TAMPEREEN TEKNILLINEN YLIOPISTO
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MODELLING AND CONTROLLING BOARD MOISTURE AND TEMPERATURE IN A CORRUGATOR

Master of Science Thesis

Examiner: prof. Risto Ritala
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ABSTRACT

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The costs from the boards used as a raw material are the biggest individual source of costs in the corrugated board manufacturing process. The manufacturers continuously aim to reduce raw material costs, which leads aiming to reduce waste production and at the same time to minimize the basis weight of liner and fluting boards. Because of the above-mentioned, the industry has been showing an increasing interest in moisture and temperature controls.

In the theoretical part of the work, the corrugator is introduced from a process control point of view: what can be measured and controlled on the machine, and what kind of effects they have. The temperature is found out to be important for successful gluing while moisture has a major impact on the warp. Too dry or too moist corrugated board cause problems in converting. The optimal moisture and temperature levels are found out to be grade depending.

The impact of preheating into moisture and temperature in a single facer is researched via trials held in Spain. Based on the trials, a simple static process model is generated. The reliability of the model is validated by using it for predicting in a real process environment. The moisture prediction is found to be accurate but challenges are faced with temperature predicting.

A static model-based control is implemented for controlling liner moisture and temperature in a single facer. The control is executed by adjusting the positions of the preheater wrap arms. The motor actuated wrap arms can be moved by a limited speed. The performance of the control is evaluated by simulations which reveal that the control is very robust for model error. The control offers a significant potential on stabilizing moisture and temperature.

TIIVISTELMÄ

NICO HELPPOLAINEN: Kosteuden ja lämpötilan mallintaminen sekä säätäminen aaltopahvikoneella
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Avainsanat: aaltophavikone, aallottaja, mallipohjainen säätö

Nykytrendin mukaisesti tilaukset aaltophavikoneilla lyhenevät jatkuvasti. Samaan aikaan valmistuksessa tähdätään raaka-ainekulujen pienentämiseen. Käytännössä tämä johtaa siihen, että aaltopahvin tuotannossa syntyvän hylyn määrää halutaan vähentää sekä samaan aikaan pienentää käytettävien laineri- ja flutingkartonkien neliömassoja. Näistä syistä johtuen aaltopahviteollisuus on alkanut osoittamaan kasvavaa kiinnostusta muun muassa kosteus- ja lämpötilamittauksia sekä varsinkin näitä hyödyntäviä säätöjä kohtaan.

Työn teoriaosuudessa tutkitaan miten valmistettavan aaltopahvin lämpötilaan ja kosteuteen voidaan koneella vaikuttaa. Lisäksi selvitetään mitkä ovat tärkeimmät laatuvaatimukset valmistuksessa, sekä kuinka suuri vaikutus kosteudella ja lämpötilalla näihin on. Lämpötilalla todetaan olevan suurin vaikutus liimausten onnistumiseen kun taas kosteudella on suuri vaikutus aaltopahvin käyristymiseen. Lisäksi, liian kuivaksi tai kosteaksi valmistettu aaltopahvi aiheuttaa ongelmia jalostuskoneilla. Optimaaliset kosteus- ja lämpötilatasot ovat lajikohtaisia.

Esilämmityksen vaikutusta kosteuteen ja lämpötilaan aallottajalla tutkitaan askelvastekokeiden avulla. Askelvastekokeiden perusteella ja muodostetaan yksinkertainen staattinen prosessimalli. Prosessimallin luotettavuutta validoidaan vertaamalla sen avulla laskettua ennustusta todellisiin prosessimittauksiin. Kosteuden ennustaminen osoittautuu luotettavaksi, kun taas lämpötilan ennustaminen on haasteellisempaa.

Lainerille implementoidaan staattiseen prosessimalliin perustuva säätö aallottajalle. Säädöllä ohjataan esilämmittimien taittotelojen asentoja kosteus- ja lämpötilamittausten perusteella. Moottorikäyttöisen taittotelan asennon muutosnopeus on rajoitettu. Säädön suorituskykyä arvioidaan simulointien perusteella, joiden perusteella säätö on erittäin robusti mallivirheelle. Säätö tarjoaa suuren potentiaalin kosteuden ja lämpötilan stabiloimiseen ja sitä kautta laadun parantamiseen.

PREFACE

This work was made for Valmet Automation Oy between autumn 2017 and spring 2018. I am grateful for the opportunity to utilize and develop further my knowledge from my major Process Control in the manufacturing process of a corrugated which was a totally new process for me.

I want to thank a few people who were helping me to manage through the work. At Valmet Automation, I would like to thank my supervisor Jyri Kanninen, Tommi Löyttyniemi, Mikko Talonen, Niko Posti and Markku Mäntylä. Especially Tommi and Jyri were a big help in various phases of the work, Jyri with the writing process also. The help was always there whenever I needed, or dared, to ask for it.

At the beginning of the work, when I was researching the manufacturing process of corrugated board and its pitfalls, the information I got from the interviews with Adara, Stora Enso, and with the retired corrugator specialist Pertti “Mr. Corrugated” Kaasalainen was invaluably important for me. I want to thank all of you who participated in the interviews.

This work could not have been done without the cooperation with Saica. Especially I want to thank Diego Compaired, Isabel Bernad and the personnel at the site for enabling the trials that were the ‘heart’ of this work.

Finally, I would like to thank my supervisor and examiner from the Tampere University of Technology, professor Risto Ritala, for the help throughout the work. I could not have imagined the cooperation to work more efficiently as it did with Risto.

Tampere, 15.05.2018

Nico Helppolainen

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LIST OF SYMBOLS AND ABBREVIATIONS

FEFCO	The European Federation of Corrugated Board Manufacturers
ISO	International Organization for Standardization
TAPPI	Technical Association of the Pulp and Paper Industry
CCB	CEPI ContainerBoard
CEPI	Confederation of European Paper Industries
MD	Machine direction
CD	Cross direction
MC	Moisture
SCF	Semi-chemical fluting
RH	Relative humidity
ECT	Edge crush test
FCT	Flat crush test
PAT	Pin adhesion test
BCT	Box compression test
PH	Preheater
SF	Single facer
DS	Duosaica
HS	Hidrosaica
SM	Saica medium
FbCAD	Valmet DNA Engineering Function Block CAD
QCS	Quality control system
TITO	Two-Input, Two-Output
MIMO	Multi-Input, Multi-Output
MPC	Model predictive control

G	Gain
θ	Preheater wrap arm position
m	Moisture
t	Temperature
WAR	Wrap arm rate of change
MSR	Machine speed rate of change
W	Weight factor
MS	Machine speed

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1. INTRODUCTION

1.1 Background and Motivation

The board raw material costs are the largest individual source of costs in the corrugated board manufacturing process. The manufacturers continuously aim to reduce raw material costs, which leads to reducing waste production and at the same time minimizing the basis weight of liner and fluting board.

In corrugated board production, the moisture in the containerboards varies through the production line. The moisture has a major impact on the produced board quality characteristics, however, the moisture measurements are very rare at machines. The lighter basis weight boards used, the greater are the moisture impacts on quality.

Moisture profiles in the containerboards coming from paper mills have variation. The variation increases through storage time, and the magnitude of change depends for how long time and how the reels are stored. Furthermore, in the corrugated board production process, there are several disturbances increasing moisture variation. Web tension, uneven preheating, production speed changes and numerous other factors all cause moisture variations in the process. The moisture variations, between reels of the same grade and inside a single reel are rather impossible to compensate without closed-loop control.

Industry producing corrugated board has shown an increasing interest in automation and control solutions. A growing number of moisturizers and warp measurements on the machines recently has indicated this interest.

In addition to controlling moisture according to the warp measurement located in the dry end of the corrugator and only with moisturizers, a natural step is to start controlling moisture according to direct moisture measurements in the wet end of the corrugator with preheaters.

On most of the corrugators around the world, moisture is controlled indirectly by temperature measurements or more commonly, as a function of the machine speed as an open loop control. The indirect controls are not capable of detecting or compensating moisture variations caused by machine speed changes, variations inside individual board reels, or variations between different reels of the same grade.

For reaching the goals of producing less waste and enabling the use of lighter boards, a closed-loop moisture control should be developed for the corrugator. This thesis work proposes a closed control in a single facer by preheating, based on moisture and temperature measurements.

1.2 Contents

A top-to-down approach is used in this work. Corrugated board (Chapter 2) and its production (Chapter 3) are reviewed in a more abstract and theoretical level in the beginning and at the end the focus is in one component of the corrugator, in the single facer, and suggesting a practical controlling solution.

In the theoretical part of the work, the corrugator is introduced from a process control point of view: what can be measured and actuated on the machine, and what kind of effects they have. The aim is to understand how the moisture of the boards can be controlled. The most important quality characteristics are introduced in Chapter 4, as well as how they can be affected by means of control, Chapter 5.

In the beginning of the practical part of the work, trial runs on a Spanish corrugator are presented in Chapter 6. The impacts of preheating, speed and board basis weight into moisture and temperature in single facer were studied in the trial runs. Impacts on both liner and fluting were studied. For benchmarking the importance of moisture control in the wet end, the effects of the moisture variations in single facer to the moisture in the dry end and to warp during the trials are presented. A strong correlation between moisture in the wet and dry end can be found as well with the board warp.

In Chapter 7, a closed loop control structure is proposed for controlling liner moisture and temperature by preheaters in a single facer on the corrugator. The TITO (two inputs, two outputs) controller is based on a static process model, which calculates the optimal positions of preheater wrap arms minimizing a certain cost function. The functionality of the control was validated by a simulator in Chapter 8. The objective of the simulations was to clarify how fast responses can be achieved to the most common and effective disturbance, the speed change. The impact of model inaccuracies were also analyzed in simulations.

The static process model is based on trial test results introduced in the text. The model is validated and improved by using it to predict on-line moisture and temperature data in a real process environment, see Chapter 9.

2. CORRUGATED BOARD

2.1 Overview

The corrugated board manufacturing started in the mid-1800s. It is most popular as a packaging material, while it is also used for instance in advertising and brand support. The corrugated board is an environment-friendly product as it is made of recyclable raw materials.

The corrugated board has several benefits as a packaging material. It is strong compared to the weight, corrugated board boxes are stackable and the material can be easily modified into different shapes and sizes. Corrugated board surfaces are suitable for printing which is crucial because the package itself must carry information and appear attractive.

The manufacturing process of corrugated board is cost-efficient and enables mass producing. Manufacturing speed in the most modern corrugators can be up to 450 *m/min*. For *2,5 m* wide machine this leads to a production speed of $1125\ m^2/min$.

2.2 Structure

Corrugated board is manufactured by glueing flat paper surfaces, known as liners, to a corrugated board, known as fluting or corrugating medium. Containerboard is a common naming for all boards used for corrugated board manufacturing.

Corrugated board can be categorized by the number of liner and fluting plies in the structure into four most common categories:

- Single face corrugated consisting of one liner and one fluting ply
- Single wall corrugated consisting of two liner plies and one fluting ply
- Double wall corrugated consisting of three liner plies and two fluting plies
- Triple wall corrugated consisting of four liner plies and two fluting plies.

The four corrugated board structures are presented in Figure 1.

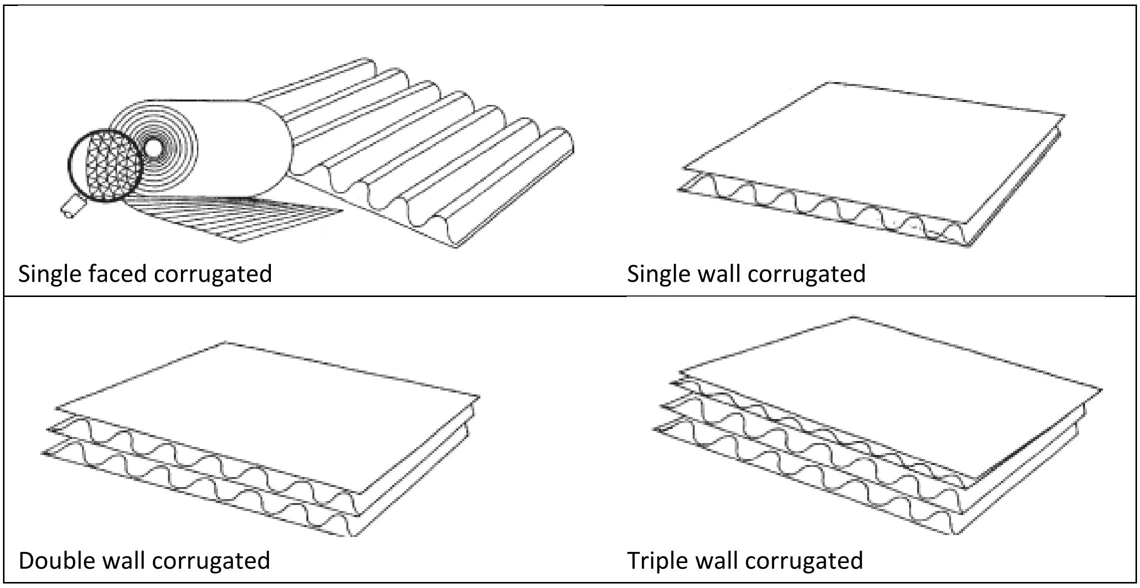


Figure 1. *Four different corrugated board structures. Adapted from* [1, Fig. 1]

Single faced corrugated is the only flexible structure, while single, double and triple wall corrugates provide a stiff structure. Double and triple wall structures are mainly used when especially high strength properties are required. Double and triple wall corrugated structures are often referred to as heavy-duty structures.

One 'wave' of fluting is known as a flute. Flute types differ by the height of the flute, by the number of flutes per meter, by take-up factor and by glue consumption per square meter [2, p. 221]. According to The European Federation of Corrugated Board Manufacturers (FEFCO), flute types can be divided into four main categories [3]. Table 1 presents indicative flute parameters for the flute types.

As an example of the take-up factor, if 100 m of corrugated board is manufactured and the flute type is A with take-up factor 1,50, 150 m (1,50×100 m) of fluting is needed.

Table 1. *The most common flute types* [3]

Flute	The height of the flute [*mm*]	Flutes/m length of the corrugated board web	Take-up factor	Glue consumption *g/m²*, the glue layer
A	4.8	110	1.50-1.55	4.5-5.0
B	2.4	150	1.30-1.35	5.5-6.0
C	3.6	130	1.40-1.45	5.0-5.5
E	1.2	290	1.15-1.25	6.0-6.5
F, G, N	0.5-0.8	400-550	1.15-1.25	9.0-11.0

The B flute has traditionally been the most common. As a rule of thumb, A and C flutes provide better stacking properties and smaller flutes, whereas B, E, F, G and N are more suitable for printing [4, pp. 15–16]. In double wall structures, these features can be combined by using, for example, A or C as lower flute type for offering good stacking properties and a lower flute type as upper offering better properties for printing.

2.3 Raw Materials

Raw material consumption in European corrugated industry is presented in Figure 2 in percentages (%). The numbers are based on FEFCO annual statistics from 2016 [5]. Consumption of liners and flutings is around 94.8 % of the total consumption of raw materials, with liners 55.5 % and flutings 44.5 % of the total liner and fluting consumption. The remaining 5.2 % raw material consumption consists of adhesives, printing colours and from other additives. Adhesive consumption can be estimated to be around 3 % [4].

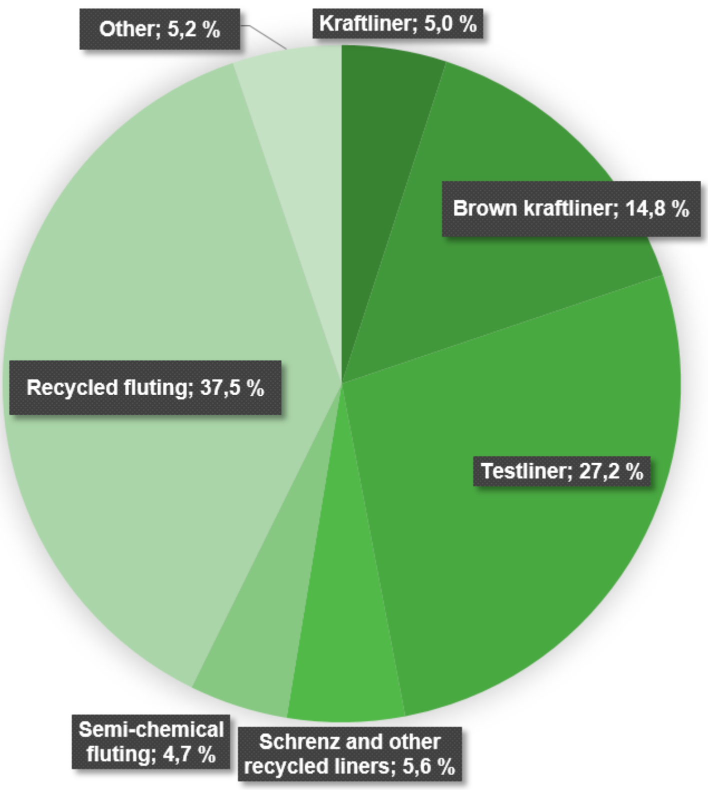


Figure 2. *Raw material usage in the corrugated industry in 2016. Numbers from FEFCO annual statistics* [5].

