming and hardness	Torque difference between two drum rolls	#
	Nip load against drum roll	Reel forming and hardness	Force between customer reel and drum rolls	kN/m
Packaging	Amount of wrapping	Reel protection	Number of layers around a customer reel	#

2.12 Packaging

After the customer reels has been winded, reels will be packed. Main purpose of a reel packaging is to protect customer reels from a moisture and dirt, and it also gives some protection against mechanical hits. Reel packaging is the final process in the board mill before the reel will be supplied further to a customer. It is the last process in which board mill has a full control, which makes it remarkable. (Ponkamo, 2005) Paperboard reels are typically handled for example by clamp forklifts at various stages during the transportation and warehousing thus proper mechanical resistance is needed from the reel wrapping. Referring to above mentioned, reel wrapping needs to be resistant also for punctures and abrasions. (Climenhage, Heijmans & Borgel, 1996) It is possible, that changes in surrounding air temperature and humidity might cause changes in the humidity either inside the reel or on the outmost layers. Humidity changes in a reel might cause malformity and it can be seen as disturbed runnability at a printing machine or other converting stages. (Rautiainen, 2010) Reel wrappings are typically made from polyethylene (PE) plastic or kraft paper with PE layer. In the case of folding boxboard, PE plastic wrapping is widely accepted. PE plastic gives a good vapor protection for the reel. Reel packaging includes also inner and possibly outer heads placed on both sides of the reel, which are typically made from a corrugated board with vapor protection layer, made from low density PE (LDPE). LDPE layer material amount is typically around 20 g/m2, which is enough for forming a sufficient vapor protection. At the last stage, labels are attached on the reel. The main controlled variable in the reel packaging is the amount of wrapping around the reel. (Rautiainen, 2010)

3 QUALITY MEASUREMENT IN PAPERBOARD MANUFACTURING PROCESS

Paperboard is produced to fulfil the required quality level by as little costs as possible. To be able to achieve these quality targets, quality measurements should be done accordingly. Properties of the folding boxboard can be divided into seven categories: basic, strength, stiffness, structural, surface, absorption and optical properties. (Levlin, 1999) Variations in the paperboard quality can be divided into three groups: cross-machine direction variations, machine direction variations and residual variations. (Mäkelä et al., 2007) During the paperboard manufacturing process, several quality values are measured on-line at the board machine and off-line in a laboratory. On-line measurements are carried out at the board machine during the production by various scanning sensors. Laboratory measurements are done according to requirements. In addition to specific quality targets, it is especially important to achieve as uniform quality as possible. Quality variation especially in the main quality properties like in a grammage, moisture or thickness might be seen as unstable runnability in a printing machine and other converting processes. (Leiviskä, 2009) The main runnability requirements for the paperboard in printing generally are flatness, dimensional stability and delamination strength. Paperboard should not release debris or dust either in the printing or other converting process. (Kuusipalo, 2008)

There are typically defined certain target values and specification limits for each quality parameter for each produced grade. If measured values of some quality parameters are outside the specification, rejection needs to be evaluated case by case. (Levlin, 1999)

3.1 On-line measurements

In a modern board machine, paperboard quality is measured on-line during the process. Typically, these measurements are done by online quality measuring frames, in which are traversing scanners scanning back and forth the paperboard web. (Münch & Holik, 2006) Example of the quality measuring frame is shown in Figure 12. This method is economically more sensible than equipping the board machine with the several similar sensors side by side in cross-machine direction. Most of the quality sensors measures through the paperboard web so, that on the other side of web is a source and on the other side is a detector. Source can be for example optical or radiating. Modern traversing scanners can move at constant speed of 0.5 m/s. For example, with the web speed of 15 m/s and the web width of 5 m, the web could run 300 m in a machine direction during one scan. (Leiviskä, 2009) There can be several quality measuring frames in the board machine. Quality measuring frame is typically located at least before the reeling but there can be frames also for example before and after a coating section for measuring and controlling the coating amount. Scanners are integrated to a quality control system (QCS), which contains paperboard quality measurements and machine directional and cross-machine directional controls and it is part of the overall automation and process control system. (Leiviskä, 2009, Münch & Holik, 2006) QCS system can control in machine direction for example the basic quality variables like grammage, moisture and thickness. Cross-machine directional controls could include grammage, moisture, thickness, gloss, coating profile and fibre orientation. Actual controlling measures are done by actuators in various parts of the machine. Actual cross-machine direction controls can be done for example in the headbox, press section, drying section, coating units, after coating section, before reeling and in final calendering. In addition, there can be also on-line measurements for an ash content, shade, brightness, smoothness, gloss and coating amount. Controlling machine direction and cross-machine direction quality at the board machine includes typically multivariate variables. Therefore, multivariate model predictive control (mMPC) algorithms like for example Kalman filter algorithm, are typically applied on the quality control. (Leiviskä, 2009, Jämsä-Jounela et al., 2013) QCS also enables fast grade changes, which is lowering the production costs. Machine direction controls are slow because of relatively long time gap between the actuator operating and measurement. If for example the basis weight valve is controlled, effect on the grammage can be seen and measured in the reeling depending on the machine speed around after one minute. QCS can be used also for quality documentation, which is required by ISO 9000 quality standard. (Münch & Holik, 2006, International Organization for Standardization [ISO], 2015)

There are also possible to measure several paperboard surface properties related to topography and structure by machine vision systems. (Kälviäinen, 2011) On-line measuring system includes typically also a web inspection system (WIS), which is monitoring and alarming different defects on the paperboard web like for example holes and surface faults. Furthermore, there can be also a web monitoring system (WMS), which purpose is to help operating personnel to analyse and find root causes for different problem situations like the paperboard web breaks. (Leiviskä, 2009, Münch & Holik, 2006)

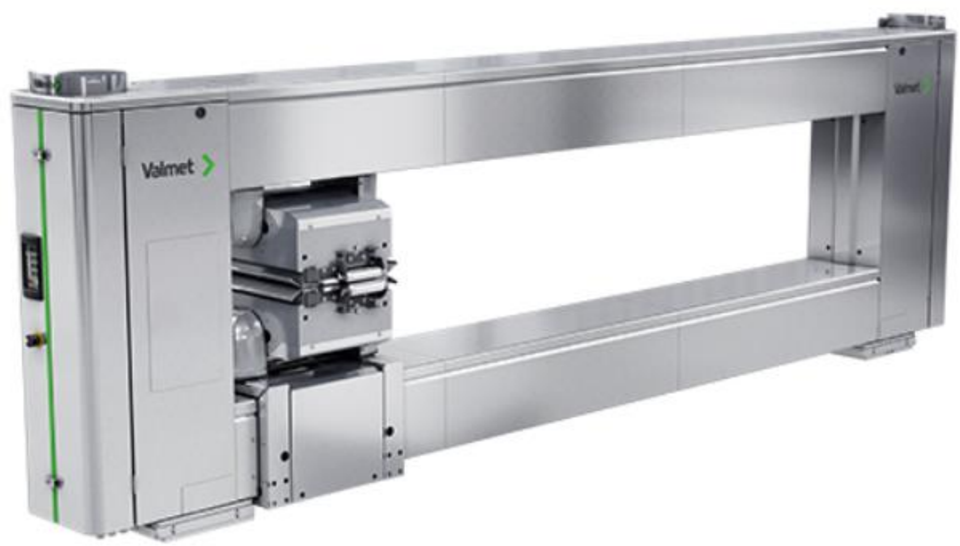

Figure 12 Valmet IQ Scanner (Valmet, 2021d)

3.2 Off-line measurements

Some of the quality measurements cannot be done on-line at the board machine and that is why some of the tests are carried out manually in a laboratory. Also, most of the on-line measured properties are tested in the laboratory for having a reference result for an on-line measurement sensor calibration. One of the main purposes for off-line laboratory measurements are lengthy period data collection for solving occasional problem situations. Process controlling can be made based on the laboratory results as well. (Leiviskä, 2009)

Product needs to be tested according to certain standards with calibrated equipment for achieving results for customer reporting. Measurements, which are needed to do as offline in the laboratory, requires usually sample breaking like for example in a tensile strength test. In this case samples are taken from the finished machine reel according to a testing plan. (Leiviskä, 2009) Main issue related to off-line laboratory measurements comes from the sampling frequency. Typically, samples are taken from the outer layers of a machine reel, and they are standing for the whole machine reel. Obviously, sampling is not very comprehensive especially in a machine direction, when one machine reel length can be several kilometers. Therefore, some remarkable quality variations between the machine reels might not be noticed in off-line measurements only. Reliability and comparability between machine reels in cross-machine direction are better, when samples are taken throughout the whole paperboard web width. (Leiviskä, 2009) Careful consideration is needed when evaluating the off-line quality measurements. It might be so, that an excellent or poor quality result taken from a relatively small area does not represent properly the quality of the whole machine reel. Actual quality controlling made based on the off-line measurements always includes a risk for unnecessary process control actions, and in worst case it might lead to increased variability in quality. (Leiviskä, 2009)

Conditions regarding temperature and relative humidity are standardized in the laboratories according to ISO 187 standard. Because the wood fibres are naturally hygroscopic, they might absorb or release moisture regarding the ambient conditions. Temperature target is 23 ± 1 °C and relative humidity target is 50 ± 2 %. By these standardizations it is possible to reach reliable and comparable results between the different laboratories. Paperboard samples should be acclimatised in standard conditions for sufficient time according to tested property. It is essential for achieving reliable and comparable results between the samples. (Levlin, 1999, International Organization for Standardization [ISO], 1990)

There are also automated testing devices on the market, which can test long and narrow paperboard samples. Typically, they are used for a testing cross-machine directional samples taken from machine reels during a production. Also, machine direction samples can be tested. Some of the automated testing device suppliers offers measuring devices, which are conformed with the industry standards like ISO standards. (Leiviskä, 2009)

4 ROTOGRAVURE PRINTING PROCESS AND THE MAIN CONTROLLED VARIABLES

History of a rotogravure (also gravure) printing can be traced back to the 18th century Europe. Rotogravure printing was developed from an intaglio printing which is used in printing high quality art reproductions. In the intaglio printing a flat engraved plate is utilised in ink transfer (Podhajny, 2000) Rotogravure printing has been traditionally used for long print runs because manufacturing of the printing cylinders is expensive, and it takes relative long time. In the past it has been a rule of thumb, that print run should be over million copies for rotogravure to be economically profitable. Technology has improved and made rotogravure printing more efficient, that nowadays it is possible to print 100 000 copies economically. Generally, market share of the rotogravure has been declining in magazines, catalogues and brochures because the increased need for shorter print runs and more flexible changes of designs. Nowadays the packaging industry is the largest segment in rotogravure printing. There has been identified two main drivers for this: growing flexibles packaging business and increasing printing quality demand. Flexible packaging, folding cartons including mainly cigarettes, labels and wrappers are the main applications for a rotogravure printing in the packaging industry. (Oittinen & Saarelma, 2009)

In this section is presented a rotogravure printing process starting from an unwinding and web conditioning ending to converting. Process is described as from the reels to cartons in-line process, meaning that all the process stages happen sequentially without a break between the stages. Rotogravure printing machine is shown in Figure 13. The main controlled variables and their functions are presented in each described process. (Licini, 2018)

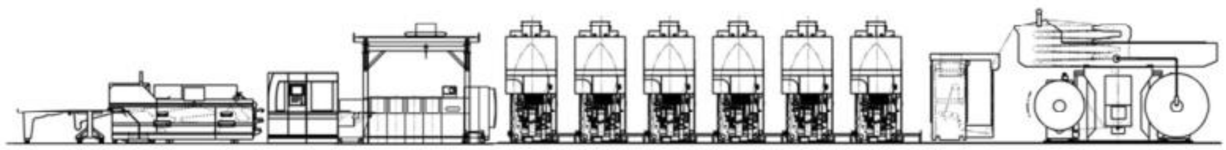

Figure 13 Rotogravure printing machine (Bobst, 2018)

4.1 Unwinding and web press in-feed

Unwinding is the starting process at a rotogravure printing machine. Reel is attached into a reel stand and a reel core is locked with cones or expanding chucks. The mains tasks of the reel stand are rotating and controlling the reel by accelerating and braking. Web tension and preliminary cross-machine directional register control is also formed with the reel stand into a tension control system. Two variables, diameter of the reel and rotational inertia of the rotating reel, are varying by time thus the tension control system is required to be non-linear and firmly coupling. Accurate tension control system is seen as a foundation for sufficient printing performance. (Liu et al., 2013a, Oittinen & Saarelma, 2009)

In-feed section of the rotogravure machine is located after the unwinder reel stand. In-feed section may include a de-curling device and a web cleaning device. With the de-curling device machine-direction curl is adjusted. Paperboard webs tend to have down curl in machine-direction because of a memory effect from being wound on a reel. Machine-direction curl can be eliminated by directing mechanical stress to the paperboard web by different de-curling layouts. In practice, down curl in machine direction is controlled with de-curling bar which is pushing the paperboard web from above. Cleaning of the paperboard web can be done with or without contact. In conventional set-up paperboard web goes between two brush-rollers, which are rotating against the web direction. Brushes are cleaning loose particles like fibres or pigments from top and reverse side of the paperboard web. Paperboard web can be cleaned without contact with an air blower. (Licini, 2018, Oittinen & Saarelma, 2009) In-feed section includes also so-called pull-unit, which controls web tension and alignment by cylinder with drive. At this point, web tension is the main controlled variable. In paperboard rotogravure printing a web tension is approximately 500 N/m. (Oittinen & Saarelma, 2009) The main controlled variables in the unwinding and web press in-feed are listed in Table 11.

Table 11 The main controlled variables in the unwinding and web press in-feed (Oittinen & Saarelma, 2009, Licini 2018)

Process	Controlled variable	Main impact	Definition	Unit
Unwinding	Speed	Web tension	Brake system	m/min
Web press in-feed	Infeed speed	Web tension	Regulates web tension between unwinder and printing units	kN/m
	De-curling	MD curl control	De-curler bar setting	±mm

4.2 Printing

Rotogravure printing machines in the packaging industry has typically 6-12 printing units depending on the requirements of application. There is a possibility for additional units for spot colours, varnishes, glues or similar. Every printing unit has own drying because the ink needs to be dried before the next unit. In a rotogravure printing, ink transfers to image areas from engraved cylinder cells. Printing cylinder is rotating in an ink fountain, where ink is applied on the surface of a printing cylinder. (Oittinen & Saarelma, 2009) Quality demand for the printing cylinders is high. Typical defects on the printing cylinders caused during the production are dents, scratches, inclusions, spray, curves, offset, smearing and excessive, pale or missing printing or colour errors. The most common defect is dents. (Villalba-Diez et al., 2019) Printing process is shown in Figure 14. An ink pump pumps ink from an ink tank through a filter to an ink fountain. Filter screens out impurities which could effect on the print quality. Doctor blade is taking away the surplus ink from a non-image area, so that the ink is filling only the engraved cylinder cells. Friction between the printing cylinder and a doctor blade has noticeable effect on quality of the printing. Additionally, friction between the printing cylinder and doctor blade effects also on the printing cylinder endurance. Greater the friction is, more the printing cylinder wears and that leads to printing quality problems. (Lu, Zhang & Li, 2013) Surplus ink circulates back in the ink tank. Ink is transferred to a substrate in a printing nip, which is formed by the printing cylinder and impression roller. Impression roller has typically soft rubber covering made typically of elastomers or polymers like rubber or polyurethane. (Oittinen & Saarelma, 2009) Nip pressure is typically around 1.5-5 MPa, depending on the application. Nip pressure should be controlled precisely according to optimal printing result. Too low nip pressure does not allow the ink transfer properly onto substrate from the cylinder cells. It has been also noticed that too high nip pressure decreases the ink amount transferring onto the substrate. (Pujun, Wei & Jiandong, 2014) Surface properties of the substrate are one possible cause for decreasing ink amount when increasing the printing nip pressure. This has been noticed especially with super calendared paper which has low absorptivity and porosity i.e., high density. It was concluded that a dense surface of the substrate may limit the ink flow, which may happen with a folding boxboard as well. (Elsayad et al., 2002)

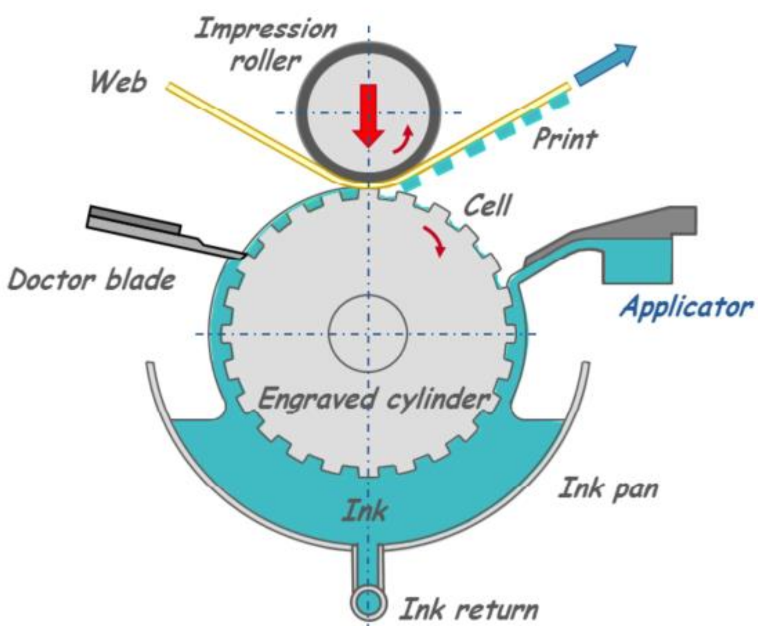

Figure 14 Rotogravure printing process (Bobst, 2018)

One of the main challenges in rotogravure printing is relatively short dwell time in the nip. One concrete problem coming from the short dwell time is possible appearance of missing dots. Missing dots are created, when the ink does not transfer onto the substrate properly. It has been determined, that if the defect size is under 0.05 mm, it cannot be seen by a naked eye in normal conditions. Based on the above mentioned and depending on the end use, quality demand of the rotogravure printing is exceedingly high. (Ceyhan & Morris, 2016) Missing dots are typically caused by substrate roughness, low substrate compressibility or too low nip pressure. Time for the ink transferring from the engraved cells onto the substrate is around 1-3 ms. ESA (electrostatic assist) is one of the technologies invented for improving the ink transfer. ESA system creates a charge on the surface of an impression roller, which is semi-conductive. There are usually two ways of creating the charge, internal or external. Internally charge is made simply inside the impression roller. With an external system, charge is led onto roller surface through an air gap. Electrostatic charge on the impression roller surface helps the printing cylinder cells emptying from the ink. There happens always some splitting of the ink layer in the end of the nip area. Because of splitting of the ink some ink remains in the printing cylinder cells and does not transfer to the substrate. Without ESA system remaining ink amount is around 35-50 %, when with ESA system remaining ink amount decreases to 5-20 %. ESA system is effective way to prevent missing dot problems. (Oittinen & Saarelma, 2009, Licini, 2018) Ink transfer to the substrate is affected by the printing speed as well. Naturally when the printing speed is higher, dwell time in the nip is shorter, which reduces the ink transfer. It has been noticed that this phenomenon is stronger on darker tones than on lighter tones. (Pujun, Wei & Jiandong, 2014, Elsayad et al., 2002) The main controlled variables in the rotogravure printing are shown in Table 12.