Containerboard requirements for moisture and variation specified by Cepi ContainerBoard (CCB) are presented in Table 2. It is important to have a relatively even moisture profile, especially in liner reels, to enable production of flat and uniform quality corrugated board [6, p. 81].

Table 2. Containerboard requirements for moisture and variation. Adapted from [7, p. 18].

	Kraftliner	Testliner & other recycled liners	Semi-chemical fluting	Recycled fluting medium
Average moisture of a customer reel in %	6.5 – 9.5	6-0 – 9.0	7.5 – 11	6.5 – 9.5
Without reference, in %	8.0	7.5	9.0	8.0
Maximum CD moisture peak to peak difference over the width of customer reel with measuring a box of 16 cm (6 inches) width around the average content in %-unities	± 1.5	± 1.5	± 2	± 2
Maximum CD moisture peak to peak difference between two adjacent measuring boxes of 15 cm (6 inches) width in a customer reel in % -units	2.8	2.8	2.8	2.8

The moisture balance of a containerboard reel depends on relative humidity (RH). For example, when RH is 80-95%, the balanced containerboard moisture is approximately 15 %, and the moisture travels into the reel at an approximate rate of 1-2cm in a month [8]. This means that in worst scenario the outside layers may have 15 % moisture, while inside the reel the moisture is closer to the designed moisture, 7-9%, depending on the grade.

In an ideal situation, the paper reels are stored indoors, in an air-conditioned storage, as in the case of Stora Enso corrugator in Lahti, Finland [9]. If reels are stored outside, they should be covered to minimize humidity effects on them. These actions reduce the moisture variations met in the reels on corrugator and improve the runnability of the containerboards on the corrugator [6, p. 79].

2.3.1 Fluting

The basic requirements for the fluting are that it is expected to be both elastic and stiff. Fluting must be elastic enough to be corrugated while the corrugated fluting must handle vertical pressure. The two most common fluting types are semi-chemical fluting and recycle-based fluting, often called simply medium. Basis weight for fluting is in the range 75-275 g/m^2 and typically it is a single-ply product. [10, p. 327], [11, p. 70]

Semi-chemical fluting has a high content of semi-chemical virgin fibre hardwood pulp, more than 65 %. The basis weight of the semi-chemical fluting is typically in the range 115-275 g/m^2. [10, p. 327], [12, p. 268]

Recycle-based fluting, medium, is not considered as a high-quality product as the semi-chemical fluting because of the high recycled fibre content. The medium is easier to corrugate than the semi-chemical fluting. The basis weight of the medium is typically around 75-175 g/m^2 [10, p. 327]. [11, p. 70]

2.3.2 Liner

Liner basis weight in corrugated production can vary widely in the range 80-440 g/m^2. However, the lighter grades are becoming increasingly popular. Three most common liner grades are kraftliner, testliner and Schrenz, but other types of board can be used as a liner also [4, pp. 28–29], [10, p. 327], [11, pp. 66–69].

Kraftliner is traditionally produced from two or more layers where the base layer offers strength properties and the cover layer is more suitable for printing. Kraftliner contains roughly 80 % or more sulphate wood pulp. The upper layer can be unbleached, bleached, mottled, white or coated depending on the esthetic and printing requirements set to the liner. Kraftliner has a high virgin fibre content. [4, pp. 28–29], [12, p. 268], [13]

Testliner has a high recycled fiber content and a multilayer structure. Testliner strength properties are not as good as those of kraftliner but the printability of testliner is comparable to kraftliner. Testliner is not considered to be as sensitive for preheating as kraftliner [4, pp. 28–29], [12, p. 268]

A liner board made entirely of recycled fibres is often called Schrenz. Schrenz's strength properties are the lowest of the three most common linerboard types. [12, p. 268], [13]

2.3.3 Corrugating Glue

Corrugating glue is used for attaching liner to fluting. Adhesives can be purchased as a ready-to-use substance that only needs to be mixed with water, known as 'one bag glue', or it can be manufactured in the glue kitchen located next to the corrugator. The manufacturing volume determines which option is the most cost-efficient. [4, pp. 56–57]

Maize, wheat, corn and potato are the most common starches used as a main raw material for the glue. In addition to the starch, the glue contains typically water, NaOH (lye) and boric acid or borax [4, pp. 56–57]. The three most common glue recipes are Stein hall, No-Carrier and Minocar [14].

The gelatinizing point, viscosity and dry content are the most important glue characteristics [4, p. 59]. By controlling the proportions of the glue ingredients, the characteristics can be adjusted to the preferred values. As tentative values, the gelatinizing point is $50 - 62$ °C, viscosity $40 - 80\ s\ SH$ and dry content $20 - 30$ % [4, p. 59].

The tank where the glue is stored needs to be drained and cleaned at regular intervals, else bacterial growth will develop and deteriorate the glue quality. Spoiled glue can be detected by its smell and as a decrease in the viscosity [15].

2.4 Technical Properties of Corrugated Board

The strength properties of corrugated board and boxes made from it are ensured with many tests. The most important quality tests in corrugated board plants are listed below. Test specifications are based on [6, pp. 121–124].

- **The basis weight** of the corrugated board. The unit is *g/m²*.
- **Thickness** or caliper of corrugated board. The unit is *mm*.
- **Bursting strength** describes the toughness of the corrugated board material. The unit is *kPa*.
- **Bending stiffness** defines the moment needed for bending the corrugated board. Refers to the compression strength of the corrugated board. The unit is *Nm*.
- **Edge crush test** (**ECT**) refers to the compression strength of the corrugated board. The unit is *kN/m*.
- **Flat crush test** (**FCT**) indicates if the fluting was damaged during manufacture. The unit is *kPa*.
- **Puncture test** describes the energy needed to penetrate the board. The unit is *mJ/m*.
- **Pin adhesion test** (**PAT**) evaluates the adhesion of liner and fluting. The unit is *N/m*.
- **Box compression test** (**BCT**) refers to how much compression the manufactured box can support. The unit is *kN*.

The FEFCO, ISO and TAPPI standards of these tests are listed in Table 3.

Table 3. *Technical properties of corrugated board and their FEFCO, ISO and TAPPI standards. Based on* [16].

	FEFCO	ISO	TAPPI
Basis weight	TM 2	536	T 410
Thickness	TM 3	3034	T 411
Bursting strength	TM 4	2759	T 810
Bending stiffness		5628	
ECT	TM 8	3037	T 811
FCT	TM 6	3085	T 808
Puncture test	TM 5	3036	T 803
PAT	TM 11		T 821
BCT	TM 50	12048	T 804

3. MANUFACTURE OF CORRUGATED BOARD

3.1 Manufacturing Process

Corrugated board is manufactured with a corrugating machine, called corrugator. The machine can be divided into two main parts, wet end and dry end. The names wet end and dry end have their origins in the papermaking industry while their meanings are different in a corrugator. In corrugated manufacturing, “wet” only comes to the process from the adhesives used for glueing flutings and liners together and from the steam used for moisturizing.

The wet end process can be further divided into sections: single facer and double facer. In the single facer, single faced corrugated is manufactured. If double or triple wall corrugated is produced, there are two or three single facers in the corrugator. All the single side corrugates and the outside liner are glued together in the double facer to form a multi-sided corrugated board.

The dry end process consists of creasing, cutting the continuous corrugated board into sheets, and stacking the sheets into piles in stack chambers. An example of a corrugator is presented in Figure 3. The figure represents a corrugator that has two single facers and two stack chambers in dry end. Single wall and double wall corrugated board can be produced with this machine.

A modern corrugator is an over 100 m long production line. The fastest corrugators produce corrugated board continuously with a maximum speed up to 450 m/min. The classical and most common width of a corrugator is 2,5 m although wider lines have also been built. For example, the German corrugator vendor BHS offers a 3,350 m wide corrugator in its *Width Line* series corrugators [17].

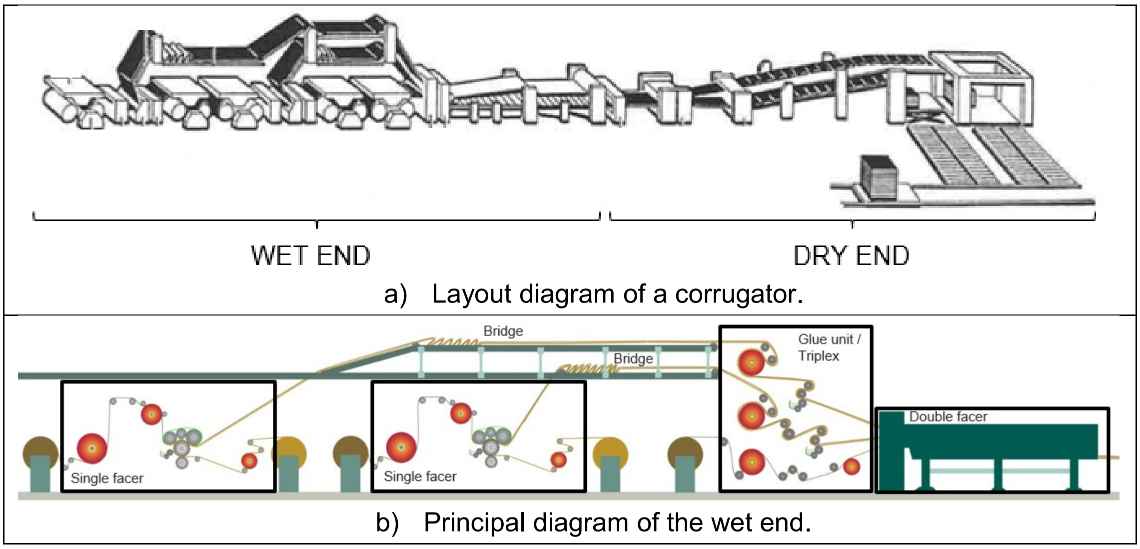


Figure 3. *An example of a double-wall corrugated manufacturing corrugator. Layout diagram is adapted from* [4, Fig. 5.1].

3.2 Wet End

3.2.1 Roll Stand and Splicer

Fluting and liner reels are mounted on roll stands from where the webs are unwinded to the corrugator. At each roll stand, two reels can be mounted at the same time, one that is being unwinded and another waiting for the reel change. A splicer handles the splicing of the old and new reel automatically during the reel change and enables continuous production of corrugated board. The most recent splicers can handle the splicing in speeds up to 400 m/min. This means the reels can be spliced at any time at full production speed. In older machines, the speed must be lowered for successful splicing during reel changes. The roll stand brakes controlled automatically keep the web tension stable at machine speed changes. Roll stand and splicer structure are presented in Figure 4.

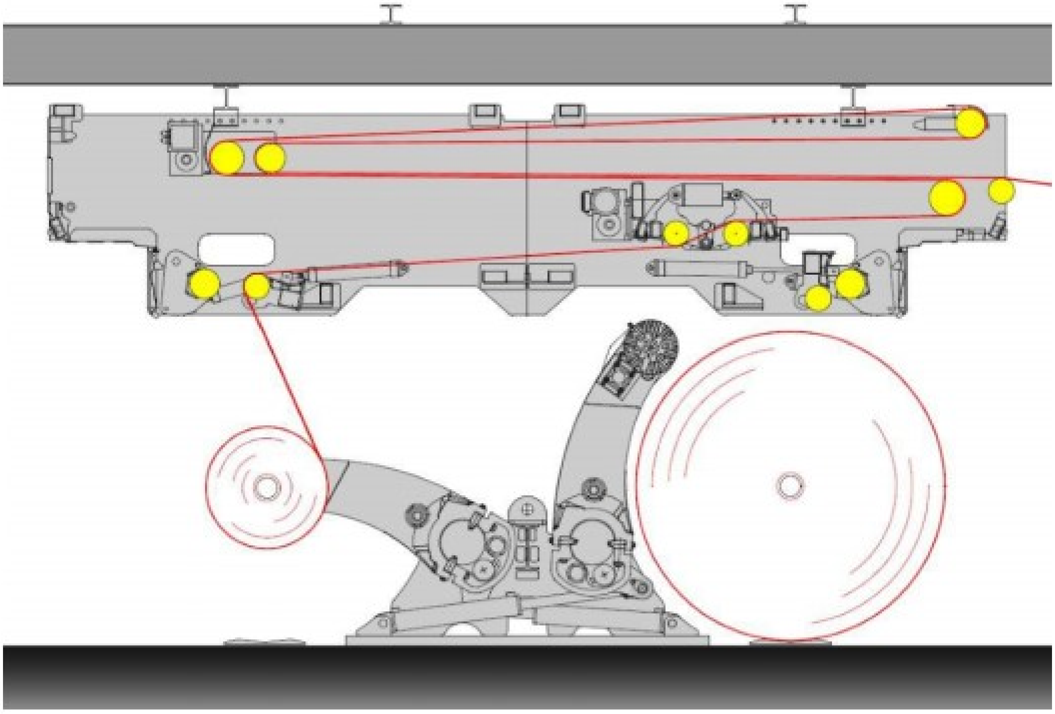
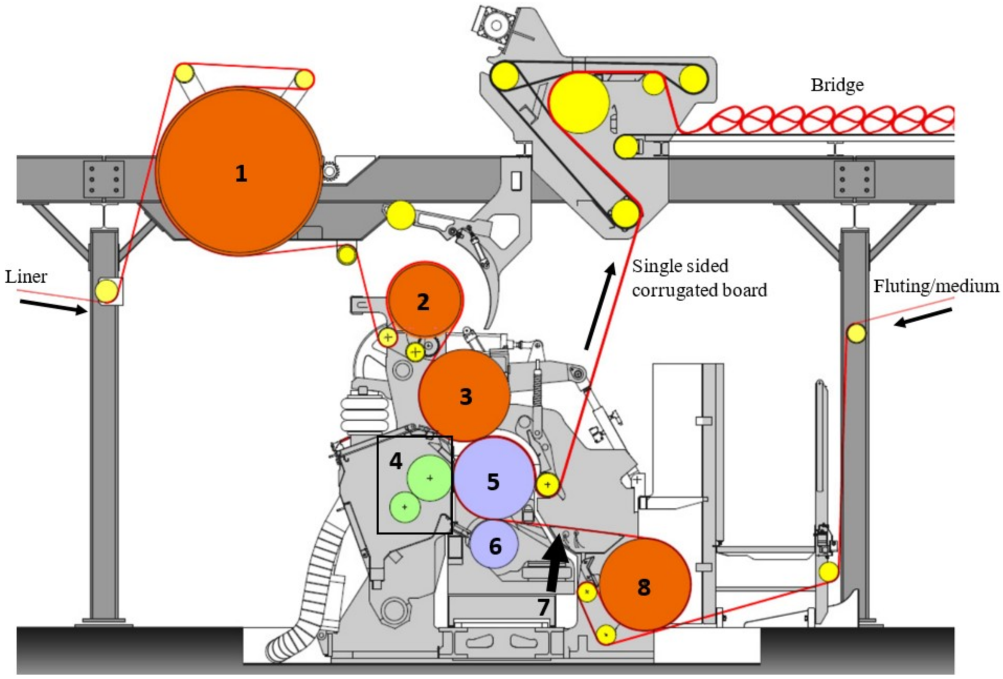


Figure 4. *Roll stand and splicer structure* [18].

3.2.2 Single Facer

The main process phases of single facer are preheating, pre-steaming, corrugating, and glueing liner and fluting together. The principle of a single facer is presented in Figure 5. The single faced corrugated board can be used as packaging material as it is or it can be used as one layer of single, double or triple wall corrugated board.



1. External preheater (liner)
2. Internal preheater (liner)
3. Pressure roll
4. Glue unit
5. Upper corrugating roll
6. Lower corrugating roll
7. Steam box
8. External preheater (fluting/medium)

Figure 5. *The structure of a single facer. Adapted from* [19].