Table 12 The main controlled variables in the printing (Oittinen & Saarelma, 2009, Licini 2018, Pujun, Wei & Jiadong, 2014, Elsayad et al., 2002)

Process	Controlled variable	Main impact	Definition	Unit
Printing	Impression roller pressure	Ink transfer	Press force against printing cylinder	bar, MPa
	Ink viscosity	Ink transfer	Effects on flow properties	mPa*s, sec
	Ink temperature	Ink transfer	Effects on flow properties	°C
	Drying temperature	Ink drying	Temperature in drying hood	°C
	Doctor blade angle	Ink transfer	According to printing cylinder	Degree (°)
	Doctor blade pressure	Ink transfer	Against printing cylinder	bar
	Register correction	Register quality	in MD and CD	mm
	Infeed/outfeed speed	Web tension	Web tension between the printing units	kN/m

4.3 Inks

Rotogravure printing inks are composed of pigments (5-20 %), binders (10-40 %), solvents (30-70 %), additives (1-5 %) and possibly fillers (0-10 %). Viscosity of the rotogravure inks are relatively low, around 5-25 mPa*s, because smooth flowing on the printing cylinder engraved cells is required during the short dwell time. There are also so-called UV inks, which have higher viscosity. Achieving an optimal ink viscosity is balancing between the runnability and print quality. Low viscosity ink flows better on the printing cylinder cells when running printing machine at higher speeds but on the other hand colour density is lower. High viscosity ink enables to print details better because of less ink spreading but on the other hand ink might dry in a cylinder cell. (Oittinen & Saarelma, 2009) According to above mentioned, the ink viscosity needs to be controlled inside the predetermined limit. (Pujun, Wei & Jiandong, 2014) Viscosity of the ink tends to increase during printing when quickly evaporating solvents are used. This may lead to quality variations if the viscosity is not controlled properly by automation system or rotogravure printing operator. (Ng et al., 2018) Solvents are one of the main components in rotogravure inks because in the rotogravure printing ink dries by solvents evaporation when dried with hot air. This is a reason why volatile solvent are used in the rotogravure inks. Typically used solvents in the packaging industry are ethyl alcohol, mixture of ethyl acetate and ethyl alcohol or in some cases even water. Problem with the solvents is, that not all the solvent are evaporating, but small amounts can penetrate paperboard pores as a residual solvent. Typically, this amount of the residual solvent is between 1-3 %, and it can cause smell and taste problems in a product. Fully water-based inks do not have the similar problem of residual solvent, but on the other hand they require 3-5 times more drying compared to solvent based inks. Additionally, it has been noticed, that with the water-bases inks quality problems in printing appears more often. (Oittinen & Saarelma, 2009, Licini, 2018)

4.4 Register correction

Printing register describes how accurately each printing unit has been synchronized together. It is describing the alignment of two or more colours printed on top of each other. If there is too much difference between the printing units, depending on the printing design, it can be clearly noticed. Difference between the printing units is called as misregister. Printing result inside the register and out of register are illustrated in Figure 15. For example, in cigarette packages register tolerances are typically 0.15-0.20 mm both in cross-machine and machine direction for the misregister. Misregistering may appear on both directions, in cross-machine or machine direction. In cross-machine direction registering can be too much on the drive side or operator side from the zero point. In machine direction registering can be below or above the zero point. Zero point is referring to an absolute register accuracy. (Licini, 2018) Printing register can be adjusted in machine-direction and in cross-machine direction. Control marks for a register measurement are printed by each printing unit. Printed control marks are read by sensors and the information is transferred to a register control system. If the system measures inaccurate register in machine or cross-machine direction, corrections will be done accordingly depending on the used technology. (Zhang, Zhang & Wu, 2011) Machine-direction control can be performed with movable compensation rollers before the printing units. Movable compensation roller basically applies stretch on the paperboard web according to the need of register correction. Each of the printing cylinders are controlled by own servo motor in modern rotogravure printing machines. In this type of rotogravure printing machines machine directional register correction is performed by adjusting the speed of each printing cylinder's servo motor accordingly. The latter method has faster response frequency, and it can be controlled more accurate than conventional mechanical shaft drives. (Liu et al., 2013b) Cross-machine directional printing misregister is typically corrected by moving the printing cylinders in cross-machine direction by servo motors according to the need of correction. (Licini, 2018) Printing register can be affected for example by a substrate uniformity, paperboard web tension, rotogravure printing machine speed, temperature and relative humidity in a printing hall and accuracy of the rotogravure printing machine parts and assembling. (Liu et al., 2013b)

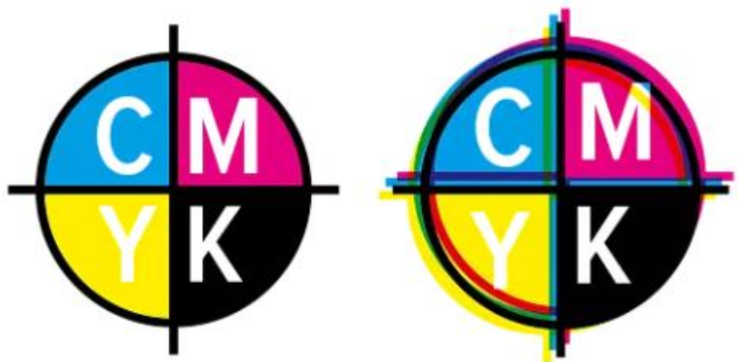

Figure 15 Printing result inside the register (left) and out of the register (right) (Tesa SE, 2021)

4.5 Converting

Paperboard converting includes typically embossing, creasing and cutting. Converting is typically characterized as a process, which are modifying the structure of the paperboard or other substrate. Before the paperboard web enters to a converting section, web tension and alignment needs to be precisely controlled for achieving required register level between the printing and converting processes. The main controlled variables in the converting are shown in Table 13. (Licini, 2018)

4.5.1 Embossing

Embossing is used, when some details is wanted to place into a carton. With an embossing it is possible to emphasize for example some printed area or image. Hot-foil stamping can be also used with the embossing to create even more contrast for some certain area on a carton.

Embossing is produced with special pair of plates, where another plate is negative and other plate is positive. Paperboard is then pressed between these plates for creating the embossing. Embossing plates can be installed in a flatbed unit, or they can be two rollers forming a nip. (Licini, 2018) Rotary tooling allows higher speed and better productivity compared to the flatbed converting but it might be also over ten times more expensive. Regardless of the high price of the rotary tools, it is economically better solution in many cases because of higher production speed. (Pfaff, 2001) During the embossing, a paperboard is exposed to a high pressure, which results to a permanent change in the paperboard shape. It is possible to improve the embossing effect by heating the plates or applying moisture on the paperboard before the embossing unit. Embossing can be made in two-dimensional or in three-dimensional. In two-dimensional embossing, paperboards embossed surface is formed so that the whole embossed area is at the same level. In three-dimensional embossing, paperboards embossed surface is formed to several levels. High register accuracy is required, because even a small difference between the printing and embossing can be easily noticed. Typical problems in embossing are cracking of the paperboard or coated surface in or next to embossed areas. Paperboards with a higher caliper enables higher embossing. For achieving good embossing result, flexibility of fibres and coating layer is required. Paperboard grades having more of chemical pulp are usually working better in embossing than the grades containing less chemical pulp. Also, higher moisture content seems to prevent cracking. (Kuusipalo, 2008)

4.5.2 Creasing

Creases are made to cartons, because the paperboard is easier to fold from predetermined crease. Creases are made with a creasing rule and a counterpart. Paperboard is pressed with the creasing rule against a counterpart or channel, which creates locally a deformed area. At the creasing zone, bending stiffness of the paperboard is reduced compared to surrounding areas. (Li et al., 2016) One of the fundamental issues with creasing and folding is also cracking of the paperboard surface like in the embossing. Cracking does appear on the creased area of the paperboard, and it could have a negative impact on the visual outlook of a carton. High surface strength reduces the cracking tendency of the paperboard. (Kim, Lim & Lee, 2010) Creasing tool can be either flatbed or rotary. (Licini, 2018)

4.5.3 Cutting

Cutting is the final converting stage before cartons enters on the delivery section towards to a packaging. In the cutting section carton is cut in its shape. When the paperboard is cut to a carton by a flatbed die-cutter, cartons relate to each other by the connecting portions also called to nicks. Function of the nicks are to keep the cartons stable during the transportation towards a delivery section. (Nagasawa et al., 2007) With the flatbed die-cutter waste parts between the cartons needs to be stripped away after cutting the cartons. Cutting tool can be either flatbed or rotary. (Licini, 2018)

Table 13 The main controlled variables in the converting (Licini 2018, Kuusipalo, 2008)

Process	Controlled variable	Main impact	Definition	Unit
Converting	Outfeed speed	Web tension	Regulates web tension between the printing units and converting	kN/m
Embossing, creasing and cutting (rotary)	Tool circumference	Quality	Separated processes	mm
	Tool speed	MD adjustment	Machine directional adjustment of the processes	m/min
Embossing, creasing and cutting (flatbed)	Pressure	Quality	All the processes can be installed in the same tool	N

5 QUALITY MEASUREMENT IN ROTOGRAVURE PRINTING PROCESS

Demand of the printing quality is high in the packaging industry and there are no signs for decreasing of the required quality level in the near future. Competition in the rotogravure printing market is tough and printing quality is one of the main factors which is closely monitored by the end-customers. Therefore, quality of the printing is one of the main competitive factors between the printers around the globe. (Pankaj & Pankaj, 2016)

5.1 On-line measurements

Printing quality can be measured as on-line during the rotogravure printing process. On-line detection systems are widely used in the rotogravure printing machines for achieving the required quality demands. On-line measurement systems can be roughly divided into two categories: active and passive. (Shang et al., 2007) With active systems a rotogravure printing operator involvement is needed for example to making the decision whether some material needs to be rejected or not. Example of the active on-line quality measurement system can be, that the system is showing two pictures to a rotogravure printing operator. Other picture is reference, and another picture includes some defect according to the system. Operator is needed for the defect evaluation and decision making. Passive systems can operate totally without the need of operator involvement. These on-line quality measurement systems can inspect quality variations independently, and they can also sort defected material out automatically. Example of the passive system can be a register correction which works like closed loop like in a quality control system in the board machine. On-line quality measurement system detects for example cross-machine directional register fault, and it triggers cross-machine directional correction of printing cylinder in the particular printing unit or units. (Shang et al., 2007) Development of the computer science and machine vision has enabled on-line detection device manufactures to bring various models on the market. One of the main drivers behind machine vision development are printers desire to reduce print waste and therefore costs. Also increase in the printing machine speeds demands better on-line quality measurement systems. (Shang et al., 2007) Modern on-line detection systems can detect all the typical defects in printing. One of the crucial issues with an on-line detection are false alarms. (Sun, Zhang & Chen, 2011) On-line measurement devices can include also spectrophotometer for controlling different types of printing defects according to a dot feature. Quality control system can analyse for example a dot size, boundary roughness, blotchiness and streaking according to spectrophotometer data. Quality control system can give feedback to a rotogravure printing operator to adjust some process variable like speed or impression roller pressure for reaching better quality value. (Brown, Jackson & Parkin, 2003)

5.2 Off-line measurements

Traditionally printing quality has been evaluated subjectively by rotogravure printing operators without any specific measurement equipment. To achieve the modern quality requirements, quality should be measured with different testing equipment in addition to a visual inspection. Spectrophotometer and densitometers are typically used for a colour evaluation and matching. Densitometer can be used only with so called process colours like cyan, magenta, yellow and black, often referred as CMYK. Spectrophotometer is suitable for identifying all the colours and therefore it is typically used in rotogravure printing, where spot colours are vastly in use. (Bohan, Claypole & Gethin, 2000) Matching of the spot colours are difficult, when trying to achieve the correct colour density in ink. There has been developed special software for the spot colour matching. (Rubai et al., 2012) Rotogravure printers and substrate suppliers may also use laboratory scale proof presses for example on evaluating substrate roughness. Results can be used in planning of the commercial scale print runs on full size rotogravure printing machines. (Heintze, 2003) Quality of the printed and cut carton blanks should be ensured, that it reaches all the end-customer needs as well. Speed of the packaging machines has been increasing simultaneously with rotogravure printing machine speeds. Quality of the folding and gluing ability should be ensured for good runnability at the end users' packaging lines. (Raney, 2005)

6 TRANSPORTATION AND WAREHOUSING

Transportation is seen as fundamental part of the supply chain. Typically supply chain is considered to consist of networks of different companies, who are working together for supplying some product to a market. In the supply chain, activities related to transportation are considered to happen between or in boundaries of different companies. Transportation is typically also including inventory, warehousing and handling of a material. (Koskinen & Hilmola, 2007) Customers demand their orders in right time, in right quantity and in right quality. Paperboard reels and pallets should be free of dirt and damages. (Ponkamo, 1995) Fulfilling this demand, transportation from a folding boxboard mill to customer’s premises requires lots of strategic, tactical and operational planning to manage the material flow smoothly. This advanced planning is typically done in one of the ERP (Enterprise Resource Planning) systems like in SAP or Oracle. (Carlsson et al., 2009) There can be different ordering models invented for the varying customer needs. Choosing the most suitable model for each customer need is necessary for succeeding in the overall supply chain planning. Right ordering model can be depending for example on the urgency and size of the order. For example, Metsä Board offers five different models: direct mill order, common stock, Express Board, customer dedicated stock and vendor managed inventory. (Metsä Board, 2021b) In this section are presented typical transportation modes, warehousing and reel handling.