The fluting is heated up before corrugating by the preheater and the steam box. Heating softens the fibres of the board, which eases the corrugation [12, p. 250], [20]. The steam box is located after preheater. The function of the steam box is, in addition to increasing temperature, to increase the moisture of the fluting which decreases the softening temperature of board fibres [4, p. 41], [20]. The steam box is used mainly for semi-chemical flutings and for high basis weight medium (for example, $> 150\frac{g}{m^2}$) [4, pp. 40–41].

As fluting, also liner is preheated. The liner must reach a temperature at which the adhesive glue starch gelatinizes. In addition to the gelatinizing point of the adhesive glue the required liner temperature depends on whether liner is made of recycled fibres (testliner) or of virgin fibres (kraftliner).

The basic single facer structure consists of two preheaters for liner, the internal and the external. To maintain high enough web temperature, the internal preheater is located directly before liner web enters glueing The external preheater is located a few meters before the internal preheater. The function of an external preheater is firstly to provide more heating power for higher basis weight liners, and secondly to enable web moisture control. As the default setting, the liner is treated so that the internal preheater is in contact with the glue side of the liner and the external preheater is in contact with the opposite liner side.

A preheater consists of a steam-heated cylinder and wrap arms, which enable controlling the preheating by adjusting the distance the board is in contact with the hot cylinder surface. The cylinder temperature is kept constant by controlling the steam pressure. The online controlling of the preheating is done by moving the wrap arms with an electric motor actuator.

Fluting is corrugated between two corrugation rolls, which are set very close to each other, in parallel. With pressure difference, or mechanically in older corrugators, fluting is kept tightly against the lower corrugating roll until glueing together with the liner. Corrugation rolls are heated from inside by steam to a surface temperature typically between $170 - 190$ °C [4, p. 40]. The corrugating of smaller flutes is more challenging and may require lowering the speed [9], [15].

When fluting is against the lower corrugating roll, the applicator roll applies adhesive glue on the tips of the flutes [4, pp. 40–41], [12, pp. 252–253]. Operators prefer to apply a higher proportion adhesive at low machine speeds to ensure proper bonding and to avoid the premature crystallization of the adhesive starch [9].

Because the dry content of the glue is only $20 - 30$ %, adding glue to the bond between liner and fluting means also adding large amounts of water. As an example, using low grammage fluting and liner, $80 \frac{g}{m^2}$, and E-flute, means, according to Table 3, approximately $6{,}0\ g/m^2$ of glue. If the glue has a dry content of 20%, $0{,}8\times 6{,}0\ g/m^2 = 4{,}8 g/m^2$ of water is added to the bond. This means roughly an increase of $\frac{4{,}8 g/m^2}{80+80 g/m^2} * 100\% = 3\%$ in total moisture. However, some of this water will evaporate in the gluing process.

Fluting with glue on the flute tips and preheated liner are glued together and the one-sided corrugated board is produced. Pressure is applied to form the so-called green bond between liner and fluting [4, pp. 42–43]. Green bond converts into lasting bond as the bond cures.

The two dominating systems for applying pressure for liner and fluting bonding are presented in Figure 6. The older version is a pressure roll system where the pressure nip is shorter but the pressure applied is higher. In the more recent pressure belt system, the nip is longer and the pressure applied is smaller. The pressure-belt system is believed to be a gentler operation, leading to less caliper losses and smoother board surfaces. [21]

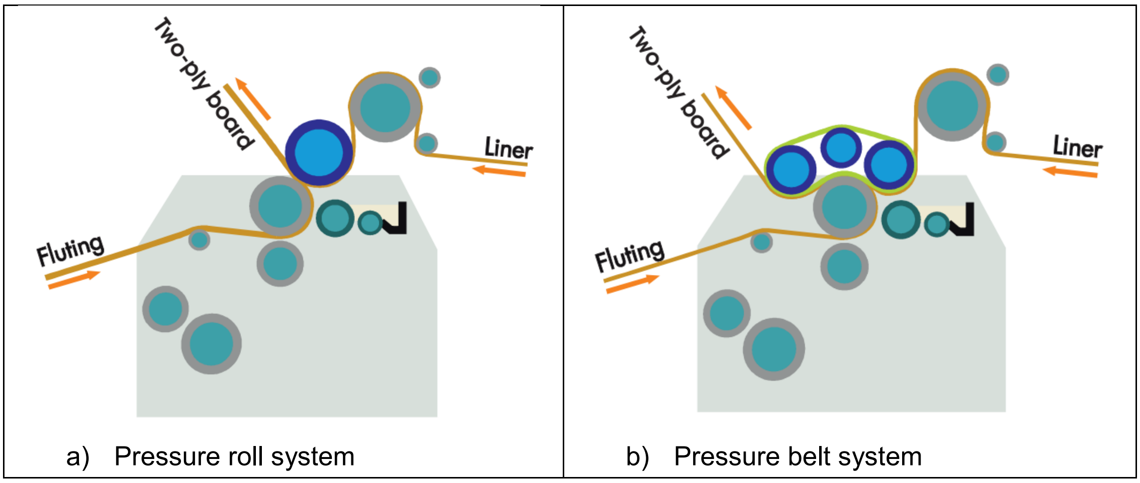


Figure 6. *Examples of a pressure belt and a pressure roll systems. Adapted from* [22, Figs. 7-8].

3.2.3 Bridge

The bridge is a stock for the single-sided corrugated board. It enables speed difference between the single facer and the double facer as the storage of single faced board in the bridge can be increased or decreased. Furthermore, the bridge gives additional time for the bond between liner and fluting to cure before the single sided board is joined to the second face [23, pp. 412–413].

In Figure 7 three examples of speed change situations and the corresponding bridge stock quantities are presented. In the top example, the splice speed in single facer is so close to the double facer speed that no speed change in double facer is needed when double facer proactively increases the bridge quantity. In the middle example also the double facer needs to slow down because single facer is not able to compensate proactively fully the speed change. In the bottom example, a disturbance in double facer speed is compensated by a lowered single facer speed so that the bridge quantity is returned to its setpoint. Dry end speed is the master speed of the corrugator because it determines the production speed. Dry end speed should thus be constant, to maximize the production. Single facer must react to dry end speed changes and, preferably proactively, compensate for situations when it is lowered. However, the single facer speed being the reactive one increases the challenges in wet end moisture and temperature control.

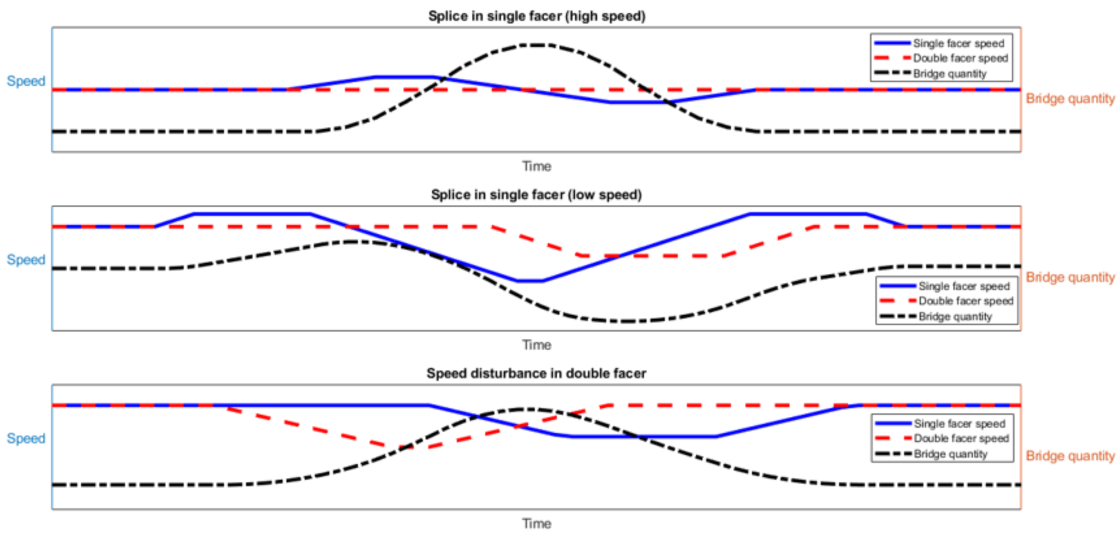


Figure 7. *Three examples of speed changes in a corrugator and the bridge quantity during the changes.*

3.2.4 Glue Machine/Unit

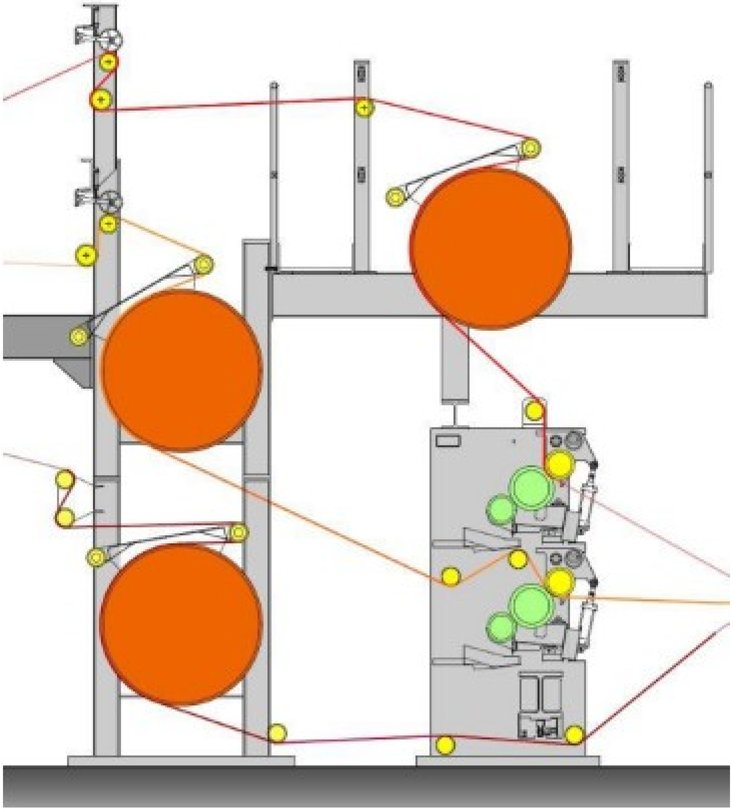


Figure 8. *Glue unit*

The glue unit, which is known also as glue machine or triplex, is presented in Figure 8. The function of the glue machine is to add glue to the flute tips of fluting in single sided boards. The liner webs are preheated before dosing the glue. The primary function of the preheaters is to ensure enough heat for proper bonding on the double facer. In addition, the preheaters can be used for controlling the moisture of the liners.

3.2.5 Double Facer

In the double facer, single side corrugated board, or boards, and bottom liner are glued together. After glueing layers together, heat and pressure are applied for gelatinizing the adhesive starch in the bonds so that the bond is firm enough for the creasing and cutting operations in dry end. [4, p. 47]

Heat is applied by heat chests, which are located below the corrugated board. Corrugated board is pressed from above against the heat chests to enable efficient heat transfer. In manufacturing of double wall corrugated board, the challenge is in transferring enough heat to the bond between the two single faced webs. In some corrugators, steam boxes have been installed just before the double facer to bring more heat and moisture to the webs, and thus to enable better bonding.

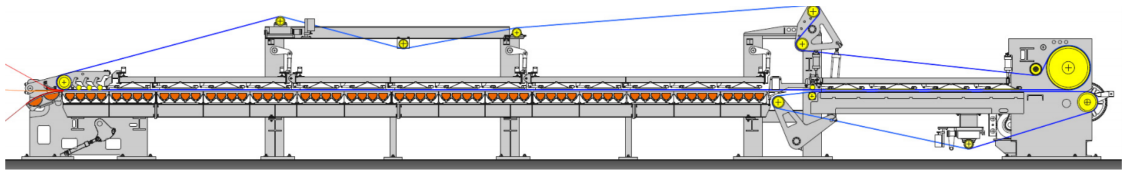


Figure 9. *Principal diagram of a double facer* [24]. *Below the web are the steam chests and above the pressure shoes ensuring better heat transfer to the web.*

The temperature of the heating chests is controlled by the steam pressure inside the chests. However, the time constant of the temperature change due to steam pressure change is rather minutes than seconds. Therefore steam pressure cannot be used for board temperature control during speed variations, grade changes or other rapid changes. [4, pp. 47–48]

Temperature responds more rapidly to changes in how strongly the board is pressed against the heating chests. There are two solutions for varying the pressing.

The traditional solution is a top belt and weight rolls above the belt. The weight rolls enable automatic control of double facer heating but the pressuring is discontinuous in the machine direction (MD)and the force higher in the edges than in center in the cross direction (CD) [4, pp. 46–47].

Pressure shoes pressing the web against steam plates is the other solution. The steam plates can press directly the corrugated board or via a belt in between. The shoes enable more precise pressing in both machine direction and cross direction, and therefore has become a more favored solution [4, pp. 46–47].

3.3 Dry End

At the dry end, the continuous corrugated board is cut in machine direction and cross direction to corrugated board sheets. First, the board is cut in the machine direction. Usually, the board can be cut into max 6-8 tracks in MD [4, p. 49]. At the same section, creasing can be done.

After creasing and cutting the board in MD, the sheeter knives, or cut-off knives, cut the board in CD to produce the individual sheets. Usually, there are two sheeter knives while machines with one or three knives are also met [4, p. 51]. The sheeter knives can limit the machine speed when cutting the web into under approximately 60 cm long sheets [15].

Two knives are required in the normally wide machines, one knife in narrower machines, and three knives in machines using wider webs. The number of knives defines how many orders can be produced at the time [4, p. 51].

The sheets cut from the continuous corrugated board arrive at a stacker that piles them into stacks of suitable size. The corrugator has as many stack chambers as it has sheeter knives. The stacker must receive the sheets gently at corrugator speeds to enable stacking into balanced piles. [4, p. 52]

3.4 Process Control

Corrugators use a wide range of liners and flutings when manufacturing customer specified corrugated board. The board structure and flute type have a major impact on the optimal process parameters. Because of the variations in the specifications of the produced corrugated board between orders, individual recipes are used in corrugators.

The recipes define basic information such as:

- how many single facers are in use
- which single facer(s) used
- liner and fluting grades
- flute(s)
- target machine speed
- creasing
- slitter-scorer positions and
- cut-off knife positions.

Additionally, the controllable variables, such as web tension, glue dosing, preheating and steam chest pressure setpoints in double facer are usually defined in the recipes. For example, the corrugator manufacturer BHS Corrugated has a product named *Quality Data Manager (QDM)* for saving the grade-specific wet end settings to facilitate the production of the board with the same quality characteristics [25].

In recent years, corrugated board production business has been more interested in developing closed-loop controls to the machine. Fosber Group has a closed loop control based on temperature and moisture measurements at strategic positions for controlling wrap arm positions, steam pressures along the corrugator, steam showers, all glue gaps and double backer steam shoe pressure settings [26].

Most of the corrugators around the world do not have closed-loop controls. Instead glue dosing, preheating and double facer pressure shoes are controlled using open-loop control according to speed curves that are defined in the recipes.

3.5 Production Scheduling

The objective of the production scheduling is to deliver the ordered products to the customer at the agreed time while minimizing the production costs. The production scheduling needs to consider for example that:

- orders are delivered to customers at the time promised
- utilization of every converting machine is maximized

- trim waste i.e. the waste from cutting continuous corrugated board to sheets must be minimized
- the number of machine stops are minimized
- stop times are minimized
- number flute grade changes are minimized.

Converting machines are designed for handling different corrugated board types [15]. Corrugator production must be designed so that the utilization rate of all converters is maximized at all times.

At present, the shortest orders take only a few minutes to manufacture. Furthermore, they are getting even shorter in the future because clients aim to reduce their storages and product specifications are getting increasingly individualized. As a result, need for process control increases to compensate for that the grade-change and speed-change waste will be an increasing part of the total production.

4. THE QUALITY CHARACTERISTICS OF CORRUGATED BOARD

4.1 Overview

The fundamental requirements for the produced corrugated board are that all the layers in the structure are bonded tightly, the board is sufficiently flat for feeding the board to conversion, the board surfaces are sufficiently smooth for successful printing, and that the moisture level of the board is in the required range. The common quality characteristics are discussed in following Sections. The effect of board temperature and moisture on the quality characteristics is reviewed.

4.2 Warp

Warp, also known as curling, means the curvature of the corrugated board. It is the most common quality concern faced in single wall corrugated board manufacturing. Warp is caused by non-uniform dimensional changes between liners after cutting the board into sheets. High warp causes problems when feeding the corrugated board to conversion machines. [6, pp. 76–78], [27]

Warp can be defined in three main directions, in the machine direction (MD), in the cross direction (CD) and diagnonally. The diagonal warp is called twist warp. Furthermore, direction of each of the CD-, MD- or twist warp can be defined with respect to the y-plane as up-warp, down-warp or as a combination of these two, known as s-warp. With these definitions, there is altogether 15 combinations of different kind of warps that can be result in the produced corrugated board sheets, see Figure 10. [27]

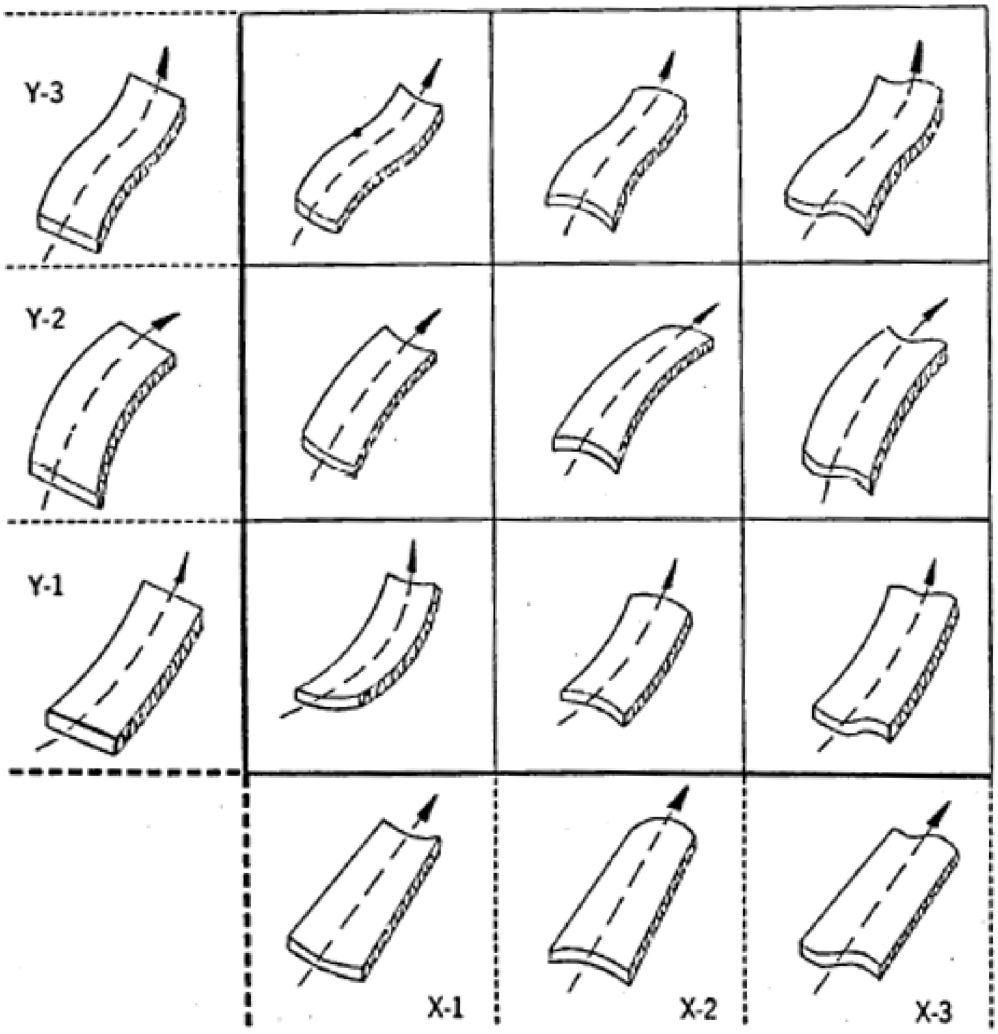


Figure 10. *15 different forms of warp. X-1 CD-up-warp, X-2 CD-down-warp, X-3 CD-s-warp, Y-1 MD-up-warp, Y-2 MD-down-warp, Y-3 MD-s-warp. Modified from* [27, Fig. 1].

The warp phenomenon in MD is typically caused by uneven web tensions between liners in the produced corrugated board. If the tensions are uneven in the continuous corrugated board, the sheet curls up or down after it is cut in cross direction. Up-warp results from the upper liner tension being higher and down-warp from lower liner tension being higher. Thus, up- or down-warp in MD can be removed by adjusting the liner tensions. The s-warp in MD is usually due to machine malfunction causing the web tension to oscillate in upper or lower liner. [27], [28, p. 22]

Moisture-induced uneven dimensional changes in the liners are the most common cause of warp in the corrugated board sheets. Warp caused by uneven moisture balance dominates in the cross direction [6], [27]. This is explained by the dominating fibre orientation being in the machine direction. Because the fibres shrink/expand much more in thickness than in length, the resulting warp is in CD in the corrugated board [23, pp. 238–239]. If upper liner shrinks more due to drying, up-warp is detected and vice versa, if lower liner shrinks more due to trying down-warp is detected [27].

Warp caused by an uneven moisture balance is a more difficult to eliminate than the warp caused by uneven web tensions. It can be removed by controlling the preheating and double facer's heat plates. Furthermore, moisturizers can be installed before the single facer for adding moisture instead of only removing it by heating. Typically, there are no moisture measurements in corrugators which makes the controlling more challenging. By closed-loop moisture control in the wet and dry end, board moisture could be stabilized, which would make the warp control less complicated.

Twist warp is claimed to be caused as a combination of differing fibre orientations and moisture imbalance between liners, assuming that web tension variations and mechanical defects are excluded [29]–[32]. Obviously, corrugators cannot affect the orientation of liner fibres, but it has been shown that the twist warp can be removed or minimized same way as the CD warp – by adjusting liner moisture balances [30].

4.3 Post Warp

The post warp refers to the warp developing after the corrugated board sheets have been piled into stacks at the end of the corrugator line. The dominating reason for the occurrence of post warp is the change in moisture of the top and bottom liners, but also a difference in liner grade or basis weight will most likely cause post warp. [27]. The liner moistures change until reaching the equilibrium with the surrounding atmosphere [27].

The degree of the post warp depends greatly on the method of stacking and on the surroundings of the stacks. [27]

4.4 Moisture Level in Produced Corrugated Board

Producing the corrugated board at the right moisture is important due to various reasons. If the moisture of the corrugated board falls too low, it will cause problems in converting. Too dry corrugated board tends to crack easily when it is converted into a box. If the moisture of the corrugated board is high, the board is soft. The softness causes troubles in converting. [15]

A given corrugated board grade should always be produced to the same moisture because of the post warp discussed in Section 4.3. Producing the corrugated into the same moisture makes it easier to predict if the post warp will occur and if so, in which direction and at which magnitude. If post warp of certain direction and magnitude can be predicted to occur, it can be compensated by producing the corrugated board with a warp in the opposite direction.

4.5 Washboarding

Lower basis weight liners in corrugated board manufacturing has led washboarding to become a more common quality problem. The name washboarding comes from the board surface looking like a washboard as a result of liner board bending down between flute tips after glueing. Washboarding weakens the printing quality and overall affects negatively on the looks of the board surface. An example of the phenomena is presented in Figure 11.

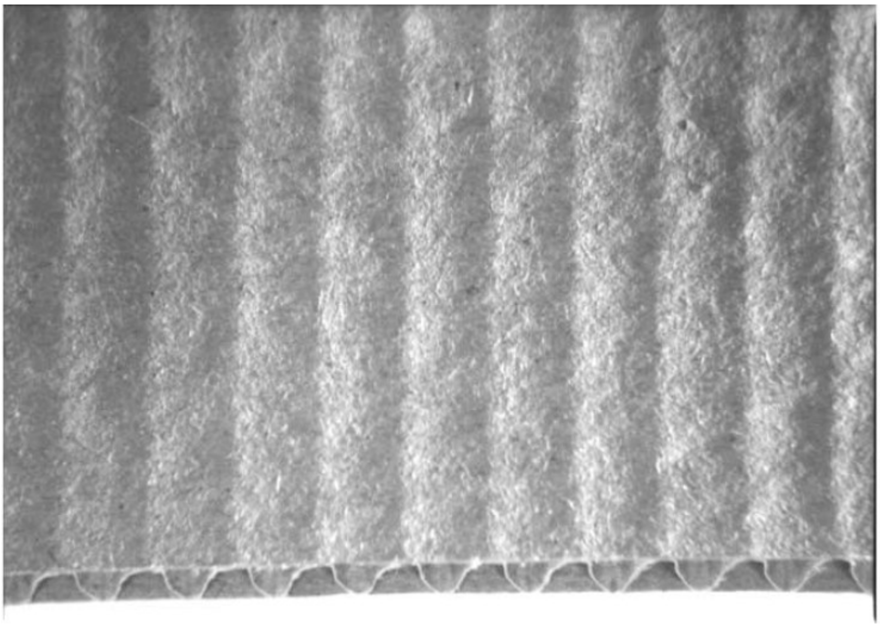


Figure 11. *Washboarding – naming comes from the surface looking like a washboard. Picture from Netz's paper* [33].

Washboarding can be reduced by reducing the amount of glue and by using heavier liner grades that will not bend as easily. Furthermore, too high liner moisture at the single facer or double facer at the time of gluing may cause washboarding [28, p. 8].

4.6 Corrugation

High/low flutes refer to height variations in the fluting web after the corrugation. It has a negative effect on the corrugated board strength properties and may cause uneven bonding [34, p. 9].

Typically high/low flutes is a cause of mechanical issues [28, p. 35], [34, p. 16]. Lack of preconditioning, pre-steaming or preheating also have an effect on formation of high/low flutes [34, p. 16]. Preconditioning softens the fibres, which eases the corrugation and therefore prevents high/low flutes.

Fractured flutes are another problem faced in the corrugation process. A simple solution for avoiding the problem is to increase the preheating or pre-steaming. More softened fibres decrease the risk of fractures in the corrugation [34, p. 32].

4.7 Bonding

4.7.1 Delamination

Delamination is maybe the most critical quality defect met in the corrugator. Delaminated board is practically always waste. If the machine is mechanically working properly, delamination, i.e. unsuccessful bonding, is most probably caused by either too high or too low liner temperatures at the moment of gluing [9], [15]. Crystallization occurs when the adhesive glue gelatinizes too rapidly, before the liner and fluting have been pressured together. Too high temperatures make the adhesive to gelatinize before the adhesive has penetrated to the boards which prevent a firm bond to form. [35] If liner temperature is too low, there is not enough heat to gelatinize the adhesive. When the adhesive is not gelatinized, the firm bond between liner and fluting does not form [20].

Thus, delamination can be prevented by keeping temperatures in the right range at the time of gluing at both single and double facers. The temperature range is learned by experience, because it depends on the amount and properties of the glues.

4.7.2 Blistering

Blistering means an unbounded bulge in liner surface. Blisters appear in single facer and double facer after glueing. Blisters occur due to low starch dosage or due to low moisture of the liner [28, pp. 2–6]. Blisters appear when liner moisture goes down, roughly, under 3 %, before glueing liner and fluting together. After glueing, liner receives moisture from glue and air, which leads to liner fibres expanding. The expansion occurs as blisters [12, p. 264].

4.7.3 Wrinkles

Wrinkles or creases are met on liner and fluting boards [12, p. 264], [28, p. 43]. Wrinkles can be already on liner or fluting reels coming from the paper mill or they can arise at the wet end on the corrugator because of wet streaks in reels [28, p. 43].

5. THE PHYSICAL FUNDAMENTALS OF THE PREHEATING IMPACT ON THE BOARD MOISTURE AND TEMPERATURE

The impact of preheating and pre-steaming on containerboard moisture and temperature has been relatively marginally studied in the literature. The dryer section in a paper machine is a similar process and much more studied. Analogies can be found from there, even the processes have differences.

Maybe the most comprehensive research is by Andrew Nevins in his Dissertation *Significant Factors Affecting Horticultural Corrugated Fibreboard Strength*, published in 2008 [36]. In Nevins's study, a numerical model for predicting fluting medium temperature and moisture before corrugating process in a single facer has been developed. The Nevins model is based on a model for newsprint paper machine dryer section, developed on Reardon's Dissertation [37].

Nevins provides a public-domain Matlab code for predicting the board moisture and temperature in a case described in the Dissertation. The Matlab model is implemented so that it can be edited and developed further relatively easily.

The Nevins model predicts moisture and temperature based on heat and mass balance equations that are solved numerically. The web running from the fluting unwinding till fluting enters the corrugator rolls is divided into sections. In each section mass and heat balance equations are formed for the top and bottom surfaces of the board based on whether the surface is in contact with ambient air, preheating roll or steam box. The board in thickness direction between top and bottom surfaces is divided into nodes, for which the heat and mass balance equations are also solved. The nodes in the original model are as presented in Figure 12.

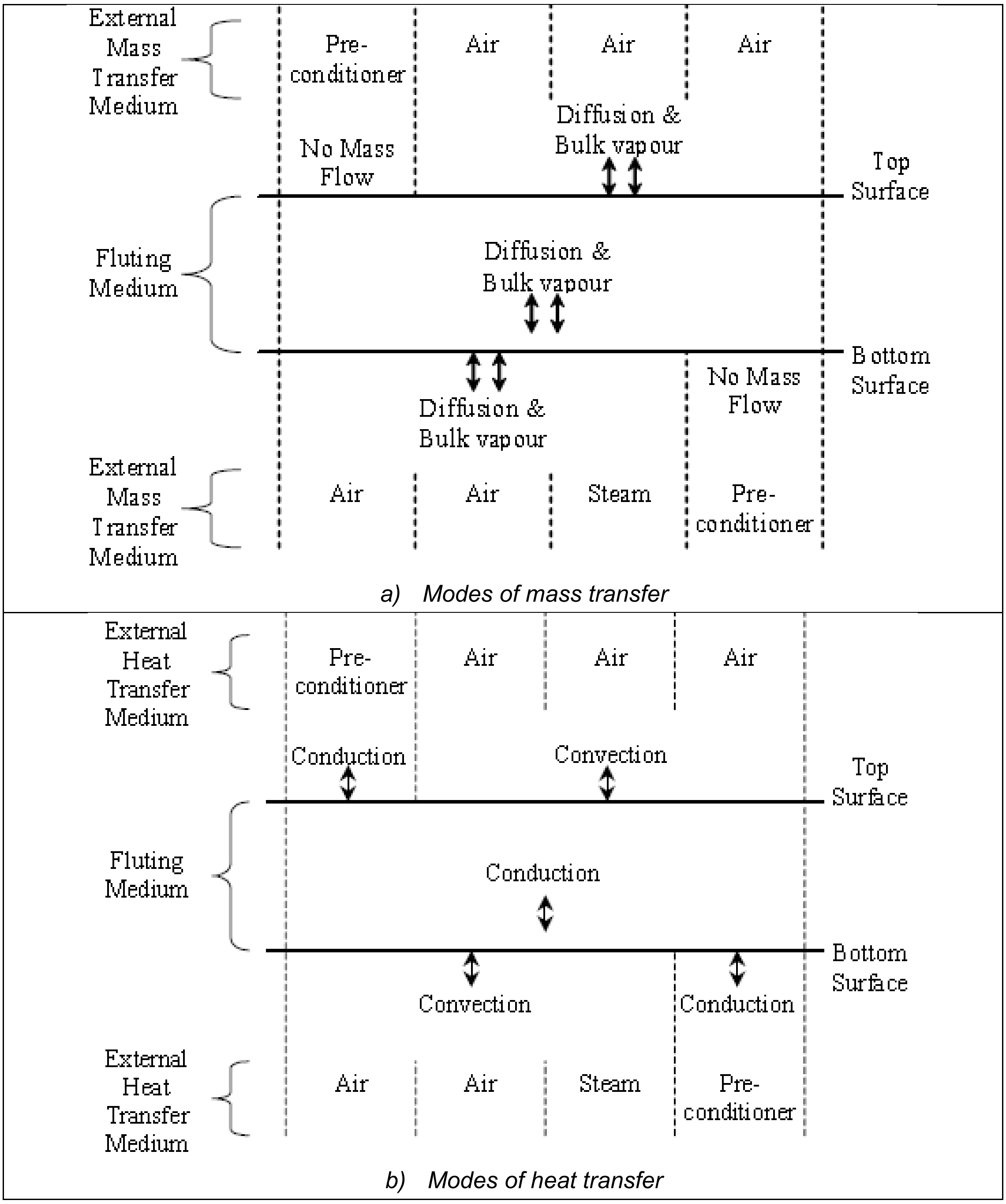


Figure 12. *Modes of a) mass transfer and b) heat transfer in Nevins's Dissertation* [36, Fig. 7.1 and 7.2]. *Preconditioner refers to preheater.*

The nodes in the type of single facer on which this thesis concentrates are presented in Figure 13, where L. starting nodes refer to liner and F. to fluting. The nodes L.ME and F.ME are the locations of the moisture and temperature measurements.