6.1 Transportation modes for a paperboard

Paperboard reels can be transported by four main ways: ship, railway, truck or airplane. There are different pros and cons for each of the transportation modes. For example, ship is very cost efficient because of large capacity but at the same time it is the slowest mode of transportation. Airplane is the fastest but also the most expensive mode of transportation. In theory, all the mills can supply paperboard to any customer around the globe. Obviously, the mills which are located closer to a certain customer, have smaller transportation costs and thus competition advantage compared to the mills which are located far. (Philpott & Everett, 2002) When choosing a transportation mode for a certain product, multiple factors need to be considered. It is not possible to transport goods only by rail or airplane to everywhere in the world, so typically some sort of combination is needed. Location of a board mill and customer's site determines, which modes of transportation are possible and further, sensible to use. (Philpott & Everett, 2002) General rule for choosing the transportation modes are following the product value. In high value products like pharmaceuticals transportation mode typically highlights responsiveness, when in low value products efficiency is more emphasized. (Hugos, 2018) In the case of the paperboard reels efficiency is underlined. Customer orders should be as large as possible for achieving minimum transportation cost per unit. By creating as simple transportation process from a mill to a customer, enables to lower warehousing times in different stages of inventory. Simplifying the transportation process means that as little amount of different transportation modes is used as possible which lowers the costs. (Hämäläinen & Tapaninen, 2009)

6.2 Warehousing

In general, warehouses or distribution centers as they can be called, are playing a major role in global supply chains. Warehouses are supporting businesses in many ways like for example holding an inventory or reacting rapidly to customers' orders. (Hilmola & Lorentz, 2010) Typically the paperboard reels are first transported from a mill into a warehouse, where the reels will be dispatched further to the customer. Typically, the reels are transported into a warehouse by railway or truck. Typically, reels are warehoused in various locations at the same time. Reels can be stored in mills dispatching warehouses, in dispatching and discharge ports, in distribution centers and in customers premises. (Hilmola & Lorentz, 2010) Warehousing time should be as short as possible for avoiding unnecessary costs. One of the case studies made decade ago found out, that the paper reels made by North-European producers stayed approximately 45 days in different stages of inventory before reaching the customer. (Koskinen & Hilmola, 2007) This was considered to be too high. It was also found out, that for achieving a smooth material flow, transportation service suppliers need to have certain amount of free unused capacity. It means, that when for example warehousing or railway transportation capacity is full or near to full, material flow tends to slow down.

Careful planning of warehousing operations is important. If the logistics does not work fluently inside the warehouse, it may result into cumulating problems. When the new batch of paperboard reels arrive, they are typically unloaded by a clamp forklift at the unload-load zone. Then the reels are carried to certain cells, which are named areas, and stacked one on each other. Warehousing cells can be allocated for example according to a reel size and grade or customer. If the allocation is not planned well, a clamp forklift may need to travel unnecessary long distances several times. Also filling the warehousing cells should be designed so, that there is no need to move other reels away first during the normal operations. Up-to-date inventory documentation is crucial for success in the warehousing operations. If the inventory documentation has discrepancies for example according to positions of the reels, it is time consuming to find out the real situation. (Lai, Xue & Zhang, 2002) So-called ghost reels are typical inventory documentation related problem. Ghost reels are appearing in an inventory documentation, but they do not exist. It may also be another way round; individual reels are physically in the warehouse, but they are not mentioned in the inventory documentation. (Schult, 2014) Warehousing is estimated to stand for 15 – 70 % of total costs created by the manufacturing a certain product. (Lai, Xue & Zhang, 2002)

6.2.1 Conditions

Folding boxboard is a sensitive product regarding surrounding conditions. Metsä Board paperboards are produced to be in the state of equilibrium when surrounding temperature is 23 °C and relative humidity is 50 % thus these are the recommended conditions for printing and converting. When a paperboard is kept in these conditions it will not absorb nor lose moisture. In other words, the paperboard will be in good balance and stays dimensionally stable thus it does not start to curl. (Järvinen, 2016) Fibres can expand or shrink 3-4 times stronger in cross-machine direction compared to machine direction. This causes cross-machine direction curling in the paperboard. (Baral & Sharma, 2014) When storing paperboard reels, proper warming-up time needs to be considered before printing or converting. Dew point phenomena is related to this meaning the temperature at which the moisture held in the air begins to condensate in water droplets on. If the paperboard reels or pallets have been stored in cold conditions and taken into a warm printing hall, they start to attract moisture immediately in terms of condensation. That is why it is important to follow warming-up instructions provided by a paperboard supplier to prevent unwanted condensation. Minimum warming-up time depends on the temperature difference between the storage and the printing hall, and a weight of the paperboard reel or a pallet. In practice paperboard reels or pallets needs to be warmed-up in their original moisture-proof packaging before taken into use. If the paperboard is not allowed to acclimatise in the surrounding conditions, changes in quality will happen. (Niini et al., 2021) It also effects on the runnability causing for example register problems when dimensional stability and balance are disturbed. (Järvinen, 2016)

6.3 Reel handling

Paperboard reels are typically handled with forklifts, when they are loaded or unloaded for a transportation. Forklifts are usually equipped with a clamp, which are designed for handling reels. Clamp has typically two arms, which are able to grab around a reel from opposite sides. Reel handling clamps are also usually coated with rubber pads for achieving better grip on the reel. Typically, paper roll clamp devices can rotate full 360 degrees for quicker and more efficient reel handling. (MHPN, 2014) Reel damages can be formed in theory in any stage in the production and transportation chain. Reel damages can occur in a mill, when the reels are wrapped and handled by conveyors or clamp forklifts. They can occur during the warehousing in a mill or in dispatching as well. Reel damages can be formed also during a transportation in a truck, train, ship or an airplane. Also, when the reels are unloaded and carried to a warehouse at the customer's premises, damages can be done by an improper handling. Reel damages can be formed also during a last stage: when the reels are transferred from a warehouse to a printing press hall or other converting machine hall. Also, when the reels are unwrapped and loaded into a printing machine or other converting machine. According to studies, most of the reel damages are formed whenever the reels are transferred or lifted (Ponkamo, 1995) For example unloading a truck is a critical process, where mechanical damages can be easily done by careless handling. Damages can be done for example if a clamp pressure is too high, or the reels are touching too heavily on some surface. Too high clamp pressure may also have an impact to roundness of a reel. If a reel becomes ovate, it may influence on the runnability at a rotogravure printing or other converting. (Geis, 2005) Proper reel identification is important for reducing the need for a reel handling. If for example the location of sought reel is not clear, it may require moving other reels out of the way, which always reduces the quality of the handled reels. (Avrahami, Herer & Shtub, 2013)

7 SUMMARY OF THE LITERATURE REVIEW

Folding boxboard is a multilayer paperboard which is classified to a packaging boards. Typically folding boxboard has three layers which are reverse layer, middle layer and top layer.

Middle layer is made from a mechanical pulp and mill broke. Mechanical pulp is used for achieving high bulk. Top and reverse layers are typically made from chemical pulps and another or both sides could be coated. Manufacturing of the folding boxboard customer reels contains several processes starting from a stock preparation and ending to a finishing section.

Accurate control of a fibre pulp suspension consistency and flow are important variables on the paperboard quality. These variables should be controlled carefully already in a stock preparation and further in a short circulation. Any variations in the fibre pulp suspension consistency or flow in above mentioned processes may cause unevenness in the paperboard which can effect on the runnability or quality at converting.

Headbox supplies a fibre pulp suspension at low consistency on a wire and the paperboard web is formed. It is a critical process because orientation of the fibres cannot be later affected. It is important for the later processes that cross-machine direction profiles are formed as optimal as possible by the headbox.

Large amounts of water need to be evaporated during the paperboard manufacturing process. That is why a drying section requires most of the space needed for the folding boxboard machine. Drying has a key role in ensuring even moisture profile and wanted cross-machine direction curl level. Variation between customer reels cut from different web positions may cause issues at the customers converting processes if there are noticeable differences in a moisture or curl profiles. This applies on other cross-machine direction profile features as well.

Rotogravure printing requires high surface quality and printability from the paperboard. Surface sizing and coating sections are in a key role when producing these qualities.

Winding is a process where customer reels are formed from machine reels coming from the board machine. It is the last process before a reel packaging. Wound customer reels should have a wanted hardness, that is even or slightly decreasing from the core towards to outer layers.

Varying hardness may cause runnability problems like for example register issues at converting processes.

Reel packaging should be robust enough against moisture, dirt and mechanical hits to a certain point. If the package is not fully protecting the reel, humidity and temperature changes during the warehousing and transportation might cause malformity to the reel which may disturb runnability at the printing machine or other converting stage.

It can be summarized that any kind of variation happening during the paperboard manufacturing process or transportation and warehousing has probably a negative impact on a runnability or quality at converting processes. Therefore, all the variations during the manufacturing process, transportation and warehousing should be minimized for achieving optimal quality and runnability for converting.

EXPERIMENTAL PART

8 STUDY SET-UP

In the experimental part, a large data set was collected from the board machine, winder, transport chain and rotogravure printing machine. Data set was collected during the specified trial run of 28 reels. Additional board machine and winder process and quality data were gathered from the five customer orders specified by the converter to support the correlation analysis. Three of these orders were reported having register stability issues. These three claimed orders included 63 reels and they were consumed with lower printing speed due to a register instability. Converter announced two orders as a reference, which were consumed without any issues. Those orders included 20 reels. Transportation and warehousing or rotogravure printing machine data were not available for the additional orders as they were normal customer orders produced and consumed before the trial order set-up was created. Aim of the study was to explore the possibilities of an artificial intelligence analytics and methods in quality optimisation of the overall folding boxboard manufacturing process, that the register stability at a rotogravure printing can be improved. In other words, to find out which controlled variables of the overall paperboard manufacturing process are affecting on register stability. Project principle illustrated in Figure 16.

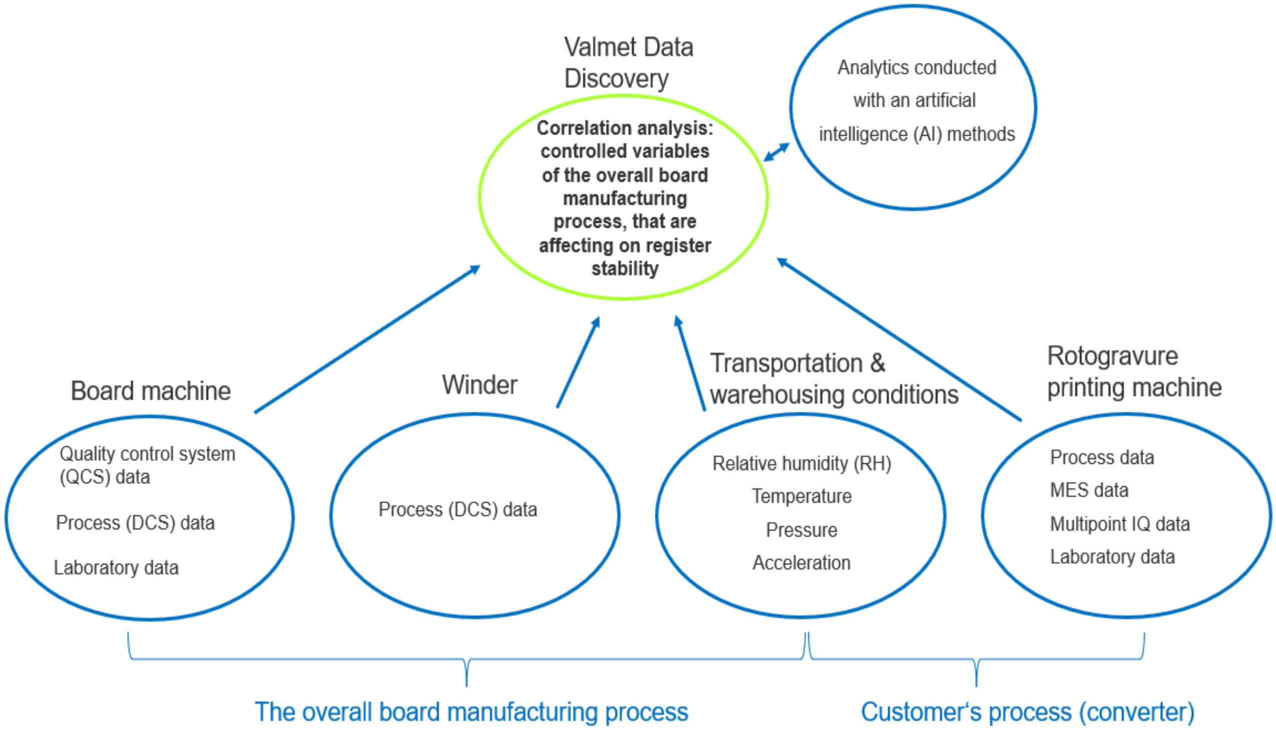

Figure 16 Principle of the project

Data analysis was performed to the collected data. Data analysis was performed by Valmet using an artificial intelligence analytics and methods. The leading idea of the data analysis was to find correlations between the controlled variables of the overall paperboard production process and a rotogravure printing machine register stability. All the data collected from different locations described in this section were utilised in the data analysis made by Valmet. Data from different processes were linked to each other by using a customer reel ID number as a connection point. Every customer reel has an individual reel ID after they have been cut from the machine reel, which is also called as a jumbo reel. (Matinlauri, 2021) Principle of the customer reel ID creation is shown in Figure 17.

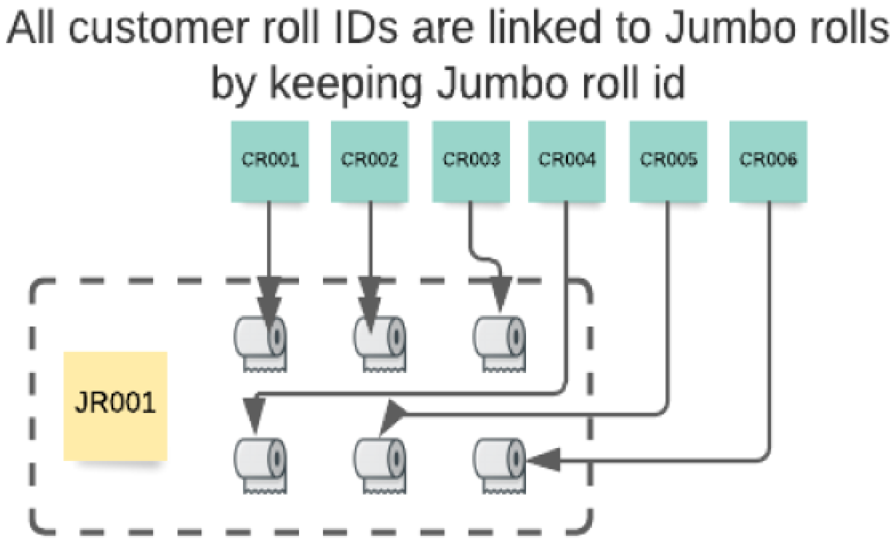

Figure 17 Principle of a customer reel ID creation (Matinlauri, 2021)

By the found correlations, paperboard production process would be adjusted in terms to achieve better register stability at a rotogravure printing machine. Improved register stability will allow to increase production efficiency at the rotogravure printing machine for example by printing with higher speed and generating less waste related to register stability problems.

Data analysis was made based on the data collected from the trial run of 28 reels. In addition, board machine and winder process and quality data gathered from the five normal customer orders mentioned earlier were analysed. The controlled variables of the overall paperboard manufacturing process were presented in the literature review. In conclusion the data analysis was examined based on the findings in the literature review and a plan for the future work was established.

9 DATA COLLECTION FOR THE DATA ANALYSIS

For data collection purposes, the special trial order was created in cooperation with the converter. It was decided to take 28 reels on the test for achieving enough data to start the data analysis. In addition, process and quality data were collected from the five normal customer orders specified by the converter. All the data collected from various sources and used for the data analysis were collected to Valmet's cloud server. In this section the data collection process is described starting from the board machine ending to rotogravure printing machine. Details of the orders used in the data analysis are covered as well.

9.1 Trial order details

Trial order was produced with Metsä Board Tako board machine 1 (BM1). Paperboard grade chosen for the trial was Metsä Board Pro FBB CX 215 g/m2 because it is currently the most used grade by the converter. Grade chosen to the trial is a three-layer folding boxboard and it has coating on the top layer, and it is designed for a high demanding end use of cigarette packaging. (Metsä Board, 2021c) Size of the order was 34 tons and 28 customer reels which means that one customer reel weighted roughly 1.2 tons. Trial order was produced on four machine reels from which it was cut to customer reels. Four reels were trimmed in one set that it was possible to cover the whole board machine web width in this trial. It was important to cover the whole paperboard web width to study possible web position related correlations. Width of the trial reels were 740 mm when reel diameter was 1800 mm. Diameter of 1800 mm is the most used in reels produced by Metsä Board Tako board mill.

The converter also announced three normal customer orders, where register problems were reported. These orders included in total 63 reels and they were consumed with a lower speed due to a register stability problem. Width of the reels were 819 mm when diameter was typical 1800 mm. Reels weighted roughly 1.35 tons. As a reference the converter announced two orders, which were consumed without any problems. Two orders contained in total 20 reels. Orders mentioned above were produced with the same BM1 and cut with the same winder than the trial order, so they were suitable to involve in the data analysis. Customer orders were consumed in another site of the converter in Russia on reel to sheet process. Paperboard grade and grammage were also the same, Metsä Board Pro FBB CX 215 g/m2. Transportation and warehousing or rotogravure printing machine data were not available for the additional orders as they were normal customer orders produced and consumed before the trial order set-up was created. Order information and data availability are shown in Table 14. Data collected from the board machine, winder, transportation and warehousing, and rotogravure printing machine will be explained more precisely later in this section.

Converter's site is in St. Petersburg, Russia. Reels were transported to customer's site with a normal procedure. On the paperboard production day 12.10.2021 the reels were at first transported by a shuttle truck from the mill to Metsä Board Tako external warehouse located in Viinikka, Tampere. External warehouse is operated by a subcontractor SeaRail Oy. From Viinikka warehouse the reels were transported by a truck to the external warehouse in Kouvola at 12.-13.10.2021, which is operated by subcontractor Kouvola Cargo Handling Oy. Reels are staying the longest period in Kouvola warehouse during their journey from Tako board mill to the customer's site in St. Petersburg. After the customer does a call off, reels will be transported by truck to St. Petersburg at the customer's premises. Reels were picked up by a truck from Kouvola on 3.11.2021, where they were transported to St. Petersburg. Based on the presented transportation dates, reels stayed at Kouvola warehouse approximately three weeks.

Table 14 Order information and data availability for the data analysis

Production order number	Description	Production date (board machine)	Number of reels	Board machine data	Winder data	Transportation data	Rotogravure printing machine data
305408887	Trial order	12.10.2021	28	X	X	X	X
305390489	Normal order, register issue reported	10.08.2021	17	X	X		
305390488	Normal order, register issue reported	10.08.2021	18	X	X		
305369310	Normal order, register issue reported	30.05.2021	28	X	X		
305393008	Normal order, reference	18.08.2021	11	X	X		
305393009	Normal order, reference	18.08.2021	9	X	X		

9.2 Board machine

Metsä Board Tako BM1 produces a high-quality coated folding boxboard mainly for the high demanding end use of cigarette packaging. Machine's maximum speed is around 515 m/min, and the maximum trim width is 3330 mm. BM1 produces currently grammages varying from 200 to 250 g/m2 and a yearly production capacity is around 140 000 tons. (Metsä Board, 2021d)

BM1 has a process control system supplied by Valmet and it is called as Valmet DNA. Valmet DNA is a DCS (distributed control system) system which can be applied for different areas like process controls, drive controls, machine controls and quality controls. (Valmet, 2021a) Process control system has been supplied by the same company as was doing the data analysis so there were no issues in collecting the data from the system to Valmet's cloud server. Process data is stored at least one year so it was possible to collect the process data of the five normal customer orders mentioned above as well. In addition to process data, laboratory data was collected from the trial order and additional normal customer orders.

Trial reels were produced on 12.10.2021. Amount of the collected data for the data analysis was largest from the board machine. There are thousands of signals measured in the board machine and therefore it is not appropriate to list them all here. All the signals connected to Valmet DNA system were available for the data analysis. Data measurement frequency in a board machine is typically 1 minute but higher frequencies may be required because of nature of the register stability at rotogravure printing. One minute aggregate most probably is not enough for the data analysis as the register movement happens typically on a scale of seconds. According to a preliminary project information, the most interesting controlled variables regarding to a register stability issue are related to changes and variations in moisture, dry weight and stock flows. Stability in these above-mentioned areas is important which was also indicated in the literature review section 2. Profile analyses will be done for different machine direction and cross-machine direction profiles like grammage and thickness. Valmet carried out an additional fixed-point measurement with a traversing scanner during the trial run. In fixed point measurement, the traversing scanner stays specified time at a static position in cross-machine direction. For the data analysis fixed point data was collected from all four web positions from where the trial reels were cut. Purpose was to collect more data for machine directional stability analysis. Laboratory data will complement the process data in the data analysis.

9.3 Winder

Metsä Board Tako winder no. 2 has been supplied by Valmet. Winder is so called two drum winder where formed customer reels lie on two winding drums. Winder's maximum speed is 1600 m/min.

Trial reels were winded on the same day, 12.10.2021, immediately after they were produced by BM1. Winder's process control system is isolated from the mill's main process control system, so the data was collected by an offline data dump after the trial reels were cut. Process data will be stored at least one year so it was possible to get process data from the five normal customer orders as well. Number of the controlled variables in winder are much less compared to the board machine. There may be close to 200 signals measured in a winder, but the exact amount varies from a winder to winder. Most interesting controlled variables are related to a reel forming and tightness, which importance was indicated already in the literature review section 2. Also, any type of vibrations or winding faults are interesting regarding to the register stability at a rotogravure printing machine. According to Valmet, data measurement frequency has been typically higher in winder analytics compared to a board machine. Typical measurement frequency is 200 ms, which is considered to be frequent enough for the register stability investigations.

9.4 Transportation and warehousing

Trial reels delivery conditions were monitored with data logger devices developed by Valmet. Data loggers were installed inside each reel core of the trial order reels after the winding. Data loggers were carefully protected so they did not get harmed during the transportation. These devices monitored four variables during the transportation: humidity, temperature, pressure and acceleration. (Valmet, 2021f) Regarding register stability problems, the main concerns during the transportation and warehousing are related to humidity and temperature. Rapid changes in the above-mentioned variables in addition to improper warming-up procedure of a reel might lead to a register stability issue. Acceleration data will reveal if the trial reels were exposed to strong mechanical hits during the transportation. Strong mechanical hits caused by for example dropping a reel or hitting by a forklift may cause runnability issue at printing or other converting. Typically, these kinds of defects will be seen visually from a reel wrapping as well. Most of the data loggers were set to 5 minutes measurement interval but some of them were set to 1 minute interval to collect more frequent data for the data analysis. (Valmet, 2021f) Data loggers were taken out from the trial reels at Kouvola warehouse just before a truck came to pick them up on

3.11.2021. Originally the plan was to take the data loggers out from the reels at the converter's site but due to concerns regarding customs clearance it was decided to take them out before exceeding the border. Data logger device without a protective wrapping is shown in Figure 18

Figure 18 Data logger device without a wrapping (Valmet, 2021f)

9.5 Rotogravure printing machine

Printing of the trial reels were carried out at the converter's site in St. Petersburg, Russia at 9.-10.11.2021. Rotogravure printing machine chosen to trial was Bobst Lemanic Drive 82 HS (R36). Bobst corporation is one of the leading suppliers of a printing and converting equipment and it has headquarters in Mex, Switzerland. (Bobst, 2021) Printing machine has 12 printing units and rotary converting tools. Register correction system was Registron S 6100. Printed design was JTI LD Autograph Blue, which is a blank for a cigarette pack. Type of the process was reel to blanks, and printing speed varied from 180 to 255 m/min during the trial run.

Rotogravure printing machine had four main data sources from where the data was collected. Data sources were Bobst Registration system, Valmet IQ Multipoint Measurement probes, MES system and manually added parameters including quality data. These data sources are explained more in a detail in this section. During the printing of the trial reels, documentation of reel ID’s in all data sources were crucial because they were the link between the data collected from the printing machine and overall paperboard manufacturing process. Also, time synchronization between different systems were carefully confirmed, that all the data collected from the printing process were possible to be connected to each other reliably and to the overall paperboard manufacturing process data.

Before the printing trial Valmet installed moisture and temperature measurement probes (Valmet IQ Multipoint) in the rotogravure printing machine in cooperation with the converter. Measurements are based on an IR principle, so they are not physically contacting to the moving paperboard web. (Valmet, 2021c) In total there were five measurement probes installed containing both, moisture and temperature measurement. Three of them were installed before the first printing unit and two of them were installed after the last printing unit. Three measurement probes installed before printing units were positioned on the gear side, middle and operator side of the machine. Respectively two measurement probes installed after printing were positioned on the gear side and operator side. Each printing unit has own drying, so the probes were basically installed before and after drying, which was seen as the most crucial phase regarding register stability.

Leading idea of installing the moisture and temperature measurement probes in the rotogravure printing machine was to monitor behavior of these variables in cross-machine direction and machine direction during the printing process. Based on the preliminary information, changes in moisture and temperature of the paperboard web are connected to a register stability. Moisture and temperature data from the rotogravure printing machine has not been available before so it required installation of the measurement probes. Measurement frequency was 1 s, which has been seen enough for the register stability research. Data from this source was directly transferred to Valmet's cloud server.

Technician from the machine supplier Bobst recorded register movement and machine speed during the trial run. Register movement in cross-machine direction and machine direction were recorded per each controlled unit with 0.01 mm accuracy. Register measurements did not have a time stamp but a sequence number as an ID of each measurement. Measurement frequency was a revolution of a printing cylinder. Unit of the machine speed was m/s instead of typical m/min. Bobst technician was required to be in place because with the current solution, recording of the register movement was not possible to do remotely. Register movement and machine speed data were shared by Bobst technician in an Excel file format, which was transferred to Valmet's cloud server.

Converter has a manufacturing execution system (MES), where certain production variables were possible to collect. Unfortunately, production variable data was not available by the reel numbers so the data cannot be linked to specified reels. This was seen more as a common information from the trial run and utilisation of this data in the data analysis would be difficult. These production variables were taken from the MES system after the printing trial and they were shared in an Excel format, which was transferred to Valmet's cloud server for data analysis. Production variables which were received from the MES system are shown in Table 15.

Table 15 Production variables collected from the MES system

Process	Production variable	Main impact	Definition	Unit
Printing	Machine stops	Production efficiency	Machine stops listed by a reason	#
	Setup waste	Production efficiency	Amount of waste created during a setup	m
	Run waste	Production efficiency	Amount of waste during a production run	%
	Total waste	Production efficiency	Total waste amount	%
	Time distribution	Production efficiency	Setup, run, downtime and maintenance	min

Some of the controlled variables from the rotogravure printing machine needed to be collected manually during the trial run as there were no signals coming to MES system nor to Bobst process control system. Below mentioned controlled variables were documented during the trial with a reel ID and time stamp. These controlled variables were shared in an Excel file, which was transferred to Valmet's cloud server. Utilisation of the manually collected data involved challenges because the measurement frequency was only per reel so only 28 measurement results were collected during the trial run. Relatively small amount of data would probably not offer enough information benefiting the data analysis work. Manually collected controlled variables are shown in Table 16.

Table 16 Manually collected controlled variables

Process	Controlled variable	Main impact	Definition	Unit
Printing	Speed	Runnability, efficiency	Machine speed	m/min
	Web tension infeed/outfeed	Web tension	Web tension between the printing units	kN/m
	Impression roller pressure	Ink transfer	Press force against printing cylinder	bar, MPa
	Electrostatic system set point	Ink transfer	Creates charge on the surface of an impression roller	% of max power
	Dryers' temperature	Ink drying	Temperature in a drying hood	°C
	Ink viscosity	Ink transfer	Effects on flow properties	mPa*s, sec
	Ink temperature	Ink transfer	Effects on flow properties	°C
	Varnish viscosity	Varnish transfer	Effects on flow properties	mPa*s, sec
	Varnish temperature	Varnish transfer	Effects on flow properties	°C

Quality data measured in the laboratory was also collected manually. Quality data was measured from the ready blanks and all the measurements were done from all the 28 trial reels. The same issue of small data amount and low measurement frequency concerned also quality data like was discussed above with the manually collected data. The data was shared in an Excel file, which was transferred to Valmet's cloud server. Executed laboratory measurements are shown in Table 17.

Table 17 Laboratory measurements done from the ready blanks (Hancock, 1997)

Process	Laboratory measurement	Main impact	Definition	Unit
Laboratory	Crease recovery	Crease quality	Measures crease resistance	mN*m
	Residual solvent level	Solvent retention	Describes solvent evaporation from substrate, (IPAC, ETAC, IPOL)	mg/m^2
	CIE L*a*b* values	Visual appearance	Paperboard shade	#
	Thickness	Runnability	Blank thickness	µm
	Grammage	Runnability	Paperboard grammage	g/m^2
	Twist	Runnability	Blank twist (PMI and JTI method)	mm
	Curl	Runnability	Blank curl (PMI and JTI method)	mm

10 DATA ANALYSIS

When starting to compile this section, data analysis work done by Valmet was ready. Only laboratory data from the board machine was not available for the data analysis because of certain data transfer issues. Nevertheless, Valmet assumed that the laboratory data would not influence on the data analysis results because of its relatively small data amount. Laboratory data is available per machine reel, which would mean only four different measurement result per quality measurement in the case of trial order of 28 reels. Additional board machine and winder process data gathered from the five customer orders specified by the converter were analysed without a laboratory data as well and findings will be presented later in this section. In this section data analysis results shared by Valmet has been used as a source. Data analysis results will be not included in the list of references because they are not publicly available.

10.1 Description of the data analysis of the trial order

Data analysis was made by Valmet after the data collection part. Valmet has named this service to Data Discovery, where Valmet analytics and process experts are involved in projects. Purpose of Data Discovery is to offer advanced analytics with artificial intelligence methods to correct issues which are already known or research underlaying potential of improvement in customer’s processes. Data Discovery projects are always individually defined for example based on the customer needs and available data. Data analysis was coded by using Python language (https://www.python.org/). In some cases, Valmet is also using MATLAB software (https://www.mathworks.com/) but in this case it was not used.

Main idea of the data analysis of the trial order was to divide reels in three groups by using a hierarchical clustering. Hierarchical clustering can be performed with agglomerative or divisive methods. In agglomerative hierarchical clustering clusters are formed from individual clusters to a cluster, which includes all the individual clusters. Divisive clustering is considered to be more difficult to form because it is implemented contrarily than the agglomerative one. Agglomerative and divisive clustering methods are both used to data organizing. Data is typically organized based on a distance matrix into the hierarchical structure. A binary tree or dendrogram are the typical ways to present the results of hierarchical clustering. (Xu & Wunsch, 2009) For the data analysis, hierarchical clustering was done based on the data collected from the Valmet IQ Multipoint sensors, which were installed in the rotogravure printing machine before the trial. Valmet IQ Multipoint sensors were collecting temperature and moisture data before and after printing units. All the collected measurements during the trial from all the sensors were available for the hierarchical clustering. Three groups were seen optimal for relatively small number of reels. Two groups would have been representing mostly differences between the two trial days, which was found out to be related to printing process itself than paperboard-based differences. Dividing reels to four groups would not have given any extra benefit for the data analysis thus three reel groups were formed. Groups and their most important differences identified by the clustering analysis are shown in Table 18.

Table 18 Reel groups identified with the clustering analysis (Valmet, 2022)

	Group 1	Group 2	Group 3	Comment
Reel amount	9	13	6	
Trial day	Includes reels only from the 1st trial day	Includes reels from both trial days	Includes reels only from the 2nd trial day	
Side register error	The highest side register values (reel 4530222606 with filtering)		The lowest side register values	
Temperature before printing units (Valmet IQ Multipoint)	Lowest		Highest	No direct correlation to transportation or warehousing
Temperature after printing units (Valmet IQ Multipoint)	Lowest		Highest	No direct correlation to transportation or warehousing
Moisture before printing units (Valmet IQ Multipoint)		Highest (edges)		No direct correlation to transportation or warehousing
Moisture after printing units (Valmet IQ Multipoint)	Lowest			No direct correlation to transportation or warehousing
Printing machine speed			> 250 m/min	Speed differences were related to cutting tool
Board machine reels			No reels from machine reels 41262289 and -90	
Deckle position	No reels from D position	Includes most of the reels from D position		
Three deviating reels	4530222606 (B position)	4530222506 (D position)	4530222386 (D position)	

After the trial reels were divided into groups by a hierarchical clustering, differences between the groups regarding several features were searched. The main idea in the data analysis was to find out correlations between the register stability data and rest of the collected data. Correlations were searched also for example between the moisture measured at the board machine and rotogravure printing machine. Researched features were for example process data, Valmet IQ Multipoint measurement data, cross-machine directional profiles, register stability, deckle position, and transportation and warehousing conditions. In this part Valmet used Mann-Whitney U-test for the correlation analysis and Benjamini & Hochberg method to P-value correction. Mann-Whitney U-test was chosen for the correlation analysis because it was assumed that the collected data does not follow the assumption of normality. Mann-Whitney U-test does not assume that the distributions would be similar in shape. Based on the Valmet's experience, this kind of process data may be often biased so Mann-Whitney U-test was the best choice for processing the data without assuming normality. (Rosner & Grove, 1999) Mann-Whitney U-test is often called as the Wilcoxon-Mann-Whitney test or the rank sum test. (Fagerland & Sandvik, 2009) After the correlation analysis from the data presented above was done and P-values were calculated by Mann-Whitney U-test, they were corrected by Benjamini-Hochberg method. Correction of the P-values are required to be done lowering the false discovery rate. It is known that sometimes small P-values are found accidentally, when relatively large amount of research are done for a large data set. Smaller the P-value are more likely the alternative hypothesis are true and null hypotheses are rejected thus in P-values 1 equals to not true and 0 equals to true. In practice P-value is used as a tool in defining are the found correlations relevant or not. (Westfall, 2008)

10.2 Data analysis results of the trial order

Register movement was relatively minor during the trial run of 28 reels. This fact sets some limitations for the correlation analysis because there were not significant differences in a register movement between the trial reels. There were also other factors which effected on the data analysis outcome. Data logger data recorded from the transportation and warehousing conditions were successful to 18 reels out of 28. 10 data loggers did not work as planned for some reason. As mentioned earlier, the board machine laboratory data was missing and rotogravure printing machine manually collected data and quality data were limited to a reel level, which means 28 results per quality measurement. Number of measurements were seen too small for considerable analysis results. Printing process production variables collected from a

MES system were not possible to link to certain a reel, so it was not either possible to utilise in the data analysis. Valmet raised a concern about how the register movement data was collected with missing timestamps. Timestamps for the register movement data were calculated out of printing cylinder revolutions and a printing cylinder circumference. According to Valmet, accuracy of this method was questionable, and it may cause some bias to the results. It was also pointed out, that used analytical methods are designed for finding differences from the data thus some differences are always found. Results were shared in a PowerPoint-show.