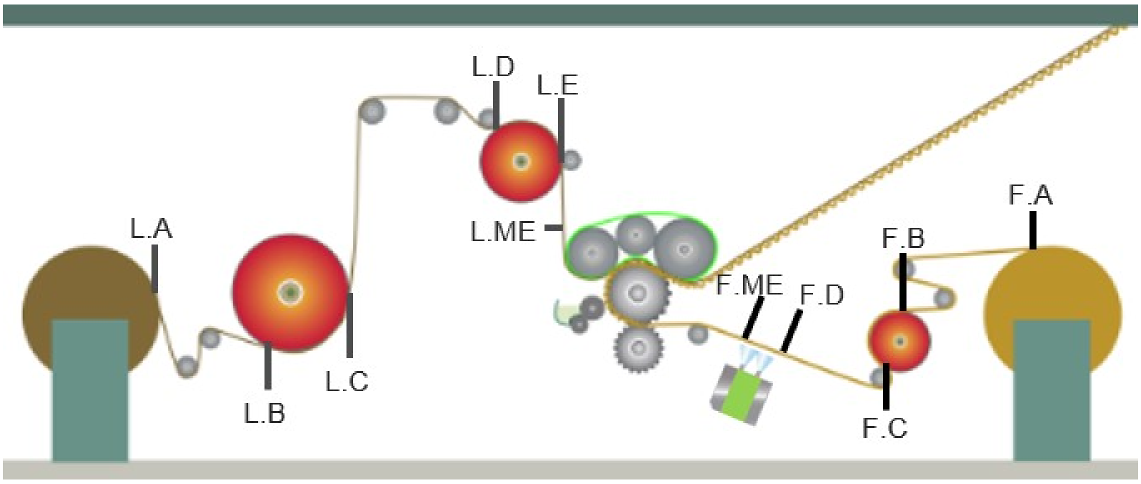


Figure 13. *The nodes.*

Based on Figure 13, the different modes of mass and heat transfer are introduced in Table 4. It follows the example of Figure 12. The distances between the nodes are divided into sections.

Table 4. *The journey from unwinding to measurement point is divided into sections.*

	Section	Start	End	Top surface contact	Bottom surface contact
Liner	1	L.A	L.B	Air	Air
	2	L.B	L.C	Preheating cylinder	Air
	3	L.C	L.D	Air	Air
	4	L.D	L.E	Air	Preheating cylinder
	5	L.E	L.F	Air	Air
Fluting	1	F.A	F.B	Air	Air
	2	F.B	F.C	Air	Preheating cylinder
	3	F.C	F.D	Air	Air
	4	F.D	F.E	Air	Air

The mass transfer consists of diffusional vapour flow and of bulk vapour flow if the temperature is over 100 C. The mass and heat transfer mechanisms in the sections are summarized in Table 5.

According to Nevins, in conducting heat transfer the net effect is that board moisture decreases, but temporarily inside the board, the moisture may rise. The pre-steaming, on the other hand, increases the board moisture slightly. [36, Fig. 7.16]

Table 5. *The techniques of mass and heat transfer in the four sections.*

	Section	Top surface mass transfer	Top surface heat transfer	Bottom surface mass transfer	Bottom surface heat transfer
Liner	1	Diffusion, bulk vapour	Convection	Diffusion, bulk vapour	Convection
	2	No mass transfer	Conduction	Diffusion, bulk vapour	Convection
	3	Diffusion, bulk vapour	Convection	Diffusion, bulk vapour	Convection
	4	Diffusion, bulk vapour	Convection	No mass transfer	Conduction
	5	Diffusion, bulk vapour	Convection	Diffusion, bulk vapour	Convection
Fluting medium	1	Diffusion, bulk vapour	Convection	Diffusion, bulk vapour	Convection
	2	Diffusion, bulk vapour	Convection	No mass transfer	Conduction
	3	Diffusion, bulk vapour	Convection	Diffusion, bulk vapour	Convection
	4	Diffusion, bulk vapour	Convection	Diffusion, bulk vapour	Convection

The two preheaters for liner in a single facer are known as external and internal preheaters, the external one being the closest one to the reel stand. The effect of preheaters on the moisture and temperature is expected to be different because the preheaters are in contact with opposite surfaces of the board, and because of the distances to the measurement point L.ME are different. The internal preheater is expected to have a stronger impact on the temperature because the distance is shorter, and because it is in contact with the inside surface of the liner. The impact to the moisture is expected to be different because the preheaters are contacted with different sides of the liner, internal being in contact with measurement side. In [36, Fig. 7.16] the impact of preheater is negligible to the opposite side in the distance examined and simulated.

In theory, the moisture and temperature of the fluting before single facer can be controlled by preheater and pre-steaming but in this context, only the position of the preheater wrap arm can be manipulated. The pre-steam is used mainly only for semi-chemical flutings but no measurement of it is available. The preheater is in contact with the bottom side, the side which is glued to the liner.

The need for preheating increases as a function of the basis weight and speed because of increase in energy needed for a given increase of drying and temperature. These impacts to liner and fluting are studied in the trials.

6. SINGLE FACER TRIAL TESTS

6.1 Objectives, Setup and Plan

Trial tests were run on 12-13.12.2017 at Saica Packaging's corrugator in Spain. The objective of the trials was to test the impact of the preheating in the moisture and temperature of the liner and fluting boards, and how machine speed, board grade and basis weight effect on these two properties. The moisture and temperature measurement points are shown in Figure 13, where

L.ME liner moisture measurement,
L.ME liner temperature measurement,
F.ME fluting moisture measurement and
F.ME fluting temperature measurement.

Moisture/temperature measurements are located just before entering the corrugating and gluing section. In addition to the temperature and moisture measurements, the double facer speed measurement was available. Single facer speed can be considered to be the same as double facer speed, excluding the speed changes and roughly one minute before and after, see Section 3.2.3.

The impact of the preheating was tested by making manually step changes to the wrap arm positions of the preheaters. Tests were run at different speeds, and for different board grades.

The trials consisted of four individual trial runs. The first two runs concentrated on the liner preheating, whereas in the last two trials, also the fluting preheating was manipulated. Board types in the trials are listed in Table 6. The trials are divided into mid-weight category (trials 1, 2, 3) and light-weight category, trial 4.

Table 6. *Board types used in the four trial runs.*

	Category	Liner type, basis weight (*g/m²*) and nominal moisture (%)			Fluting type, basis weight (g/m²) and nominal moisture (%)		
Trial run 1	Mid-weight	DUOSAICA (DS)	160	8	-	-	-
Trial run 2	Mid-weight	DUOSAICA (DS)	130	8	-	-	-
Trial run 3	Mid-weight	DUOSAICA (DS)	160	8	HIDROSAICA (HS)	115	9
Trial run 4	Light-weight	SAICA MEDIUM (SM)	85	8	SAICA MEDIUM (SM)	85	8

The four trials were scheduled according to the lengths of the orders. The orders in the first two trial runs were approximately 30 minutes each. The short duration limited the trials only for liner testing.

The order in the third trial was over 60 minutes. This enabled making tests on both liner and fluting. The fourth trial with a very light 85 g/m^2 board was used, was the only opportunity to test the light-weight boards. The detailed schedules are given in Appendix A.

Afterwards, some issues concerning the temperature measurements turned up. Temperature sensors got dirty during the time, and the calibration of the measurements needed to be rechecked. It is very likely that the actual temperatures were higher than the measurements indicate.

6.2 Results

6.2.1 Liner

The measurement points are introduced in Appendix B. Figure 14 presents the first trial measurements. The peaks that can be seen for example between 200 and 300 seconds are caused by temporary speed decreases. When the speed decreases, the board is overheated which results in a decrease in moisture and an increase in temperature. Appendix B presents the corresponding graphs of trial runs 2, 3 and 4. Overall, the results of the four trial runs are consistent, but a few points can be considered unreliable. In particular, if a step change in preheating is too early after reel change the preheating impacts cannot be separated from the impacts due to a reel change. According to the machine operator, the moisture increases for the first 500-1000 m of the reel, depending on how long the reel has been in the storage. Furthermore, immediately after the reel change the double facer speed measured here cannot be considered to be the same as the single facer speed. Such data is ignored in the analysis.

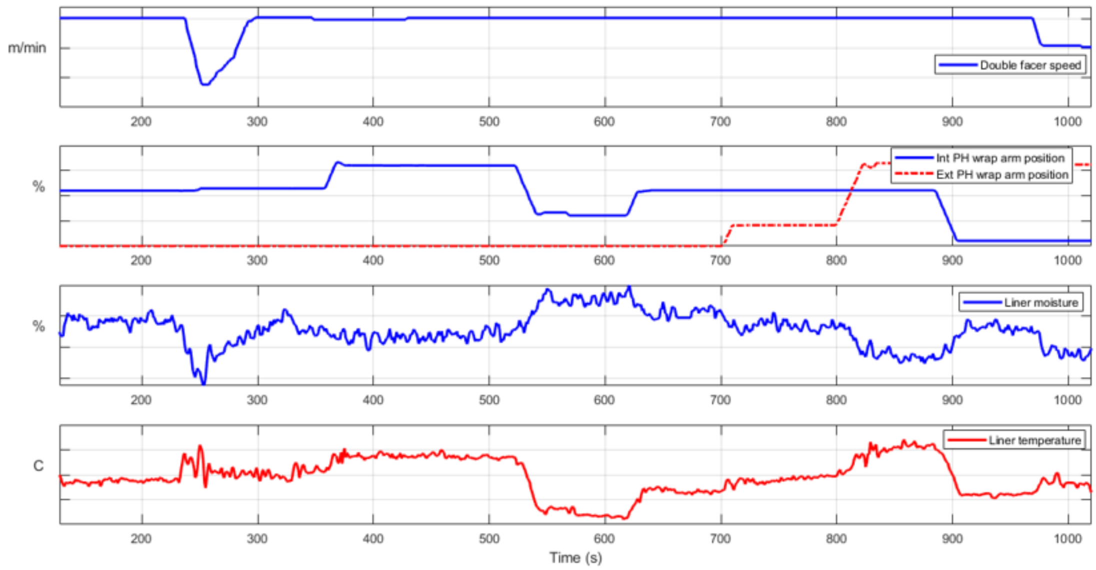


Figure 14. *Trial 1. Figures presenting the three other trials can be found in Appendix B.*

According to the trial data, the basis weight of the liner correlates with the moisture and temperature. For the light-weight liner, moisture is lower while temperature is higher compared to the mid-weight liners. The measurement ranges are slightly wider for lighter boards.

In this context, gain is concerned as the impact of 1% increase in preheater wrap arm position to moisture and temperature. The gains for moisture and temperature are opposite direction but approximately same size. The gains are higher for the light-weight board, excluding gain $\Delta\theta_{intPH} \rightarrow Temp$ which were the same. Especially for the mid-weight category, the impact of external and internal preheaters are quite identical, which can be concerned slightly surprising.

The machine speed has an impact on the moisture and temperature. For the light-weight board, the impact in moisture and temperature are nearly twice as big compared to mid-weight boards.

In most of the step changes in the trials, the impact of the wrap arm movement can be detected immediately in the moisture and temperature. Thus, no delays or time constants can be defined. However, if the start position of the wrap arm was zero, or the change was big, over 50 %, measured moisture and temperature values continue to decrease/increase after wrap arm position has settled. It is assumed that this dynamic behaviour is caused by the transient temperature change of the preheating drum: the preheating drum surface temperature is controlled by steam pressure and a large change in wrap arm position lowers the drum temperature. Drum temperature control by steam pressure is a relatively slow process, and the resulting moisture/temperature dynamics is slower than with small wrap arm changes.

6.2.2 Fluting

The test results are given in Appendix B. In this data, all test points are valid, contrary to the liner results. Figure 15 presents the third (mid-weight semi-chemical fluting) trial results. Figure presenting the fluting results in trial 4 is in Appendix B.

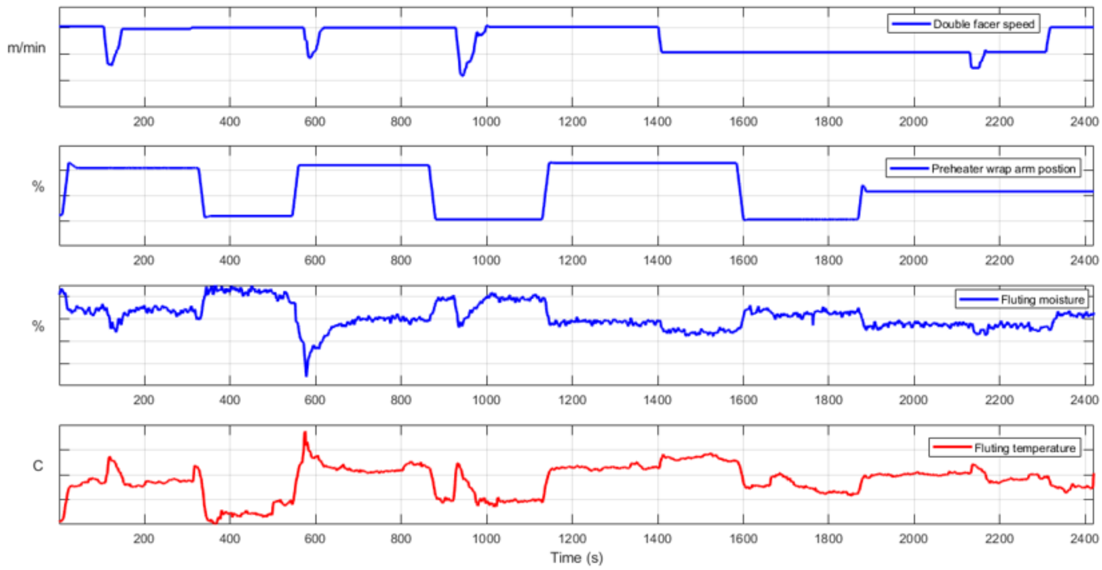


Figure 15. *Trial 3, fluting data. Th trial 4 fluting data can be found in Appendix B.*

For the mid-weight 115 g/m^2 fluting, moisture is approximately in same range than for the light-weight fluting but temperature is higher for the mid-weight fluting. The higher temperature for the heavier board is, firstly, because pre-steaming was in use for the mid-weight board but not for the light-weight board; and secondly, because of different fibre compositions react differently to heating. The mid-weight is a semichemical fluting and the light-weight board is a recycled medium type board.

The average gains of 1% increase in preheater wrap arm position to moisture and temperature are higher to the mid-weight board than to the low-weight. This suggests that less energy is needed for semi-chemical fluting than to the recycle-based medium to influence the moisture and temperature.

The machine speed has an impact on the moisture and temperature. For both the light-weight medium and mid-weight fluting, the impact in moisture and temperature is approximately the same size.

6.3 Effects of Liner Wet End Moisture Variation on Glue Unit and Dry End Measurements

The single facer liner moisture, scanner moisture measurement after double facer and warp measurement during trial 3 is shown in Figure 16. The machine speed is 200 m/min. When manufacturing this order, the web is cut into two in the machine direction, and thus there are two warp measurements. The warp is calculated by dividing the height by width and multiplying it by 100. The height indicates the curvature of the board in the cross direction that is caused by moisture variations between top and bottom liner, see Section 4.2.

From top to bottom: the wrap arm positions of the internal and external preheaters, liner moisture before single facer, liner moisture after the bridge, top liner moisture before double facer, top liner moisture after double facer, and the warp measurements 1 and 2. Warp of opposite signs indicate that both up and down warp are produced during this example.