Figures in this section (Figures 23, 25 and 26), which are presenting moisture or temperature values measured by Valmet IQ Multipoint sensors are presented in box-and-whisker plots. Box-and-whisker plots or boxplots are efficient way to present graphically a data set because they allow to show several properties of data at a time. A box-and-whisker plot shows well for example what is spread of values in an examined data. Box height represents 50 % of data and it is also called as interquartile range or IQR. Whiskers attached to a box, above and below, are representing 25 % of data. Maximum length of a whisker is 1.5 times the height of the box. If there is a data point outside the whisker, it is called as outlier. Outlier means a value which is differing remarkably from rest of the data set. An outlier having the lowest or highest value in a plot are then minimum or maximum data value in question. Without outlier values, ends of the whiskers are showing the minimum and maximum values of a data. (Ferreira et al., 2016) In this section comparison between the different measurement results are done mainly based on the median value, which has been presented with a horizontal line inside the box. Comparison made based on the median value allows to compare the difference in level of certain moisture or temperature measurement. In addition to a median value, box height and outlier values, if existing, are commented as well. Content of a box-and-whisker plot is presented in Figure 19.

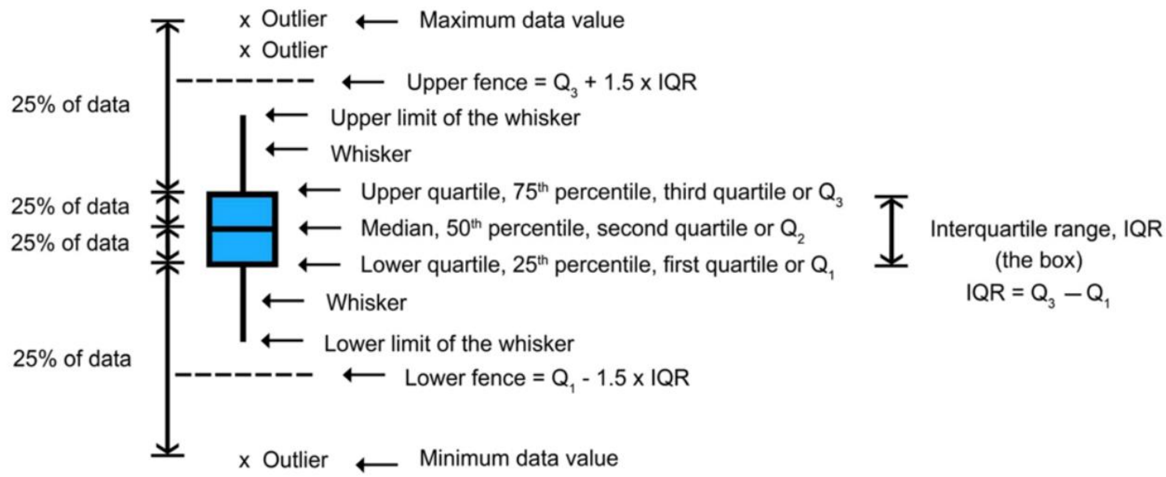

Figure 19 Content of a box-and-whisker plot (Ferreira et al., 2016)

Printing order of the trial reels are shown in Table 19. Table 19 includes also information about the reel ID, machine reel, deckle position, reel group and the trial day. Deckle position describes a cross-machine directional position, from where the reel has been cut. Position A reel is a reel cut from the front edge of a machine reel, position B reel is the next one and so on. Position D reel is a reel cut from the back edge of a machine reel. Trial reels included four deckle positions from A to D. Trial reels information table is presented in Appendix 1.

Table 19 Printing order of the trial reels (Valmet, 2022)

Printing order	Reel ID	Machine reel	Deckle position	Group	Trial day
1	4530222606	41262292	B	1	
2	4530222576	41262292	C	2	
3	4530222616	41262292	C	1	
4	4530222486	41262289	B	2	
5	4530222526	41262290	B	1	
6	4530222536	41262290	C	2	
7	4530222376	41262288	C	1	1.
8	4530222476	41262289	A	1	
9	4530222496	41262289	C	1	

10	4530222556	41262292	A	1	
11	4530222516	41262290	A	1	
12	4530222566	41262292	B	1	
13	4530222506	41262289	D	2	2.
14	4530222546	41262290	D	2	
15	4530222466	41262289	D	2	
16	4530222426	41262288	D	2	
17	4530222386	41262288	D	3	
18	4530222596	41262292	A	3	
19	4530222406	41262288	B	2	
20	4530222396	41262288	A	2	
21	4530222356	41262288	A	3	
22	4530222366	41262288	B	3	
23	4530222446	41262289	B	2	
24	4530222436	41262289	A	2	
25	4530222456	41262289	C	2	
26	4530222416	41262288	C	3	
27	4530222626	41262292	D	2	
28	4530222586	41262292	D	3	

10.2.1 Register stability

During the trial run, three deviating reels were identified. Reel ID 4530222606 was the first reel of the first trial day, and it showed high cross-machine directional register movement values in the beginning of the reel. Reel ID 4530222506 was the first reel of the second trial day, and it showed as well high cross-machine directional register movement values in the beginning of the reel. Most probably deviations in the beginning of these two reels are connected to reel splicing or a start-up of the printing machine. Reel ID 4530222386 was running during the second trial day, and it showed high cross-machine and machine directional register movement values in the middle of the reel. 7 minutes long machine stop was recorded at the same time. No explanation for the stop was found from the printing process production log. High register movement values of the third reel are then considered to be connected to un-recorded short-termed issue in the printing process instead of a paperboard-based problem. Based on the above mentioned, these three deviating reels were partly excluded from the data analysis to avoid bias. In practice the outlier values of the register movement were excluded from these reels. Sorting these non-paperboards related outlier values away, had a major effect on the data analysis results thus it was important measure to do.

Reel group 3 had the best register stability compared to two other groups. In the reel groups 1 and 2 register stability were quite on the same level but the reel group 1 had more outlier values. Nevertheless, as mentioned earlier, all the reels excluding these above presented three deviating reels had relatively good register stability with small differences. According to the converter, no finished goods were rejected due to misregister. Rejection limit for a print-to-print misregister was in this job 0.15 mm. Absolute cross-machine directional register stability measurements by reel group are shown in Figure 20. Only values larger than 1 (or 0.01 mm) are shown for the illustration purposes. It can be seen from the figure, that most of the individual measurements has been below 0.1 mm. One circle in the figure is representing one measurement result. Completely black area in the bar describes the area, where most of the measurements has been. Register stability data measurement frequency was a printing cylinder rotation. Measured values over 0.1 mm has been individual values from certain reels like can be seen on top area of the bars, where are only individual circles. It needs to be considered, that individual measurements over 0.15 mm does not directly mean exceeding the misregister rejection limit. Need for a rejection needs to be confirmed from actual finished goods. In addition, it cannot be defined from the figure in which situation the individual values exceeding 0.15 mm limit has been recorded. Rejection limit is illustrated with a red line.

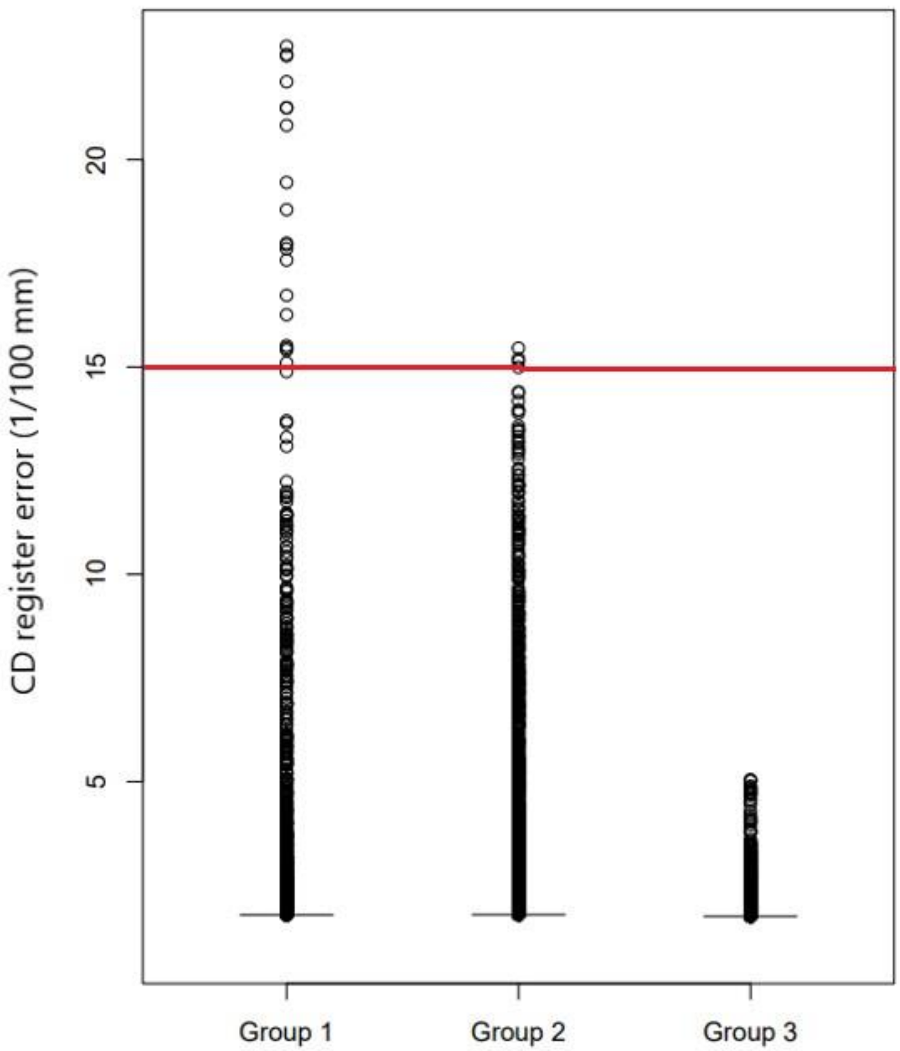

Figure 20 Absolute cross-machine directional (CD) register stability measurements by reel group (Valmet, 2022)

Absolute cross-machine directional register stability measurements by a deckle position are shown in Figure 21. Figure 21 contains the same data than in Figure 20, but it is illustrated by the deckle positions instead of the reel groups. Only values larger than 1 (or 0.01 mm) are shown for the illustration purposes. Register stability has only a small variation when comparing between deckle positions. The same individual values exceeding the 0.15 mm rejection limit can be seen in both Figures 20 and 21. Rejection limit is illustrated with a red line.

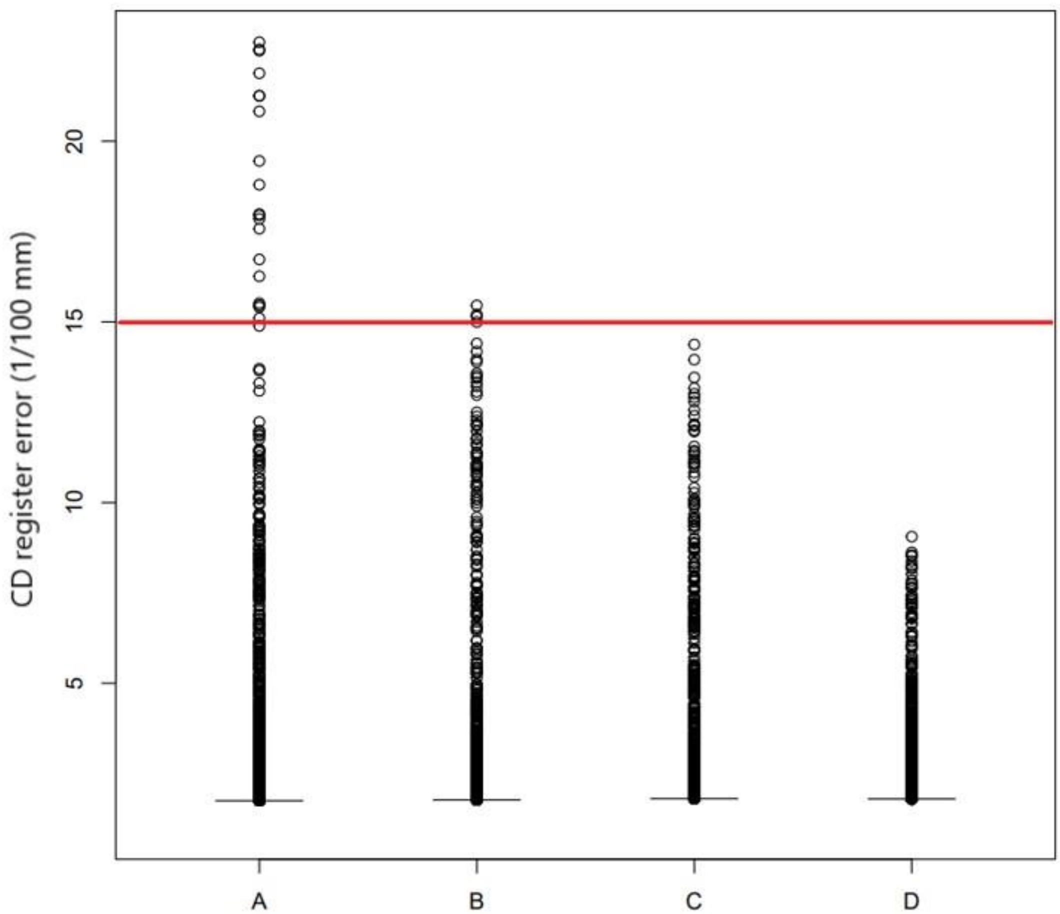

Figure 21 Absolute cross-machine directional (CD) register stability measurements by a deckle position (Valmet, 2022)

10.2.2 Rotogravure printing machine speed

An observation was, that the rotogravure printing machine speed was lower on the first trial day compared to the second trial day. On the first trial day average speed was approximately 180 m/min when on the second trial day the average speed was approximately 255 m/min. According to the converter, reason behind the speed difference was a cutting tool, which was replaced after the first trial day. This was a valuable information for the data analysis, that the speed difference was not related to the paperboard properties. Otherwise, it would have changed the correlation analysis results significantly by a biased data source. Printing machine speed is presented in Figure 22. Figure is divided to 28 sectors by grey bars. Each sector is illustrating one trial reel.

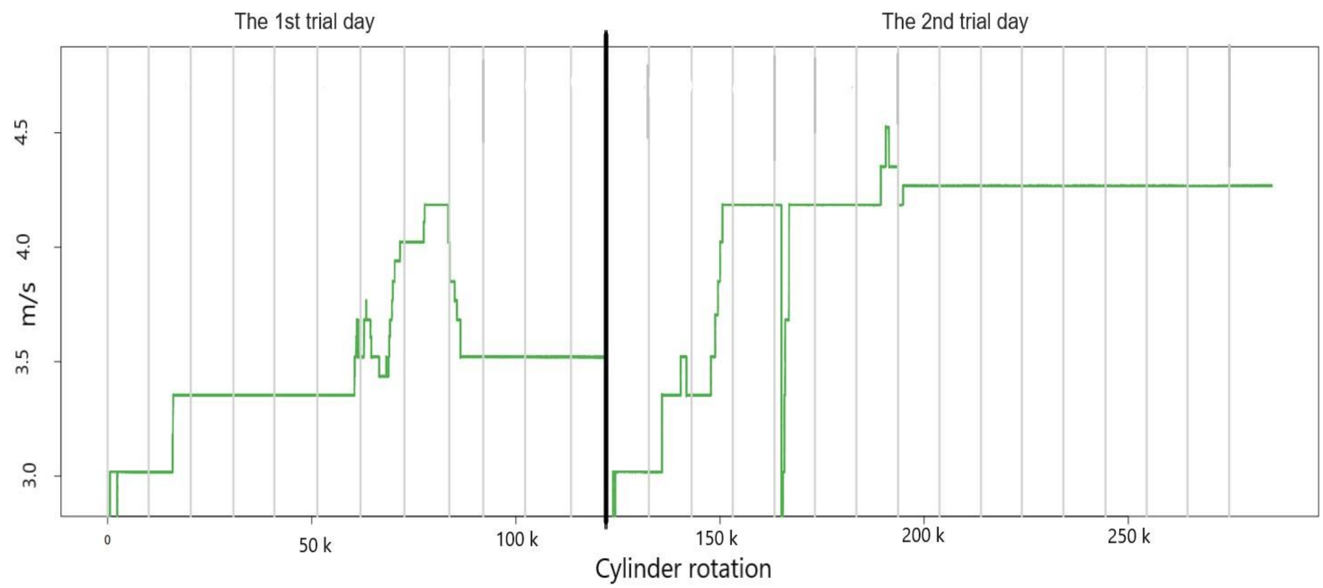

Figure 22 Rotogravure printing machine speed during the trial days (Valmet, 2022)

10.2.3 Moisture before and after the printing units

Moisture before and after the printing units were measured with Valmet IQ Multipoint measurement sensors. It was recognized that the reels from a deckle position D had the highest moisture values especially on the edge areas measured before printing units. Moisture difference in median values measured by the front edge sensor before the drying units were in average roughly 0.7 percentage points varying from 8.6 % to 9.3 % between the deckle positions. The box height describes 50 % of the data so half of the measurements have been inside 0.1 – 0.3 percent in moisture content depending on the deckle position.

Reel group 2 had most of the deckle position D reels and it was noticed to have slightly decreased in the register stability compared to group 3. Anyway, reel group 1 did not contain any reels from deckle position D, but it had the highest outlier values measured in the register stability. Based on the above mentioned we can conclude that reel deckle position nor moisture content measured before the printing units at the rotogravure printing during this trial did not have remarkable correlation on the register stability. Valmet IQ Multipoint moisture measurements by a deckle position at the front edge before the drying units are shown in Figure 23. All the deckle positions included some outlier values. Deckle positions A, B and D included outlier values below the lower limit of the whisker. Deckle position C included outlier values exceeding the lower and upper limit of the whisker. Minimum value in the Figure 23 is around 7.8 % and it was measured during a position A reel. Minimum value was outlier. Maximum value in the Figure 23 is around 9.7 % and it was measured during a position D reel. Maximum value is shown by the end of the above whisker in a deckle position D.

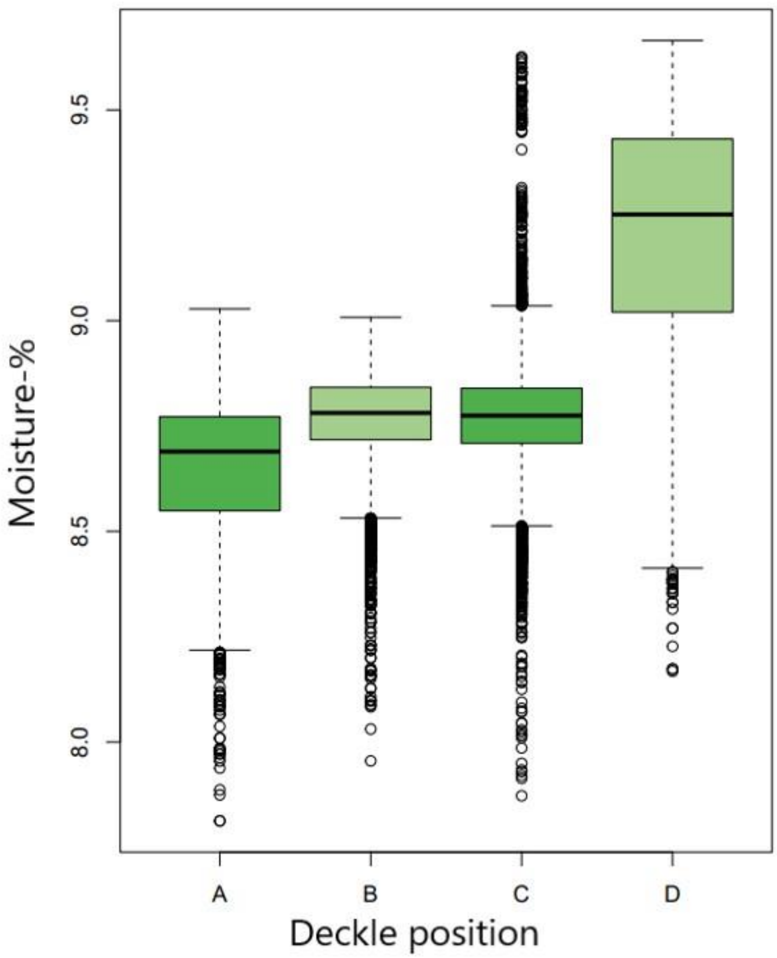

Figure 23 Valmet IQ Multipoint moisture measurements from the frontside sensor before the drying units by a deckle position (Valmet, 2022)

Trim wastes were taken 206 mm from both sides of the machine reels, which means that the material with highest moisture values did not end to the trial reels. The highest online moisture value measured at the reeler was approximately 8 % in the reels cut from D position. That supports the measurements made with Valmet IQ Multipoint sensors as they seem to be parallel. Reels from deckle positions A, B and C shows lower moisture values at the edge position compared to a reel from D position. However, it is also known that moisture peaks tend to even down during the time in transportation and warehousing, which means that the significancy of moisture profile measured during the paperboard production comes less remarkable towards time. Online moisture profiles measured at the reeler of all four machine reels are shown in Figure 24. Trial reels deckle positions have been marked on the figure.

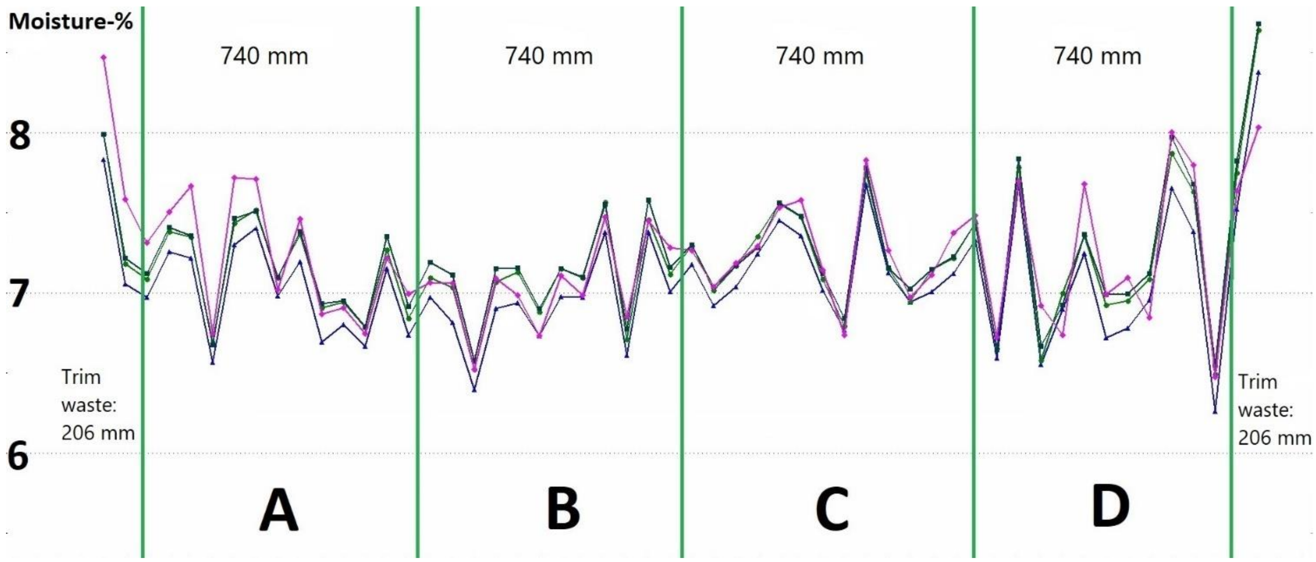

Figure 24 Online moisture profiles measured at the reeler; all the four machine reels included in the trial

10.2.4 Temperature before and after the printing units

Temperature was similarly measured before and after the printing units than moisture. It was noticed that reel group 3 had the highest temperature values before and after printing. Reel group 1 had the lowest temperature values. Reel group 3 did have slightly better register stability compared to reel groups 1 and 2. Temperature difference in median values between the groups inside a one sensor location were averagely around 3 °C varying from 11 to 16.5 °C between the sensor locations. As the box describes 50 % of the values so half of the measurements have been inside 1 – 2 °C depending on the sensor location and the reel group.

Temperature values has been generally on low level before the printing units. Before the printing units a paperboard temperature is not affected by drying units or other external heat sources. Paperboard temperature before the printing units follows the printing hall temperature and it is mostly affected by the paperboard warming-up time in the printing hall temperature. For example, Metsä Board recommends as an optimal converting condition in temperature of 23 °C with a relative humidity of 50 %. (Järvinen, 2016) Based on the collected data from Valmet IQ Multipoint sensors it seems, that higher temperature values especially before the printing leads to a better register stability result. It was also showed in the literature review section 6, that warming-up procedure before printing has a great importance. Paperboard needs enough time to acclimatise in the printing room temperature before printing. Required time for the acclimatisation depends on the reel or pallet weight and temperature difference between the material storage and the printing hall. If a paperboard is not fully acclimatised, it can lead to register stability issues because paperboards dimensional stability and balance are disturbed via moisture changes. Temperatures measured by all the three sensors before the printing units are shown by the reel group in Figure 25. Difference between the temperature scales should be noted. Data collected from the frontside, and middle sensor included some outlier values. Data collected from the backside sensor did not include any outlier values. Data collected from the middle sensor included most of the outlier values exceeding the upper limit of the whisker in all reel groups. Data collected from the frontside sensor included individual outlier values exceeding the upper limit of the whisker in the reel groups 1 and 2. Minimum temperature value in the Figure 25 is around 9 °C and it was measured by the middle sensor during a reel from the reel group 1. Minimum value of the middle sensor is shown by the bottom of the below whisker in the reel group 1. Maximum value in the Figure 25 is around 18 °C and it was measured by the middle sensor during a reel from the reel group 2. Maximum value of the middle sensor is shown as an outlier value above the whisker of the reel group 2.

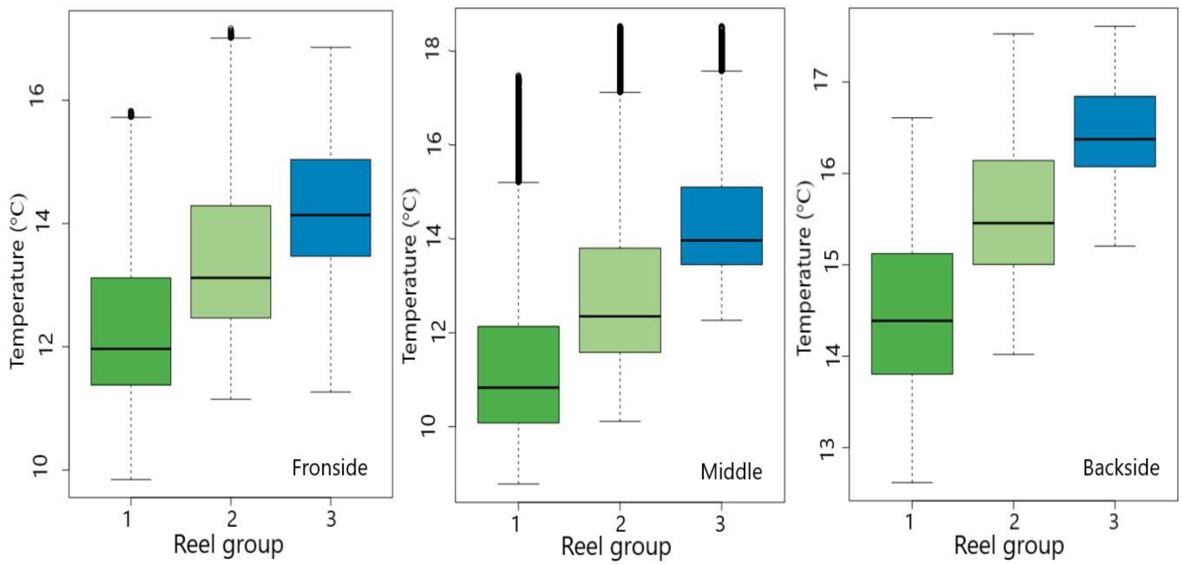

Figure 25 Temperature measurements by reel groups before the printing units (Valmet, 2022)

Temperatures after the printing units were similarly divided than before the printing units. Reel group 1 had the lowest temperatures and the reel group 3 the highest. Temperature difference in median values between the reel groups inside the one sensor location were averagely around 2 °C varying from 35 to 37.5 °C between the sensor locations. As the box describes 50 % of the values thus half of the measurements have been inside 0.25 – 1 °C depending on the sensor location and the reel group.

It needs to be considered, that temperature values after the drying units are mainly affected by a drying temperature. Drying temperatures are typically increased, when a machine speed increases. Second day of the trial printing machine speed was higher thus it can be seen in these measurements between the reel groups. Temperature measurements after the printing units are shown in Figure 26. Difference between the temperature scales should be noted. Data collected from the sensors did not contain any outlier values. Minimum temperature value in the Figure 26 is around 33.5 °C and it was measured by the frontside sensor during a reel from the reel group 1. Minimum value of the frontside sensor is shown by bottom the below whisker in the reel group 1. Maximum value in the Figure 26 is around 38 °C and it was measured by the backside sensor during a reel from the reel group 2. Maximum value of the backside sensor is shown by top of the above whisker in the reel group 2.

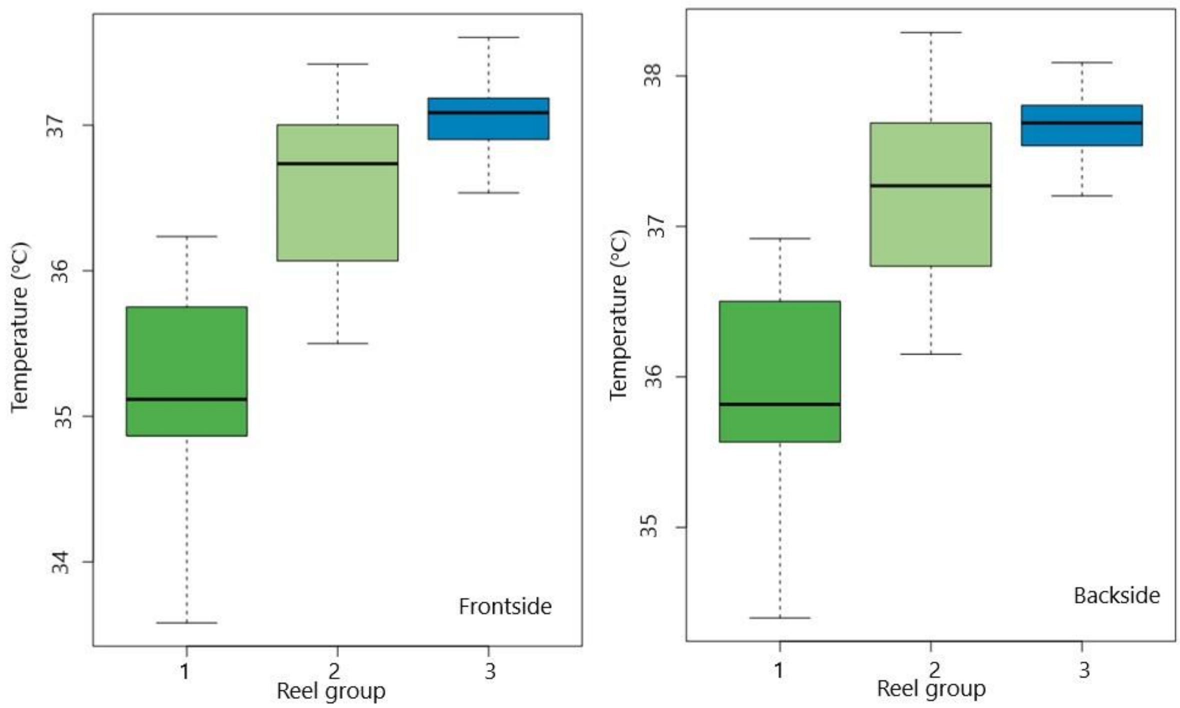

Figure 26 Temperature measurements by reel groups after the printing units (Valmet, 2022)

10.2.5 Conditions during the transportation and warehousing

Transportation and warehousing conditions were recorded with the data loggers installed inside each trial reel core. As mentioned earlier, 18 data loggers out of 28 did work as planned and 10 loggers did not work for some reason. Reel numbers connected to line colours for Figures 28 and 29 are shown in Figure 27. Relative humidity development during the transportation and warehousing is shown in Figure 28. Temperature development during the transportation and warehousing is shown in Figure 29. Both temperature and relative humidity values shows high spread especially during the first days since the production date 12.10.2021. All the reels were transported to Kouvola warehouse already on 13.10.2021 but still variation between the reels is relatively large. Temperature range was varying from 20 to 45 °C and relative humidity range was varying from 30 to 60 % in the beginning. In the end of the recording, temperature range is varying from 15 to 25 °C and relative humidity range was varying from 44 to 50 %. Two reels, ID's 4530222506 and 4530222446 were showing clearly lower relative humidity values compared to rest of the batch. Temperature values were not differing from rest of the batch. Considering, that the reels were transported with similar equipment, and they were stored in the same conditions, it can be concluded that relative humidity measurements for these two reels are most probably not valid.