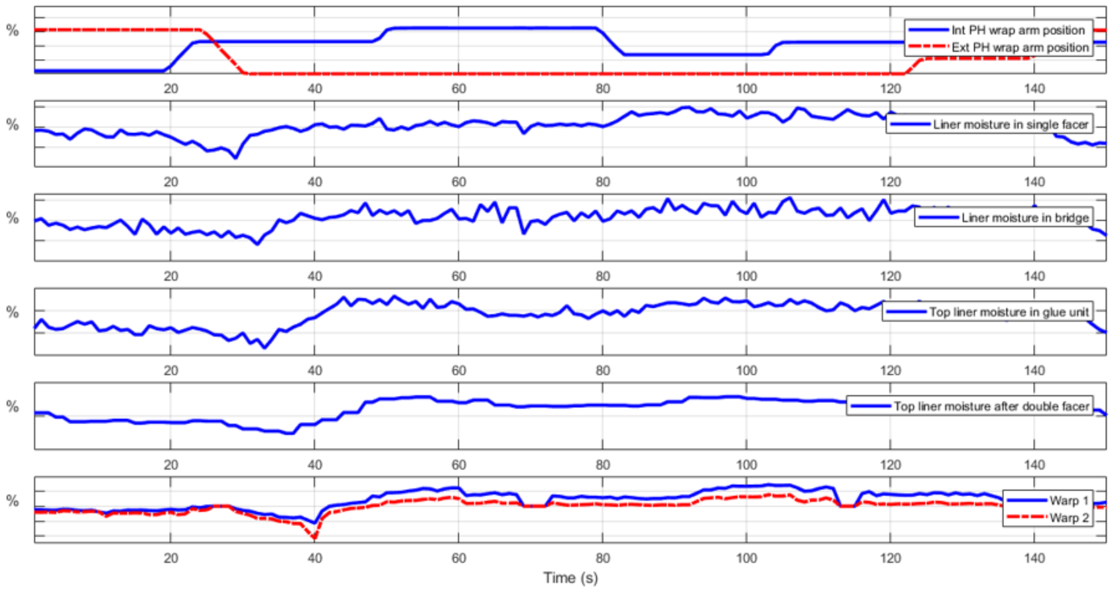


Figure 16. *The impact of top liner moisture variations in single facer in the dry end measurements. The data is from trial 3.*

7. STATIC OPTIMIZING CONTROL OF MOISTURE AND TEMPERATURE ON SINGLE FACER

7.1 Control Objectives

The quality defects that have a relation to liner and fluting moisture and temperature in single facer are listed in Table 7. Similar controls can be implemented for both liner and fluting, but in this work, only the implementation of the liner control is introduced.

The goal of the liner moisture and temperature control is to adjust preheating so that both moisture and temperature are in a range in which quality defects are minimized. The most important objective of the control is to keep the temperature all times in a range in which the firm glue bond will form. The second most important objective is to keep the moisture as stable as possible. Quality defects are expected to be minimized when these objectives are fulfilled.

Table 7. *Quality defects that can be affected by controlling board moisture and temperature by preheating in a single facer.*

	Quality defect	Text chapter where the quality defect is discussed	Moisture effect (0 = no significant effect, + = cause of too high moisture, - = cause of too low moisture, +/s = cause of too high or too low moisture)	Temperature effect (0 = no significant effect, + = cause of too high temperature, - = cause of too low temperature, +/s = cause of too high or too low temperature)
Liner	Warp	4.2	+/−	0
	Too high moisture of produced corrugated board	4.4	+	0
	Too low moisture of produced corrugated board	4.4	–	0
	Washboarding	4.5	+	0
	Blistering	4.7.2	–	0
	Crystallization	4.7.1	–	+
	Glue not gelatinizing	4.7.1	+	–
	Wrinkles	4.7.3	–	0
Fluting	High and low flutes	4.6	+	+
	Fractured flutes	4.6	+	+
	Cracking	4.4	–	0

The model-based control approach is chosen. Setpoints are given for moisture and temperature. The controlling is performed by moving the positions of the internal and external preheater wrap arms in the 0% to 100% range. The position of the preheater wrap arm determines how long a distance the board is in contact with the preheating cylinder. The control structure is presented in Figure 17.

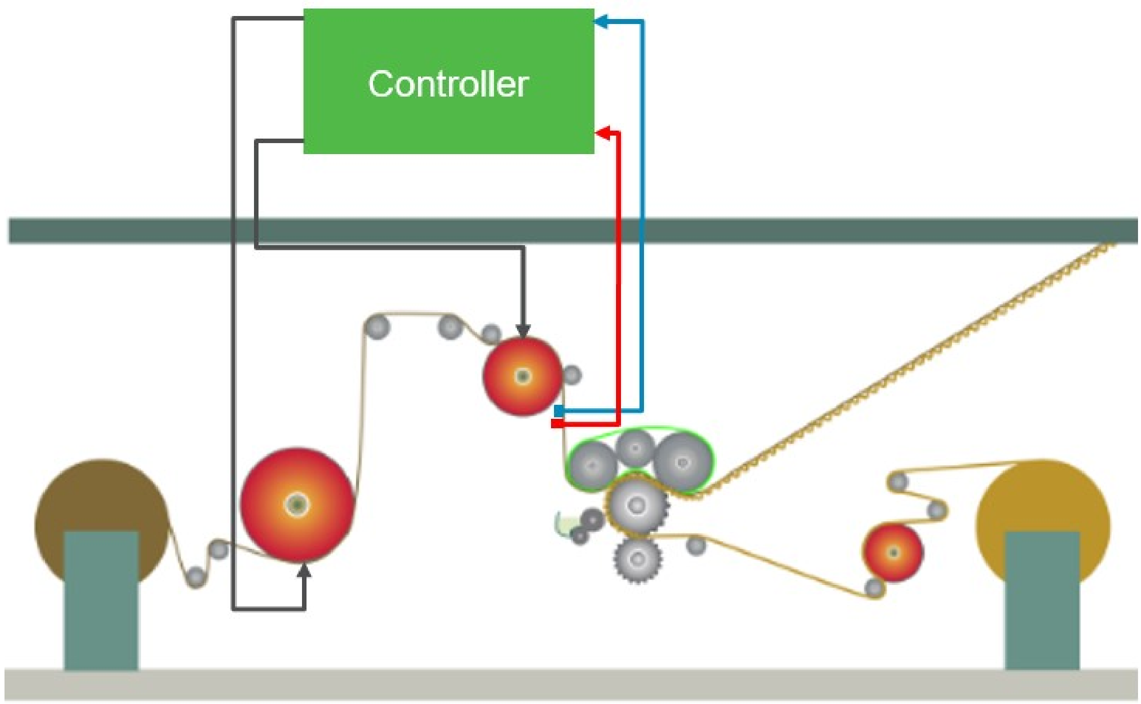


Figure 17. *The principle of the control of moisture and temperature of liner in a single facer.*

7.2 Disturbances and Limitations

There are a few major disturbance factors affecting the moisture and temperature when producing a single grade liner. Inside a liner reel the moisture can vary in MD: typically the moisture linearly increases/decreases 1-2% for the first 0-1000m of the reel being unwinded, depending on how, for how long and where the reels are stored. The moisture varies in CD also. However, it is not possible to control CD variation by the preheating. In addition to the moisture variation within reel, the moisture varies from reel to reel, even if the reels are of the same grade.

A more rapid disturbance in moisture and temperature is caused by changes in the machine speed. According to confidential data from a corrugator, there is a temporary machine speed drop in about every 5 minutes, and the drop lasts roughly 30-90 seconds. In a temporary speed change, moisture drops significantly while the temperature increases for a short time. After the speed drop is over temperature and moisture return to their normal values. If the speed drops are not compensated properly, waste is produced.

When comparing different grades, the basis weight and liner type (testliner, kraftliner) have an influence on the effect of preheating in moisture and temperature as was seen in the trial results presented in Chapter 6. This can be taken into account by updating the control model between according to the grade, if needed. However, the model based on which the control actions are chosen is always somewhat inaccurate.

The most critical limitation when controlling the preheating are the slow movements of the preheater wrap arms. The motor-driven wrap arms can move at most by a speed of 2-3%/s. Therefore, moving from 0 to 100% takes 50 seconds, or at least 33 seconds. The moving rate is too slow to compensate completely disturbances caused by speed drops, assuming that the speed changes cannot be predicted or slow down.

7.3 Static Process Model and Optimization

Optimization is based on a static process model which predicts the change in moisture $\Delta\widehat{m}$ and temperature $\Delta\hat{t}$ with given changes in the wrap arm positions, $\Delta\theta_{intPH}$ and $\Delta\theta_{extPH}$. Gain parameters $G_{intPH\rightarrow MC}$ and $G_{extPH\rightarrow MC}$ define the effect of 1% change in internal and external preheater wrap arm positions to the moisture, and gains $G_{intPH\rightarrow t}$ and $G_{extPH\rightarrow t}$ to the temperature:

$$\Delta\widehat{m} = G_{intPH\rightarrow MC} \times \Delta\theta_{intPH} + G_{extPH\rightarrow MC} \times \Delta\theta_{extPH} \tag{1}$$

and

$$\Delta\hat{t} = G_{intPH\rightarrow t} \times \Delta\theta_{intPH} + G_{extPH\rightarrow t} \times \Delta\theta_{extPH} \tag{2}$$

The gains are based on the data gathered from the trials.

The objective is to solve the optimization problem

$$min\ f(\Delta\theta_{intPH}, \Delta\theta_{extPH}) \tag{3}$$

where the cost function is

$$f = W_m \times (e_m - \Delta\widehat{m})^2 + W_t \times (e_t - \Delta\hat{t})^2 \tag{4}$$

and W_m and W_t are the weight factors, e_m is the measured difference from moisture setpoint, and e_t is the measured difference from temperature setpoint. Weight factors are chosen so that a compromise is found between ensuring a feasible temperature for gluing and keeping moisture steady. Generally this leads to grade-specific weight factors.

The cost function can be presented as function of the controllable variables, $\Delta\theta_{intPH}$ and $\Delta\theta_{extPH}$ by placing Equations (1) and (2) into (4):

$$\begin{aligned} f(\Delta\theta_{intPH}, \Delta\theta_{extPH}) = {} & W_m \times (e_m - (G_{intPH\rightarrow MC} \times \Delta\theta_{intPH} + G_{extPH\rightarrow MC} \times \Delta\theta_{extPH}))^2 \\ & + W_t \times (e_t - (G_{intPH\rightarrow t} \times \Delta\theta_{intPH} + G_{extPH\rightarrow t} \times \Delta\theta_{extPH}))^2 \end{aligned} \tag{5}$$

The actuator limitations define the constraints of the optimization problem. Minimum wrap arm position is 0 % and maximum 100 % and the wrap arms can move about 2-2,5% in a second.

Current wrap arm positions are known, so the constraints are presented as minimum and maximum changes per one control interval:

$$\begin{cases} \Delta\theta_{intPH} \geq \max\begin{cases} -\theta_{intPH_{current}} \\ \theta_{intPH_{current}} - wa_{lim} \end{cases} \\ \Delta\theta_{extPH} \geq \max\begin{cases} -\theta_{extPH_{current}} \\ \theta_{extPH_{current}} - wa_{lim} \end{cases} \\ \Delta\theta_{intPH} \leq \min\begin{cases} 100\% - \theta_{intPH_{current}} \\ \theta_{intPH_{current}} - wa_{lim} \end{cases} \\ \Delta\theta_{extPH} \leq \min\begin{cases} 100\% - \theta_{extPH_{current}} \\ \theta_{extPH_{current}} - wa_{lim} \end{cases} \end{cases}, \tag{6}$$

where wa_{lim} is the limited control action per control interval. The max/min selection takes into account that the wrap arm position control signal must be in range [0% 100%].

For solving the optimization problem, the gradients $\frac{\partial f}{\partial(\Delta\theta_{intPH})}$ and $\frac{\partial f}{\partial(\Delta\theta_{extPH})}$ are calculated:

$$\frac{\partial f}{\partial(\Delta\theta_{intPH})} = 2\times W_m\times(G_{intPH\to MC}\times((G_{intPH\to MC}\times\Delta\theta_{intPH} + G_{extPH\to MC}\times\Delta\theta_{extPH} - e_m) + 2\times W_t\times G_{intPH\to t}\times(G_{intPH\to t}\times\Delta\theta_{intPH} + G_{extPH\to t}\times\Delta\theta_{extPH} - e_t), \tag{7}$$

and

$$\frac{\partial f}{\partial(\Delta\theta_{extPH})} = 2\times W_m\times G_{extPH\to MC}\times((G_{intPH\to MC}\times\Delta\theta_{intPH} + G_{extPH\to MC}\times\Delta\theta_{extPH} - e_m) + 2\times W_t\times G_{extPH\to t}\times(G_{intPH\to t}\times\Delta\theta_{intPH} + G_{extPH\to t}\times\Delta\theta_{extPH} - e_t). \tag{8}$$

7.4 Implementing the Control in Matlab

The optimizing problem is solved with Matlab Optimization Toolbox function *fmincon* which solves constrained nonlinear optimization problems [38]. The *fmincon* is chosen because of the possibility of solving more complex cost functions, should additional terms be needed in the future.

For *fmincon*, Expression 4 is given as the cost function to be minimized, Equation 6 is expressed in a matrix form to input the inequality constraints. The gradients (Eq. 7,8) are given to speed up the computation and to make the optimization more precise. Current wrap arm positions are given as the initial values for the optimization.

The control output is calculated by summing up for both arms the current wrap arm position and the optimal change. Furthermore, a term is added that determines how many percentages of the suggested change is considered for providing more robustness if needed:

$$\begin{cases} \theta_{intPH_{opt\_lim}} = \theta_{intPH_{current}} + \frac{x}{100\%}\times\Delta\theta_{intPH_{opt}} \\ \theta_{extPH_{opt\_lim}} = \theta_{extPH_{current}} + \frac{x}{100\%}\times\Delta\theta_{extPH_{opt}} \end{cases}. \tag{9}$$

7.5 Predicting Moisture and Temperature

In addition, a model predicting moisture and temperature was developed for validating the static process model. At first, initial moisture and temperature are selected after which the new values are predicted according to changes in preheating and double facer speed. The impact of the changes are calculated as:

$$m_{pred}(t) = m_{pred}(t-1) + G_{intPH \to MC} \times \Delta\theta_{intPH} + G_{extPH \to MC} \times \Delta\theta_{extPH} + G_{DFS \to MC} \times \Delta MS_{DF}, \quad (10)$$

and

$$t_{pred}(t) = t_{pred}(t-1) + G_{intPH \to t} \times \Delta\theta_{intPH} + G_{extPH \to t} \times \Delta\theta_{extPH} + G_{DFS \to t} \times \Delta MS_{DF}, \quad (11)$$

where $\Delta\theta_{intPH}$ *and* $\Delta\theta_{extPH}$ are the preheater wrap arm position changes compared to previous control step, and ΔMS_{DF} the change of double facer speed. Because the single facer speed measurement is not available, double facer speed is used instead. This increases inaccuracy of the prediction, as double facer speed can vary from single facer speed in some cases, see Figure 7.

7.6 Implementing the Control in Matlab/DNA Environment

A standalone application is generated to run Matlab code on a target machine on a corrugator that does not have Matlab installed [39]. A standalone application can be run by first installing Matlab Runtime on the target computer [40]. The interface between Valmet DNA and the Matlab Standalone Application for a real control system with Matlab optimization is outlined in Figure 18.

For making the concept easier to use, all inputs for optimization are provided through DNA to avoid making changes to the Matlab code. The Matlab application sends back to DNA the optimal control signals and exitflag output of the *fmincon* function for ensuring if the optimization has succeeded.

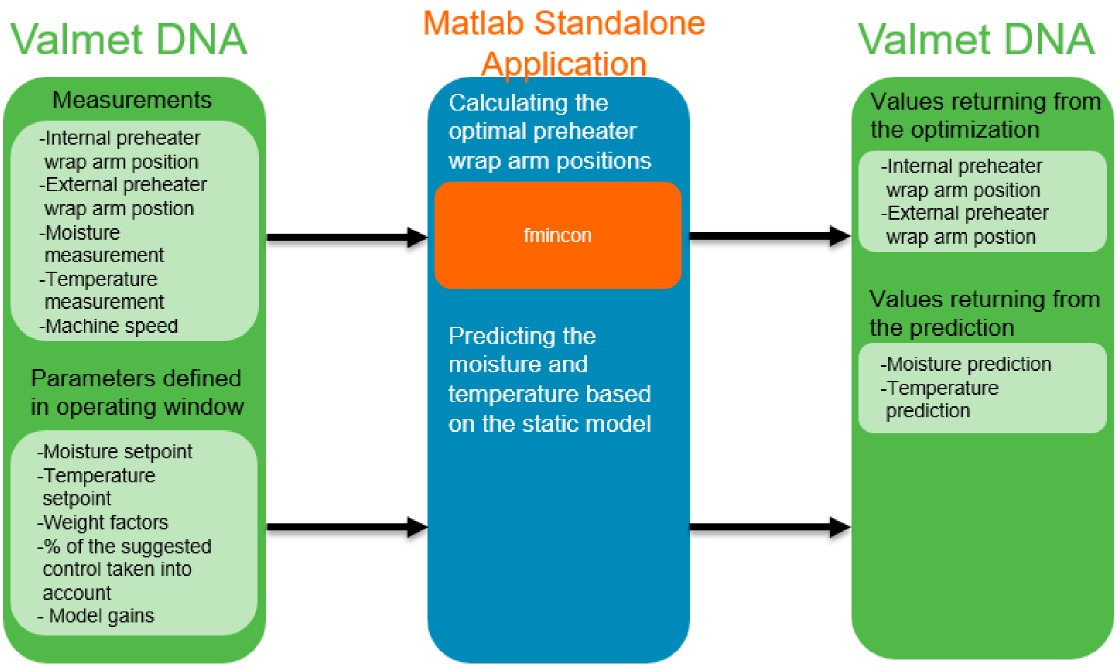


Figure 18. *The interface between Valmet DNA and Matlab Standalone Application for feeding signals for the control and control outputs back to DNA.*

Figure 19 shows the operating interface of the control in DNA. In the operating screen, operator can set the moisture and temperature setpoints, tune the controller and adjust the model based on which the optimization is solved. Moisture and temperature weights refer to W_m and W_t in equation 4. Optimizing model gains refer to parameters $G_{intPH \to MC}$, $G_{intPH \to t}$, $G_{extPH \to MC}$ and $G_{extPH \to t}$ in equations 1 and 2.