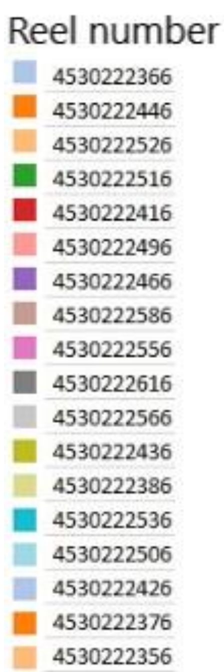

Figure 27 Reel numbers connected to the line colours in Figures 28, 29 and 30 (Valmet, 2022)

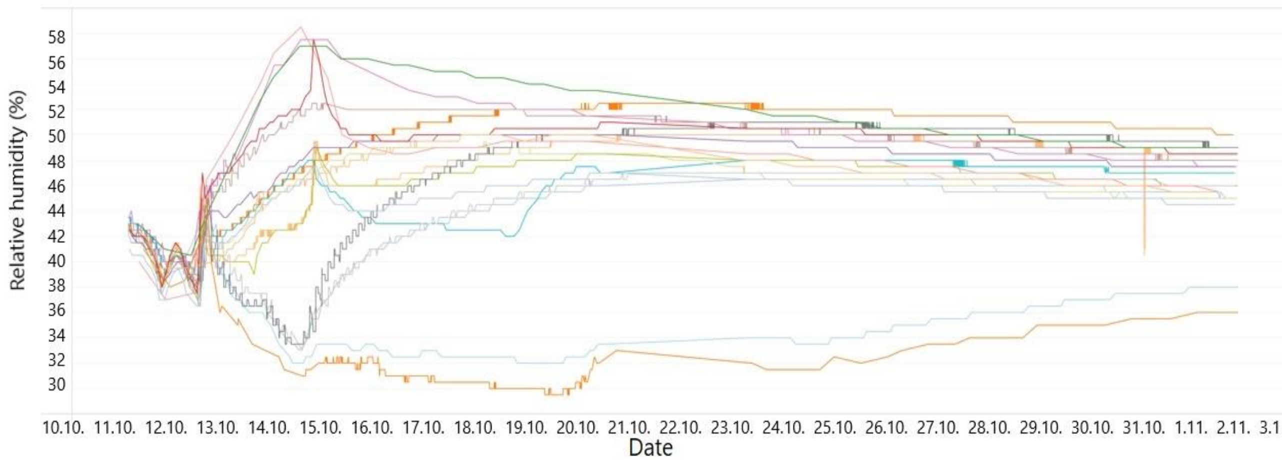

Figure 28 Development of the relative humidity (RH) during the transportation and warehousing. Two outlier reels with low RH: ID's 4530222506 and 4530222446 (Valmet, 2022)

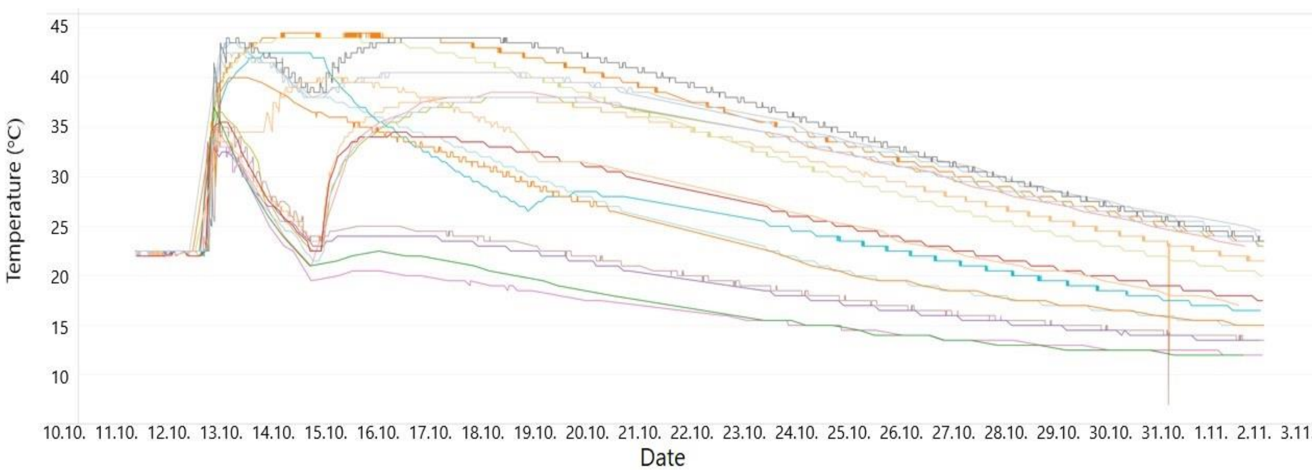

Figure 29 Development of the temperature during the transportation and warehousing (Valmet, 2022)

According to Valmet's data analysis, reels with a higher temperature during the transportation and warehousing had slightly better register stability than reels with a lower temperature. When presenting the reels in a figure, where the relative humidity is on the X-axis and temperature on the Y-axis, three reel groups can be formed. Reel groups are the following: a low relative humidity and high temperature, a high relative humidity and a high temperature and high relative humidity and low temperature. Threshold for a high temperature was set to 33 °C and for a high relative humidity it was 39 %. Temperature and relative humidity development drawn in the same figure are shown in Figure 30. Finding supports the importance of proper warming-up time for the paperboard like presented above in a discussion about a temperature before and after the printing units and in the literature review section 6. When a paperboard is having higher temperature during the transportation and warehousing, less warming-up time is required before a printing or other converting. In the case of lower temperature, required warming up time is naturally longer. According to the findings in literature review section 2, it can be concluded that if a reel wrapping is sound, temperature is then more important parameter than a relative humidity. Sound polyethylene (PE) reel wrapping gives a good vapor protection for a reel thus changes in the relative humidity does not affect much on the paperboard. However, typical PE reel wrapping cannot protect a paperboard from the temperature changes.

It needs to be considered, that data loggers were taken out from the reels already at Kouvola warehouse on 3.11.2021 before the trial reels were picked up by the converter. Printing trial took place at 9.-10.11.2021 so there were 6-7 days without conditions recording.

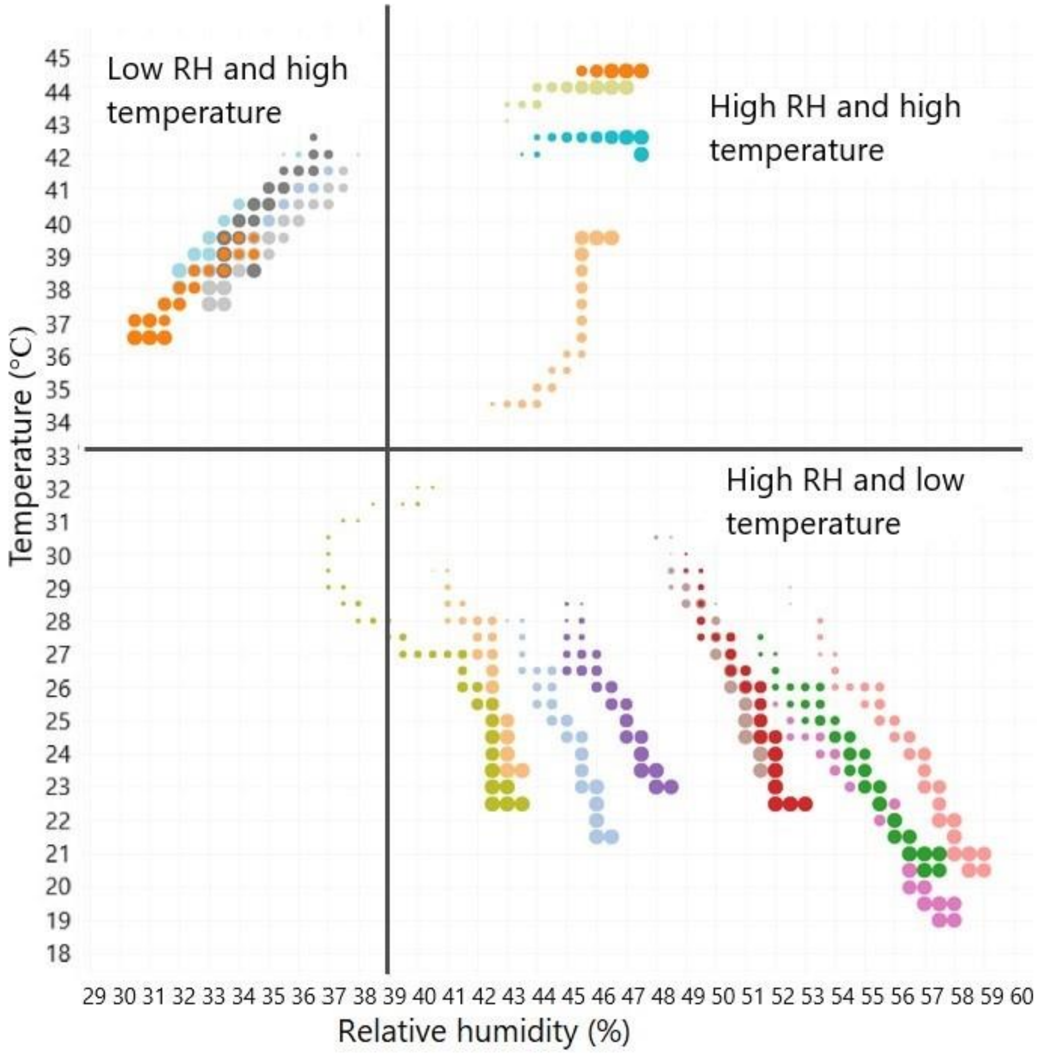

Figure 30 Temperature and relative humidity (RH) development during the transportation and warehousing (Valmet, 2022)

Example of a warming-up guide is presented in Table 20. It can be seen, that with a heavy reel or paperboard pallet, warming-up time is recommended to be 150 hours if the temperature difference is 40 °C. Temperature difference is meaning the difference between a paperboard or warehouse and printing room. It is important to remember, that reel or pallet wrapping should be removed only after the material has been fully acclimatised.

Table 20 Warming-up time of paperboard pallets or reels (Järvinen, 2016)

WARMING-UP TIME OF PAPERBOARD PALLETS OR REELS (HOURS)

WEIGHT OR SHORTEST DIMENSION		TEMPERATURE DIFFERENCE (°C)							
KG	MM	5°	10°	15°	20°	25°	30°	35°	40°
200	650	10	30	45	60	75	85	95	100
400	700	15	35	50	65	80	90	100	105
600	750	20	40	55	70	85	95	105	110
800	800	25	45	60	75	90	100	110	115
1000	850	25	50	65	80	95	105	115	120
1200	900	30	55	75	90	105	115	125	130
1400	950	35	60	85	100	115	125	135	140
1600	1000	40	70	95	110	125	135	145	150

10.2.6 Process data

Process data analysis did not offer significant correlations due to limitations of the available data thus they were not included in the results at all. The main reason for a lack of high-quality correlations was based on the fact, that the register stability in the trial reels was too similar compared to each other. In an optimal situation, researched variable contains notable long lasting differences, that high-quality and confirmable correlations for example from the process data could be recognized.

10.3 Description of the data analysis of the normal customer orders

Data analysis was carried out in a different way compared to data analysis for trial reels presented earlier. The main reason for different approach were the fact, that data for analysis were available only from the board machine and winder. Transportation and warehousing condition data or a printing machine data were not available as the analysed orders were normal customer orders produced and used before the trial set-up was created. Data analysis based on the information about the reels, which were consumed without any register stability issues, and reels which were consumed with a lower speed due to register stability issues. Valmet’s main idea in this data analysis was to compare the board machine and winder process data from the machine reels, from where the claimed customer reels were cut against the process data from the machine reels, from where good customer reels were cut. Possible paperboard web breaks and other disturbance causing situations were excluded from the data. Data analysis was made based on the assumption, that there are some visible differences in the process data values between these two reel groups. Group of claimed reels contained 63 customer reels cut from 16 machine reels. Group of good reels contained 48 customer reels cut from 10 machine reels. 28 trial reels, which had been cut from 4 machine reels were also added to the good reels group for allowing more data. This type of data analysis work based only on the reel level have some concerns, which may effect on the accuracy of results. The main concern comes from the fact, that when the register stability data was not available, exact quality and duration of register instability are unknown inside one reel. In other words, it means, that for example exact areas of the reel where the register instability has been presented are not known. Without the possibility to focus on the exact areas, where the register stability issues have been directed, they might disappear along the data analysed from longer time period. Corrective action for this concern is to ensure the register stability data availability in the next trial.

10.4 Data analysis results of the normal customer orders

Board machine analysis included in total 2356 tags from the board machine and stock preparation. Stock preparation was included in the data analysis because there might be some flow or consistency-based deviations coming from the stock preparation process, which may effect on the register stability. Winder analysis included 29 tags. Tags consisted of measurements, set points, manual/automatic selections, controls and actuator positions. Valmet’s data analysis results were shared by Excel files, where were the following columns: Tag name, Tag description, Not OK reels median, OK reels median, P-value, adjusted P-value, Ratio (not OK/OK) and Difference (not OK – OK). Tag names were not presented in the winder results. Columns and their descriptions are shown in Table 21.

Table 21 Data analysis result file content

Column	Description
Tag name	Tells a tag name, for example 30-FFIC-4794:me
Tag description	For example, CTMP1 PUMP.SÄ.LINJA
Not OK reels median	Median for a certain tag over the machine reels, where not OK reels were cut
OK reels median	Median for a certain tag over the machine reels, where OK reels were cut
P-value	Probability that the statistical finding is true, value between 0 and 1, where 1 = not true and 0 = true
Adjusted P-value	Lowering the false discovery rate
Ratio (not OK/OK)	Median value of not OK reels divided by median value of OK reels
Difference (not OK – OK)	Median value of OK reels extracted from median value of not OK reels

10.4.1 Board machine

According to Valmet, P-value limit for the process data would be good to set at 0.001. In practice it means, that all the tags with adjusted P-value equal or under 0.001 might be significant for a rotogravure printing machine register stability. By bordering the results with adjusted P-value of 0.001, there were left 377 tags out of 2356. Five controlled variables were found from the list, that could have an effect of the register stability based on the knowledge gained in the literature review section 2. Adjusted P-value of all five controlled variables were 4.21×10^{-6} or 0.00000421, which clearly goes below the set limit for a significant finding. Considerable findings from the board machine are shown in Table 22.

Table 22 Considerable findings from the board machine

Tag name	Controlled variable	Not OK reels – Median	OK reels – Median	P-value	P-value adjusted	Ratio (not OK/OK)	Difference (not OK – OK)
50-SIC-1102:av	Middle layer fan pump power, (%)	81.7	87.7	$3.77*10^{-7}$	$4.21*10^{-6}$	0.9	-6.0
50-SIC-1158:av	Reverse layer fan pump power, (%)	76.9	81.2	$3.77*10^{-7}$	$4.21*10^{-6}$	1.0	-4.3
5PIC-1192:pos	Top layer headbox pressure, (%)	28.1	66.3	$3.77*10^{-7}$	$4.21*10^{-6}$	0.4	-38.2
5PIC-1146:pos	Reverse layer headbox pressure, (%)	34.8	50.8	$3.77*10^{-7}$	$4.21*10^{-6}$	0.7	-16.1
KK1-PMSP.opr:me	Moisture before size press, (%)	15.5	13.4	$3.77*10^{-7}$	$4.21*10^{-6}$	1.2	2.1

Middle layer fan pump power median value was roughly 6 percentage points lower during the production of claimed reels compared to the production of good reels. Difference only does not explain the register stability issues in the rotogravure printing. In the literature review section 2 was indicated, that any kind of variation during the manufacturing process may cause register stability issues later in the converting stage. Based on the used data analysis method, where the tag's median values have been compared between the production of good and claimed reels, variation cannot be defined. Similar finding was done with the reverse layer fan pump power, which showed approximately 4.3 percentage points lower median value during the production of claimed reels compared to production of good reels. Fan pump is one of the most sensitive process units if thinking about sources of rapid flow and pressure variations. If there would be a flow and pressure variation coming in diluted stock flow towards to headbox, it could be seen as a deviation in the paperboard web forming. However, if there would be noticeable variation, it would be most probably seen for example in the online quality measurements like in dry weight and moisture.

Top layer headbox showed roughly 38 percentage points difference in pressure between the production of good reels and claimed reels. Respectively reverse layer headbox pressure showed approximately 16 percentage points difference. In both cases, headbox pressure was lower during the production of claimed reels. Again, not only the difference in headbox pressure can explain register stability issues in the converting stage. Similarly like with the fan pump, headbox is for sure one of the most sensitive process units if any variation is taking place. In this case it is good to point out, that the data analysis found out fan pump power median value differences from the middle and reverse layer. Headbox pressure difference in median values were found from top and reverse layer. In the next trial run, headbox pressures and fan pump powers should be followed closely. When the register stability data is available, variations in these process parameters can be explored against a variation in the register stability.

Moisture before the size press showed approximately 2.1 percentage points difference between the production of the good and claimed reels. During the production of claimed reels, moisture has been on a higher level compared to the production of good reels. Target for a moisture before the size press is 12 %. According to findings in the literature review section 2, moisture content at the size press varies typically between 4 and 11 % depending on a paperboard machine and product type. It can be concluded that the moisture content at the size press has not been on the optimal level according to literature references. As mentioned during the above findings, the same principle applies also in here, difference in moisture level only does not explain any register stability issues later at the converting phase. Some type of variation in the moisture content would be exposing to register stability issues but as mentioned it cannot be defined from the data analysis results.

10.4.2 Winder

From the winder there were 29 tags available for the data analysis. The leading idea in the winder analysis were to compare winder sets, from where the good reels were cut to those winder sets, from where the claimed reels were cut. The main concern regarding to the chosen analysis method is the same than with the board machine process data analysis. When analysing the winder data based on a winder set level, any short-termed variations lasting for example only 1/10 of the set, may disappear from a data analysed over the set.

By bordering the winder analysis results by the adjusted P-value at 0.001, there were 12 tags left from 29. Five controlled variables were found from the list, that could influence on the register stability based on the knowledge gained in the literature review section 2. Considerable findings from the winder are shown in Table 23.

Table 23 Considerable findings from the winder

Controlled variable	Not OK reels – Median	OK reels – Median	P-value	P-value adjusted	Ratio (not OK/OK)	Difference (not OK – OK)
Web tension, (N/m)	733.6	599.8	$2.26*10^{-32}$	$1.31*10^{-31}$	1.2	133.9
Web speed, (m/min)	1357.2	1499.2	$1.45*10^{-6}$	$3.23*10^{-6}$	0.9	-142.0
Unwind torque, (Nm)	-243.0	-190.0	$5.39*10^{-6}$	$1.12*10^{-5}$	1.3	-53.0
Rider roll load DS and TS, (N/m)	1397.3	911.4	$1.46*10^{-8}$	$3.93*10^{-8}$	1.5	485.9
Rider roll load reference, (N/m)	1335.9	893.5	$1.3*10^{-5}$	$2.51*10^{-5}$	1.5	442.4

Paperboard web tension showed approximately 134 N/m difference in the median value between the sets of good reels compared to sets of claimed reels. Web tension was at lower level, when the good reels were produced. Again, only the difference between median values does not explain any runnability issues like weak register stability in a rotogravure printing process. Secondly, higher web tension would typically lead in a more robust process depending on the paperboard grade, which was also shown in the literature review section 2. If there would be a noticeable variation in the web tension during the winding process, it could be seen as different winding defects or even variation in a customer reel diameter. Variation cannot be defined from the data analysis result.

Web speed had relatively high difference between the compared batches of good and claimed reel sets. Sets, from where the good reels were cut were produced with roughly 142 m/min higher speed compared to sets, from where the claimed reels were cut in the median values. This might be caused by some runnability issue during the winding, and it has been solved by slowing down the machine speed. No indication to runnability issues were found from the production logs. Speed variation cannot be defined from the data analysis results.

Unwind torque has been also on a higher level during the sets of claimed reels compared to sets of good reels. During the winding of the sets, from where the good reels were cut, unwind torque was around -243 Nm. Respectively during the winding of claimed reels, unwind torque median value was approximately -190 Nm. These values seem to correlate with the web tension values presented above. Variation cannot be defined from the data analysis results.

Rider roll load at the drive side (DS) and tending side (TS) has been on a clearly lower level, when the good reels were produced compared to the claimed reels. Rider roll load median value during the winding of the sets, from where the good reels were cut was roughly 911 N/m. Median value was around 1397 N/m during the winding of the sets, from where the claimed reels were cut. Variation of the rider roll load during the winding cannot be defined from the results. Rider roll load reference median values follows rider roll load DS and TS median values with no remarkable deviation. Values seem to correlate with unwind torque and web tension values, which were both on a higher level during the winding of set, from where the claimed reels were cut. However, variation or other concerns causing register stability issues, cannot be defined from the data analysis results.

10.5 Wrap up of the data analysis results

Regarding the data analysis results of the trial reels, main concern was related to relatively small data amount with small differences in a register stability between the reels. This fact set major limitations for the data analyses as there were not so called good and bad reels regarding a register stability. Nevertheless, correlation to a register stability was found from the paperboard temperature. Findings from the temperature measured at the rotogravure printing machine, and temperature during the transportation and warehousing were aligning. Higher temperatures seem to correlate with a better register stability, but these findings need to be confirmed by a new and more comprehensive trial.

About the data analysis results of the normal customer orders, main concern was coming from the data side as well. In this data analysis, Valmet had only process data from the board machine and winder available. Indication of a register stability came from the information of reels, which were used without any issues and reels, which were used with a lower speed due to a register stability issue. Data analysis was then performed on a machine reel set level, which can be concluded to be too rough for finding high-quality correlations between the process data and a register stability, like has been described above thus the findings can be evaluated to be approximate. Wrap up of the data analysis results are shown in Table 24.

Table 24 Wrap up of the data analysis results

Subject of the data analysis	Result	Further analysis required (Y/N) - description
Register stability	Too little differences between the trial reels for further conclusions	Yes – variation in register stability is required from the data set to be able to find correlations
Rotogravure printing machine speed	Speed difference was related to a cutting tool	Yes – machine speed may have correlation to a register stability but in this trial, difference was caused by a cutting tool
Moist. measurements before and after the drying units	Too little differences for further conclusions	Yes – larger data set is required
Temp. measurements before and after the drying units	Higher temperature showed correlation to a better register stability	Yes – larger data set is required for confirming the correlation
Transportation and warehousing conditions	Higher temperature showed correlation to a better register stability	Yes – larger data set is required for confirming the correlation, data loggers must be removed only just before printing
Board machine process data	Correlations were found but when the register movement data is missing, findings can be evaluated as approximate	Yes – larger data set is required with register movement data from the printing machine
Winder process data	Correlations were found but when the register movement data is missing, findings can be evaluated as approximate	Yes – larger data set is required with register movement data from the printing machine

11 FUTURE WORK

It has been already decided that the project will continue in the future between Metsä Board, Valmet and the converter. So far, the project has given valuable information from the data collection perspective as well the data analysis, and their results has raised the awareness, what will be required from the future work.

Based on the experiences gained during the project, similar approach of using artificial intelligence analytics and methods could be utilised in many areas related to paperboard manufacturing. By using artificial intelligence analytics and methods, it is possible to examine large amount of data collected from different parts of processes, and their relations at a time thus there is a major cost saving potential compared to conventional ways of data analysing. Artificial intelligence analytics and methods could be used for example in solving of other product quality related issues, energy and water consumption, process stability and optimisation. One of the main concerns are related to data amount and quality, which needs to be collected for the analysis. As it was noticed during this project, relatively small and partly inadequate data amount did not allow to fully achieve the set targets. Artificial intelligence analytics and methods have been developed to process enormous data amounts. When the data amount and or quality does not fulfil the demands, it can be concluded that artificial intelligence analytics and methods cannot reach the full potential and therefore it can be seen as waste of resources. Consequently, when planning to use artificial intelligence analytics and methods on some problem solving or optimisation project, data amount and quality is a key thing to ensure already during the planning phase.

According to the result of data analysis done by Valmet, data requirement for the future register stability research can be defined. As a first point, required data amount should be minimum two weeks production period at the rotogravure printing machine, which corresponds to around 800-1000 tons of paperboard. With BM1 capacity, suggested production of trial reels would last 2 – 2.5 days. By this amount of paperboard, possibility of weaker register stability reels is much higher compared to already carried trial with a small reel amount. Differentially behaving reels regarding register stability are required for further data analysis as has been showed earlier. Also register movement data is needed from the rotogravure printing machine, that the process data can be linked to a certain area of the reel, when the register stability is weaker or out of tolerance. As it was concluded from the data analysis result of normal customer orders, a reel level data is not accurate enough. From a reel level data exact area with register stability issues cannot be defined, which leads inevitably to approximate results. Conditions during the transportation and warehousing needs to be monitored all the way from the mill to converter’s printing machine. This is required for confirming the findings from the performed data analysis.

When assuming that the next trial and data analysis by artificial intelligence analytics and methods would offer high-quality correlations between the controlled variables in the overall paperboard manufacturing process and a register stability at a rotogravure printing machine, they should be tested before fully implementing in the production. For example, any major setting changes to the board machine process parameters would be needed to trialed first in terms of being sure, that the setting changes would be really improving the register stability. In practice this would mean to produce for example 10-20 tons trial order with improved settings, and it would be compared to reference order produced with old process parameter settings. After confirming the new settings with actual trial, they would be fully implemented in the production.

Bobst process control system upgrade has been discussed with Valmet and the converter. System upgrade would allow a register stability data recording without a manual intervention from Bobst. It would have also other benefits. In addition to a register stability data, other machine variables concerning register stability of a rotogravure printing machine can be recorded remotely like paperboard web tension and dryer temperatures. Data would have been also timestamped, which were missing from the register stability data recorded by a technician from Bobst. Timestamps would not have to be anymore calculated from printing cylinder revolutions and circumference. This would remove one major source of bias from the data. It was agreed between Metsä Board, Valmet and the converter, that before the next trial run will be done, process control system should be upgraded. System upgrade is also technically required, that the trial can be carried out like suggested earlier in this section. The final decision of the system upgrade is not done. Data requirement for the future data analysis is shown in Table 25.

In the future an optimal situation would be to have an open data link from the converter's process systems to an agreed cloud server, where a data could be utilised in online way instead of separately collected data batches. This type of an arrangement would allow immediate assistance for the converter for example in problem solving situation by the support of artificial intelligence analytics and methods supplied by Valmet. It would also allow Metsä Board and the converter to strengthen their partnership in business by a novel approach to a development and problem solving. Benefits for the marketing should be also recognized. Using the artificial intelligence project and its targets and outcomes in marketing might attract potential new customers without forgetting a growth potential with the existing ones. Artificial intelligence is currently strongly trending, and it is thoroughly included in the forthcoming fourth industrial revolution. It is probably highly beneficial for the companies to get involved in the artificial intelligence analytics and other topics involved in the fourth industrial revolution as early as possible. (Ahmed et al., 2022)

Table 25 Data requirement for the future data analysis

Process	**Data source**	**Description**	**Data amount/measurement frequency**
Board machine	Historical data from DCS	All available tags (stock preparation included)	≤ 1s frequency
	Laboratory measurements	All available data	
	Logbooks	All available logbooks	
Winder	Historical data from DCS	All available tags	≤ 200ms frequency
	Logbooks	All available logbooks	
Transportation and warehousing	Condition monitoring data (temperature, RH, acceleration, pressure)	Monitoring all the way from the mill to the converter's printing hall	≥ 100 reels ≤ 1 min frequency
Rotogravure printing	Historical data from the process control system (update for the Bobst process control system is required)	Register movement, speed, web tension (infeed/outfeed), dryers' temperature, impression rollers' pressure	≤ 1s frequency
	Valmet IQ Multipoint data	Temperature and moisture	≤ 1s frequency
	Logbooks	All available logbooks	
	Laboratory measurements	All available data	

12 CONCLUSIONS

In this thesis was explored the possibilities of an artificial intelligence in a quality optimisation of the overall folding boxboard manufacturing process, that a register stability in a rotogravure printing can be improved. Manufacturing processes, quality controlling, and a paperboard transportation and warehousing were presented in the literature review.

Metsä Board Tako started a project with an artificial intelligence analytics supplier Valmet and a converting customer for finding out the possibilities of an artificial intelligence in quality optimisation. Target of the project was to find high-quality correlations between controlled variables of the overall paperboard production process and a register stability measured in a rotogravure printing machine.

Trial set-up was built, and a data were collected from the board machine, winder, transportation and warehousing, and rotogravure printing machine. It was concluded after the data analysis, that the data amount was not sufficient, and it was partly inadequate. High-quality correlations between the register stability measured in the rotogravure printing and the controlled variables of the overall paperboard manufacturing process were not possible to find out mainly because there were only small differences between the trial reels. However, temperature during the transportation and warehousing seemed to correlate with a runnability in terms of register stability. Reels in a higher temperature showed a better register stability. Similar correlation was also found from the temperature before the drying units, that a higher temperature correlated to a better register stability. Differences were small thus it would need to be confirmed by a new trial. Data analysis results of the trial order are shown in Table 24.

Another data analysis was made by Valmet for a data collected from five normal customer orders. Three of these orders included reels, which the converter used with a lower speed due to register stability issues. Two of these orders were as reference as the reels were used without any issues. Data for the analysis was available from the board machine and winder. Without a register movement data from a rotogravure printing machine, data analysis was performed based on a reel level comparison between a good and claimed production. Correlations were found between the groups of good and claimed production. Results regarding the board machine are shown in Table 22 and results from the winder are shown in Table 23. Found correlations were analysed against the knowledge gained in the literature review section 2. Findings were evaluated to be approximate thus they need to be confirmed by a new trial.

It is recommended to continue the project with Valmet and the converter. In the future it is suggested to set-up a new trial, where the learnings from the previous trial will be considered. Data amount to be collected and quality requirements for the data for the new trial are shown in Table 25. Other demands for the future artificial intelligence based data analysis have been presented in the experimental part's section 11.

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APPENDICES

Appendix 1. Trial reels information table

1(1)

Machine reel	Machine reel end time	Winding start time	Winding end time	Reel ID	Reel number	Winder set	Deckle pos.	Data logger number
41262288	12.10.2021 8:54	12.10.2021 9:51	12.10.2021 10:20	4530222356	1	1	A	65200, 1m
41262288	12.10.2021 8:54	12.10.2021 9:51	12.10.2021 10:20	4530222366	3	1	B	62405, 1m
41262288	12.10.2021 8:54	12.10.2021 9:51	12.10.2021 10:20	4530222376	2	1	C	65189, 1m
41262288	12.10.2021 8:54	12.10.2021 9:51	12.10.2021 10:20	4530222386	4	1	D	65031, 1m
41262288	12.10.2021 8:54	12.10.2021 10:20	12.10.2021 10:28	4530222396	5	2	A	64060, 1m
41262288	12.10.2021 8:54	12.10.2021 10:20	12.10.2021 10:28	4530222406	7	2	B	64063
41262288	12.10.2021 8:54	12.10.2021 10:20	12.10.2021 10:28	4530222416	6	2	C	63770
41262288	12.10.2021 8:54	12.10.2021 10:20	12.10.2021 10:28	4530222426	8	2	D	65186, 1m
41262289	12.10.2021 9:28	12.10.2021 10:28	12.10.2021 10:51	4530222436	9	1	A	64934, 1m
41262289	12.10.2021 9:28	12.10.2021 10:28	12.10.2021 10:51	4530222446	11	1	B	62747
41262289	12.10.2021 9:28	12.10.2021 10:28	12.10.2021 10:51	4530222456	10	1	C	64789, 1m
41262289	12.10.2021 9:28	12.10.2021 10:28	12.10.2021 10:51	4530222466	12	1	D	64243, 1m
41262289	12.10.2021 9:28	12.10.2021 10:51	12.10.2021 10:59	4530222476	13	2	A	63736, 1m
41262289	12.10.2021 9:28	12.10.2021 10:51	12.10.2021 10:59	4530222486	15	2	B	4242, 1m
41262289	12.10.2021 9:28	12.10.2021 10:51	12.10.2021 10:59	4530222496	14	2	C	63986
41262289	12.10.2021 9:28	12.10.2021 10:51	12.10.2021 10:59	4530222506	16	2	D	65153, 1m
41262290	12.10.2021 10:02	12.10.2021 10:59	12.10.2021 11:33	4530222516	17	1	A	63729
41262290	12.10.2021 10:02	12.10.2021 10:59	12.10.2021 11:33	4530222526	19	1	B	62837
41262290	12.10.2021 10:02	12.10.2021 10:59	12.10.2021 11:33	4530222536	18	1	C	65082, 1m
41262290	12.10.2021 10:02	12.10.2021 10:59	12.10.2021 11:33	4530222546	20	1	D	64746
41262292	12.10.2021 11:37	12.10.2021 11:33	12.10.2021 11:56	4530222556	21	1	A	64733
41262292	12.10.2021 11:37	12.10.2021 11:33	12.10.2021 11:56	4530222566	23	1	B	64819
41262292	12.10.2021 11:37	12.10.2021 11:33	12.10.2021 11:56	4530222576	22	1	C	65161
41262292	12.10.2021 11:37	12.10.2021 11:33	12.10.2021 11:56	4530222586	24	1	D	64686
41262292	12.10.2021 11:37	12.10.2021 11:56	12.10.2021 12:04	4530222596	25	2	A	64455
41262292	12.10.2021 11:37	12.10.2021 11:56	12.10.2021 12:04	4530222606	27	2	B	64557
41262292	12.10.2021 11:37	12.10.2021 11:56	12.10.2021 12:04	4530222616	26	2	C	64772
41262292	12.10.2021 11:37	12.10.2021 11:56	12.10.2021 12:04	4530222626	28	2	D	63746, 1m