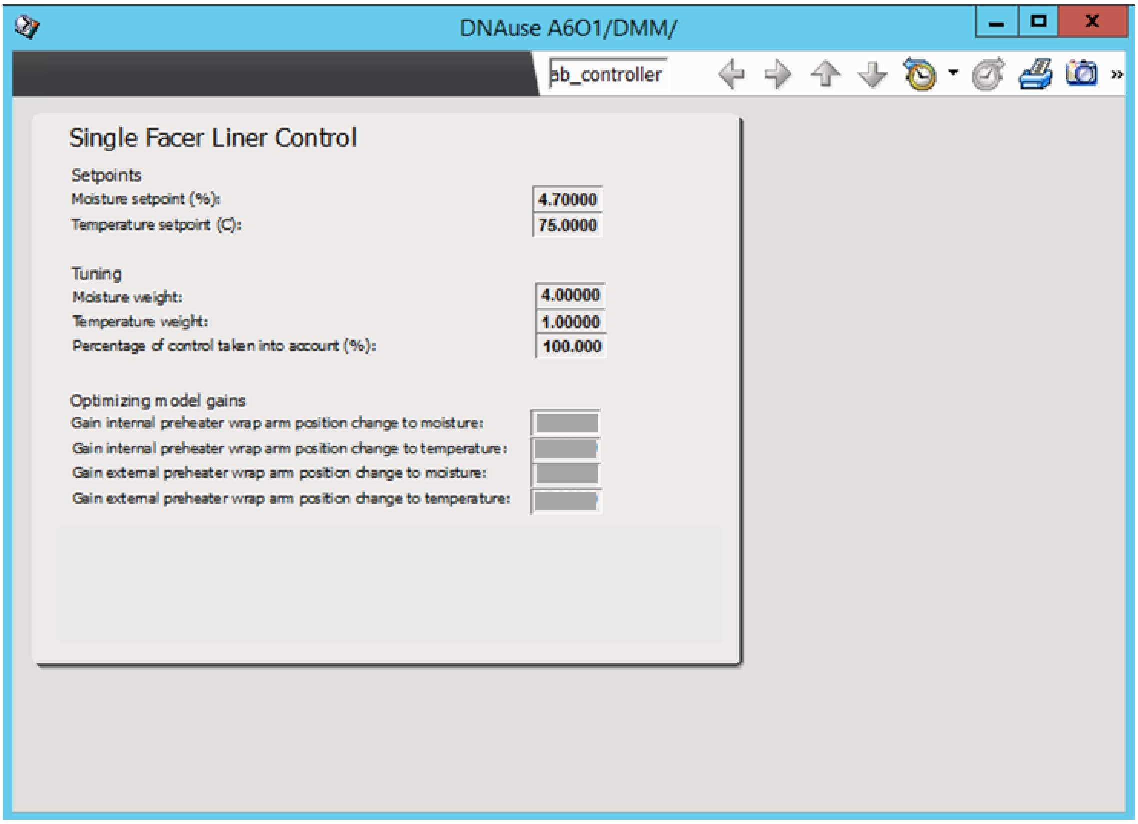


Figure 19. *The operating interface for tuning the control in Valmet DNA.*

8. SIMULATIONS

8.1 Simulation Models and Scenarios

A simulation model was implemented in Valmet DNA for testing and tuning the control. In the model, the initial state is determined, where moisture and temperature are set to the desired values with initial values of internal and external preheater wrap arm positions, and machine speed. The initial values can be set freely.

The model is implemented by FbCAD (Function Block CAD, [41]) based on the following equations for moisture and temperature:

$$m_{simu}(t) = m_{simu_{init}} + Gs_{intPH\to MC} \times (\theta_{intPH}(t) - \theta_{intPH_{init}}) + Gs_{extPH\to MC} \times (\theta_{extPH}(t) - \theta_{extPH_{init}}) + Gs_{MS\to MC} \times (MS(t) - MS_{init}) + m_{rc_{disturb.}} \quad (12)$$

and

$$t_{simu}(t) = t_{simu_{init}} + Gs_{intPH\to t} \times (\theta_{intPH}(t) - \theta_{intPH_{init}}) + Gs_{extPH\to t} \times (\theta_{extPH}(t) - \theta_{extPH_{init}}) + Gs_{MS\to t} \times (MS(t) - MS_{init}) \quad (13)$$

The model parameters and the values in the simulations are given in Table 8. The simulation model considers that wrap arms can move at the maximum speed of 2 %/s.

Table 8. *Simulation initial values and parameters in simulations 1, 2 and 3.*

	Symbol	Explanation	Value
Initial simulation parameters	$m_{simu_{init}}$	Initial liner moisture %	4.7
	$t_{simu_{init}}$	Initial liner temperature ℃	75
	$\theta_{intPH_{init}}$	Initial internal preheater wrap arm position %	50
	$\theta_{extPH_{init}}$	Initial external preheater wrap arm position %	20
	MS_{init}	Initial machine speed m/min	250
Simulation model parameters	WAR_{min}	Minimum wrap arm moving rate %/s	-2
	WAR_{max}	Maximum wrap arm moving rate %/s	2
	MSR_{min}	Minimum machine speed change rate $\frac{m/min}{s}$	-10
	MSR_{max}	Maximum machine speed change rate $\frac{m/min}{s}$	10
	$m_{rc_{disturb.}}$	Disturbance in moisture caused by reel change	Figure 21

The objective of the simulations was to test how the control reacts to machine speed changes. The single facer speed in the simulations is presented in Figure 20. The speed changes not more than 10 $\frac{m/min}{s}$. In the speed scheme speed is lowered from the production speed of 250 m/min to 150 m/min due to splicing and, after 15 seconds, increased back to the production speed of 250 m/min.

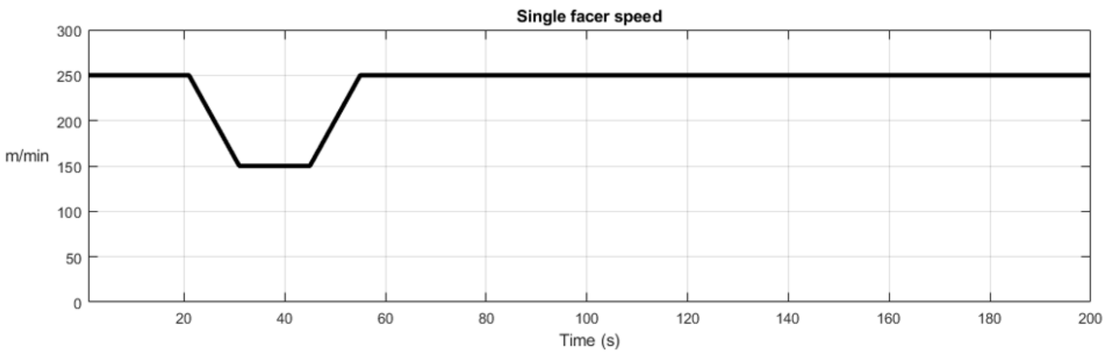


Figure 20. *Single facer speed in the simulations.*

Reel change has an effect on moisture. After the splice, the liner moisture first decreases, after which it raises back to the nominal value according to a first-order transfer function after 25 seconds. The moisture disturbance is shown in Figure 21.

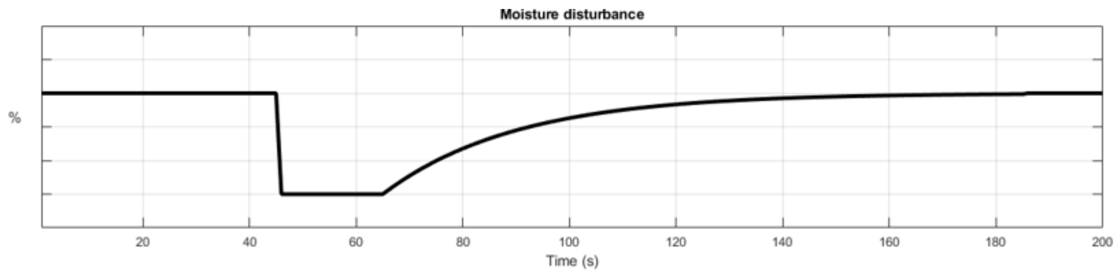


Figure 21. *Disturbance in the liner moisture due to a reel change in the simulations.*

In the first simulation, the control was not applied. The task is to verify that the simulation model is working properly and to set a base case with which the performance of the control is compared. In the second simulation, the process is controlled according to the ideal process model: the gains describing the impact of preheaters to moisture and temperature are chosen to be equal to the simulation model gains. In the third simulation, the performance of the control is evaluated when the control is based on a process model that differs from the simulation model. The absolute values of the gains are 50% smaller than in the simulation model.

Moisture and temperature setpoints and weights are kept constant in the latter two simulations. The control parameters used are given in Figure 22. The control action during one second long control interval is limited to the range $[-3\%, 3\%]$ for both wrap arms.

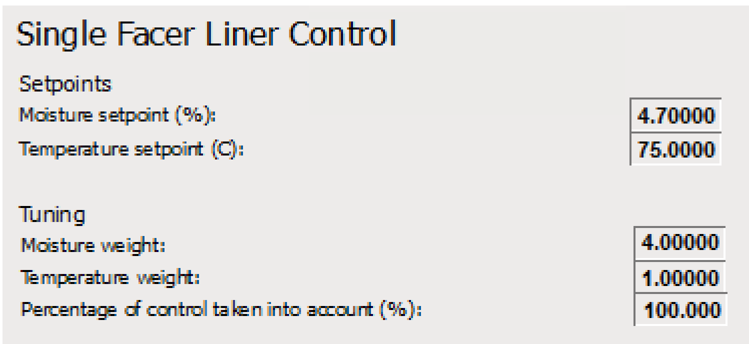


Figure 22. *Setpoints and weights chosen for the simulations.*

8.2 Simulation Results

8.2.1 Base Case – No Control

The results of the first simulation are presented in Figure 23. The internal preheater wrap arm is kept at 50% and the external at 20% throughout the simulation. The drop in the moisture after 45 seconds is due to the disturbance caused by the reel change, see Figure 21.

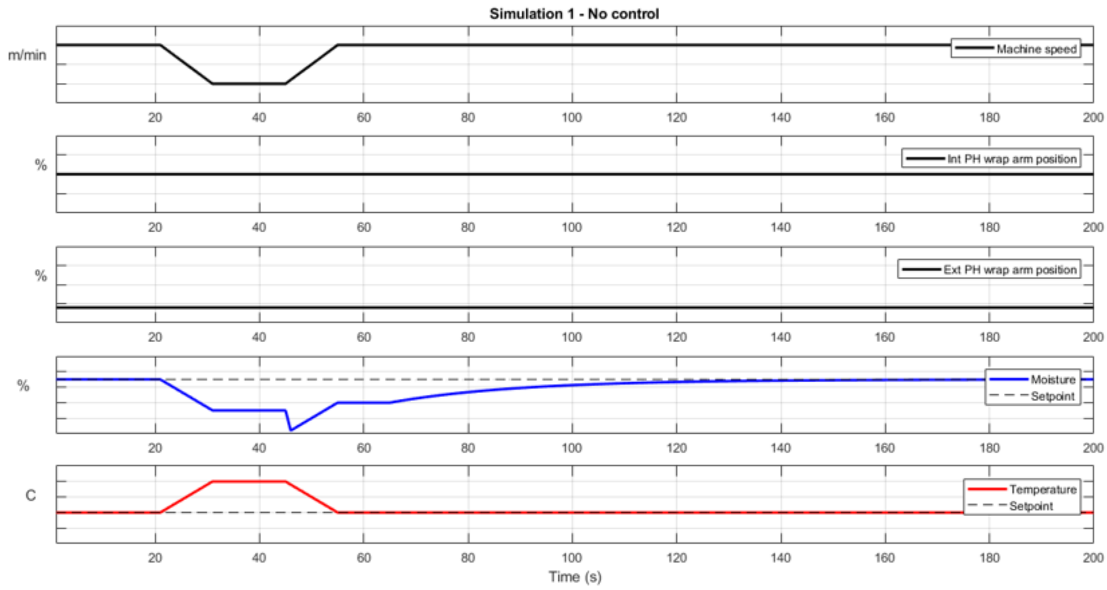


Figure 23. *Simulation with no control.*

The moisture undershoot detected is significant enough to cause quality problems, especially warp. The overshoot in temperature could also cause problems in gluing although the error is not as significant as in moisture.

8.2.2 Ideal Control Model

The results of the second simulation are presented in Figure 24. In this scheme, the control is in use and the control model is ideal. The largest undershoot in moisture is nearly 2% smaller than in the first simulation with no control and in temperature the corresponding overshoot is decreased by over 2°C. On the other hand, an undershoot is caused in temperature after the reel change. If needed, deviation in temperature could be reduced by increasing the weight of the temperature in the optimization cost function.

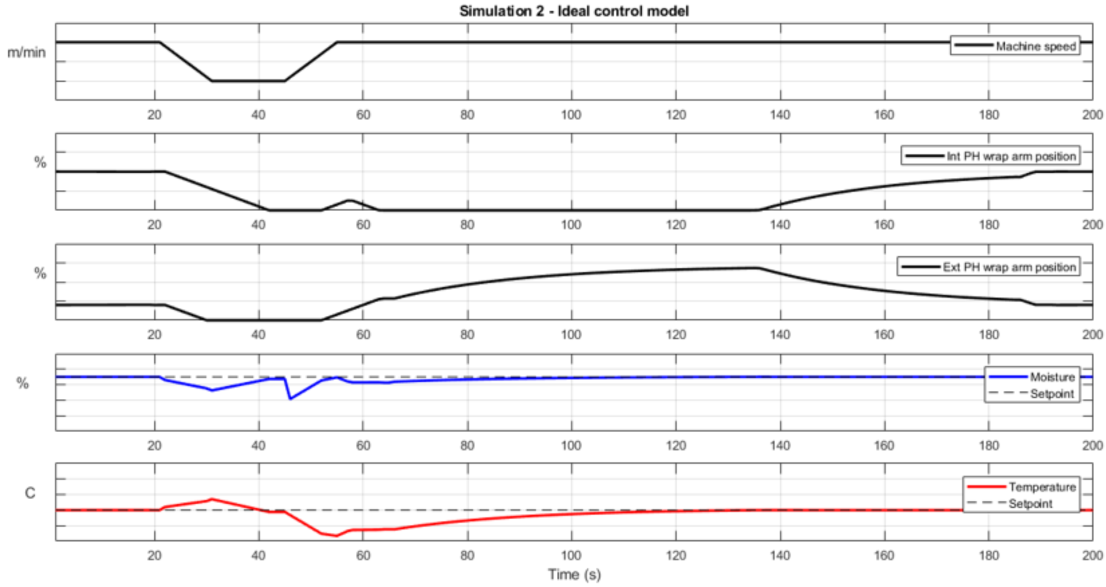


Figure 24. *Simulation with control based on ideal model.*

When the speed is increased, external preheater is first used and internal preheating is kept in zero. After 135 seconds of simulation, control drives external preheating to 20% and increases internal preheating to 50%.

8.2.3 Error in Control Model

The results of the third simulation are given in Figure 25. In this scheme, the control model is not ideal, all control model gains are 50% smaller absolutely than in simulation model. The behaviour of the moisture and temperature are almost identical to the control based on the ideal process model. Because the model error is of the same size in every gain parameter, the wrap arms are controlled to the same direction as without an error. Furthermore, the limited control action prevents the control to make oversized movements of the wrap arms, the larger control actions resulting from lower control model gains are saturated to the ones with the ideal control model.

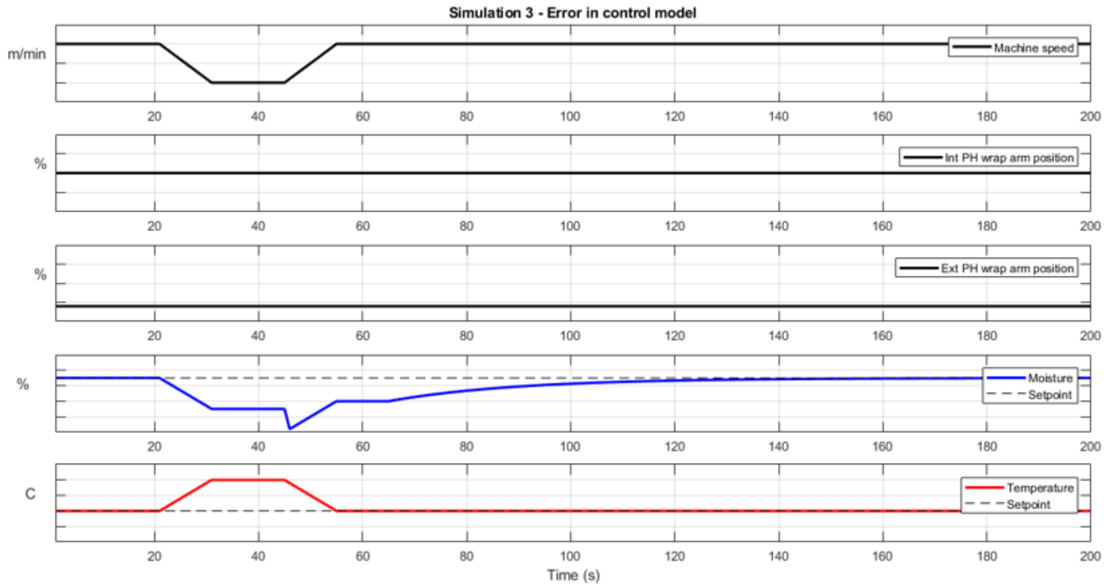


Figure 25. *Simulation with inaccurate control model.*

8.3 Summary of the Simulations

Based on the simulations, the control offers a great potential on minimizing the variation on moisture and temperature but the impact of the disturbance of the speed change is impossible to compensate perfectly by using only the preheater wrap arms because they move too slowly compared to the change of speed. In Table 9 2σ values and the peak errors in the three simulations are presented. The 2σ value tells the difference from set-point which a single measurement does not exceed by a 95% probability.

Bassed on the simulation, the control is very robust for the model error. The differences between ideal control model and incorrect control model are negligible. The robustness is due to the limited changing speed of the wrap arms compared to the speed changes. This leads to a situation where the control makes as big control actions as allowed in rapid speed changes, regardless of the model error.

Table 9. *The 2σ values and peak errors in the three simulations.*

	Peak moisture error (%)	Moisture 2σ	Peak temperature error (℃)	Temperature 2σ
Simulation 1	3	1.5	3	1.2
Simulation 2	1.43	0.45	1.66	0.85
Simulation 3	1.43	0.46	1.66	0.84

9. VALIDATING PROCESS MODEL WITH REAL PROCESS DATA

9.1 Overview

The accuracy of the process model derived from the trial data is tested by predicting board moisture and temperature with the model taking real data from a corrugator as an input. The predictions are made for two individual data sets with different liner grades. The first data set is approximately 10 minutes and the second 7,5 minutes long. The liner grades are DS160 and DS130. In the predictions, initial moisture and temperature are taken from the process data after which the entire sequence of moisture and temperature are predicted according to changes in preheating and double facer speed.

The model cannot predict all the variations in moisture and temperature. Other factors influencing the moisture and temperature can be, for example, variations in moisture inside the reel, web tension and steam pressure inside preheater drum. However, predicting based on preheating and speed is found to be accurate enough for control purposes, especially for predicting moisture. The temperature prediction is found to be more challenging. To a degree, the challenges in predicting temperature can be explained by the temperature sensor getting dirty. A dirty sensor has an offset, and thus the sensor has behaved differently in trial runs and in the measurements for prediction. Furthermore, the unmeasured factors are believed to have a larger impact on temperature than to moisture.

The double facer speed improves the predictions significantly even though the single facer speed may differ from it in some cases related to speed changes. The parameters in the prediction model are rounded-off values of those found in trials.

9.2 Results

The first data set and the corresponding moisture and temperature predictions are presented in Figure 26. During the prediction, there is altogether five changes in the internal preheater wrap arm position and one momentary change in double facer speed. The external preheating is zero.

Moisture is predicted quite successfully in all changes. After the last change in the data, the speed change, no significant difference between the prediction and measurement can be detected. However, the moisture measurement can be seen to reacting with a small delay compared to the prediction and to the temperature measurement. Most probably this can be explained by an internal pretreatment to remove noise from the signal.

Temperature is not predicted as successfully as moisture as after the last change there is about 0.8°C offset between the prediction and the measurement. The offset results almost entirely by the change of internal preheating wrap arm position from 100% to 66%. The predicted temperature change is nearly twice smaller than the measured one. Otherwise, the temperature prediction follows the measurement closely.

The prediction of temperature and moisture in a momentary speed change is more accurate than expected. After 500 seconds, a ramp-like change can be seen in moisture and temperature which cannot be explained by preheaters or double facer speed. This could be caused by the single facer accelerating to a faster speed than the double facer to catch up the bridge quantity setpoint. An alternative explanation is that the steam pressure inside the preheater increases, while this is a more unlikely scenario because pressure variations have been more commonly met only when one preheater wrap arm is moved from zero position.

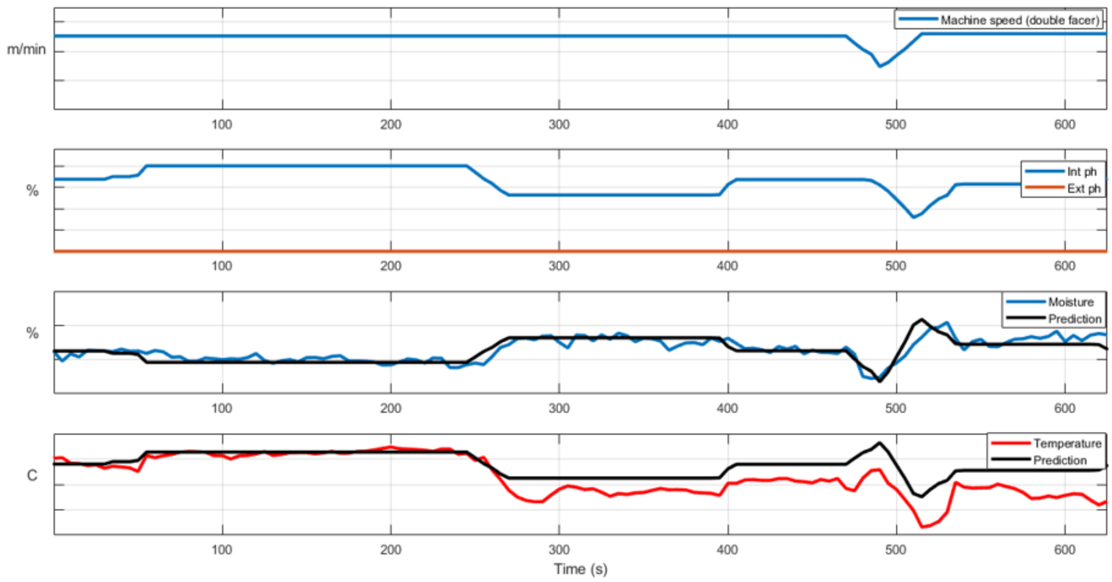


Figure 26. *Predicting moisture and temperature based on the positions of the preheater wrap arms and on the double facer speed. Liner DS160.*

The second data and the predictions are presented in Figure 27. Here, also the external preheater wrap arm is moved from the zero position. Moisture is predicted accurately based on the external preheater wrap movement, excluding when external preheater wrap arm is moved from 0→10%, in which prediction underestimates the impact.

Moisture and temperature predictions are both overestimated and a few seconds ahead of the measurement during the speed change. These may be caused by the single facer speed being different from the double facer speed.

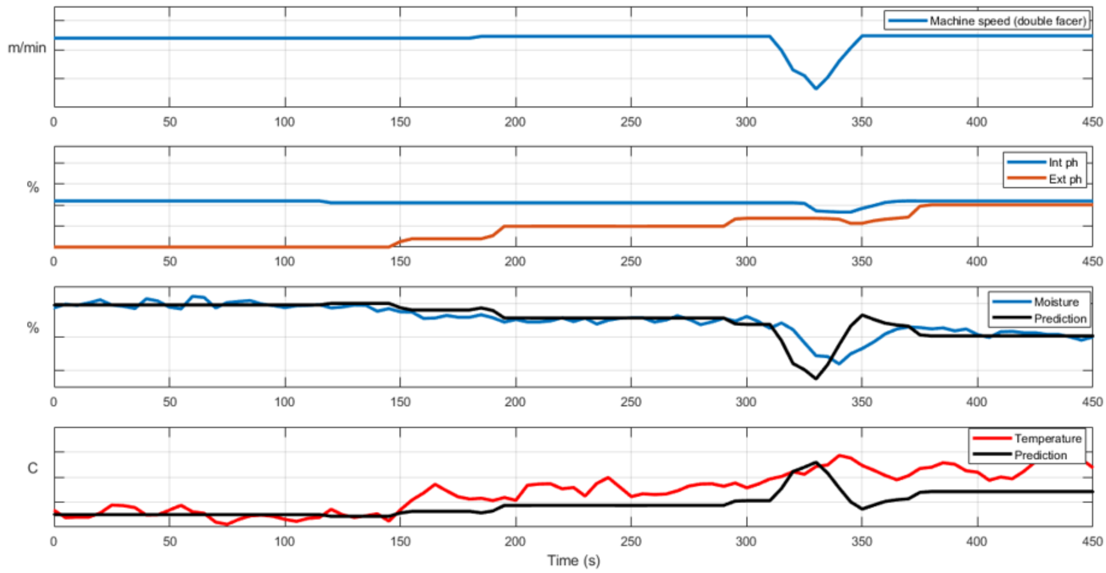


Figure 27. *Predicting moisture and temperature based on the positions of the wrap arms and on the double facer speed. Liner DS130.*

Judged by the difference between measured and predicted temperature, the impact of external preheating to temperature is clearly underestimated. The error is 1°C at the end of the prediction interval. When the gain $G_{extPH \to t}$ is doubled, the predicted temperature at the end is very close to the measured value, but still can be seen that the when external preheater wrap arm is moved from 0→10% the impact to temperature is distinctly underestimated. This is shown in Figure 28.

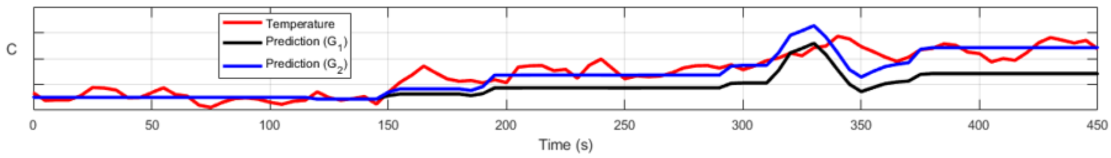


Figure 28. *Temperature prediction compared to measurement when* $G_{extPH \to t} = G_1$ *and* $G_{extPH \to t} = G_2 = 2 \times G_1$.

The temperature increases slowly between times 200 and 350 seconds. This is most likely caused by a steam pressure increase in the preheater drum. The steam pressure drops from the setpoint when wrap arm is moved from zero position and it takes about 150 seconds for the pressure to recover back to setpoint. This phenomenon is usually only seen when wrap arm position has first been zero.

Temperature appears to oscillate with a 50 second period. No explanations for this was found. A possible reason is that the steam pressure inside the preheater drum is not stable and causes the temperature to oscillate. However, this was not verified.

10. DISCUSSION

The results of the simulations are very promising. The control will help on reducing the variation of the moisture in speed changes and reel changes, which the most problematic situations without a closed-loop control. The control is quite robust for model error mostly because of the limited moving speed of the wrap arms. For now, in practice, the only requirement for the control is that it controls to the right direction and as fast as the arms can move. The importance of the model accuracy will increase if the wrap arms can be operated more rapidly.

The simulations showed that after a reel change the temperature falls below target when the moisture weight in the cost function is larger than that of temperature. The weights for moisture and temperature must be tuned together with operators to figure out the optimal compromise between reducing moisture variation and achieving acceptable temperature for gluing. The weights may need to be grade specific. With low basis weight boards moisture can be weighed more because too low temperatures are not a problem, but moisture tends to vary more. With high basis weight boards, on the other hand, temperature needs to be weighed more to ensure proper bonding all times.

The disturbance caused by speed change cannot be compensated fully when the actuators can be operated at present, much slower rates than changes in machine speed are made. Another solution could be to start controlling the wrap arms proactively or slow down the speed changes. In practice, proactive operation would require that timings of speed changes would be known beforehand. Such coordinated speed changes are more familiar with paper machine MD-control. Furthermore, a steam box could be located before the single facer to add moisture if the board is overheated otherwise.

A problem to be solved when controlling the real process is the limitation caused by actuator mechanics. The motor actuators moving the wrap arms cannot be operated constantly or else motor breakdowns will become a problem. This suggests using deadbands. Deadband zones and setpoints need to be chosen carefully to prevent the control from jumping from inside one deadband into another back and forth causing oscillation.

In the prediction schemes, the simple static process model based on the trials predicted quite accurately the moisture but temperature predictions were less accurate. Most likely the temperature gains found in the trials are too low and need to be revised once the problems with the temperature sensors are solved. Furthermore, the factors not measured but affecting the impact of preheating are causing more disturbance on temperature than on moisture. The model could be improved by utilizing the physical model introduced in Chapter 5, and by getting more measurements from the corrugator and studying their impact.

11. SUMMARY

11.1 Conclusions

In the theoretical part of the work, the operation of a corrugator was studied from the process control point of view. In addition to the literature review the Finnish corrugated board producers Adara Oy and Stora Enso were interviewed. In general, there are multiple ways to remove moisture and increase temperature but rather few ways to add moisture. The most important quality factors of the corrugated board and the impact of moisture and temperature to them were researched from the literature. It was found out that for providing better quality and less waste produced, variation in moisture and temperature needs to be decreased, meanwhile, the desired levels for these parameters should be found, depending on grades. In summary, temperature plays an important role in successful gluing and moisture is important for the other key quality factors.

For minimizing the variation of moisture, the practical part of the work concentrated on implementing a control for moisture and temperature in the 'heart' of the corrugator, single facer. To facilitate this, trials were run on a corrugator in Spain, owned by Saica Packaging. The trials studied the impact of preheating, speed and board basis weight to moisture and temperature on a single facer. Impact on both liner and fluting were studied. Simple, static process models were generated based on the data gathered from the trials. The process models for fluting and liner were based only on the changes in the preheater wrap arm positions. In the prediction model, also the impact of speed was observed.

The accuracy of the static process model was verified by using it for predicting liner moisture and temperature a few months after the trials. Moisture predictions were accurate for both preheaters and for speed changes whereas temperature predictions were less accurate. The latter could be explained partially by problems with the temperature sensors getting dirty. However, it seems that temperature is more sensitive to disturbances than moisture. A more accurate physical model could be a solution. The physical fundamentals were briefly introduced in Chapter 5.

A control based on a static process model was designed for liner moisture and temperature by preheating in a single facer. The control was implemented only for liner but the same structure can be easily duplicated for controlling fluting moisture and temperature by one preheater.

The performance of the control was studied by simulations with promising results: the chosen control strategy offers a great potential in reducing variation in moisture and temperature in single facer, and thus in making the process more stable. However, the single facer controls should be seen rather as the first step on a mission developing machine wide quality control system (QCS) for a corrugator than as a universal solution for all quality problems.

11.2 Further Development

The control implemented in this work can be with only a little effort duplicated for controlling fluting moisture and temperature in a single facer. Tentative process model has already been generated for fluting based on the trial data. The control will be a simplified version of the liner control because there is only one preheater that can be manipulated. Later, the pre-steaming will possibly be also controlled, which would enable control in a wider range.

Next challenge is to get the controls into every day -use in a corrugator so that more can be learned about the control and developed further. Before that, grade specific setpoints need to be found for moisture and temperature based on process data and on experience.

The physical model as Matlab code, see Section 5, offers great potential for a more generic simulation model for the single facer operation. The physical model can be edited relatively easily based on target machine specifications. The model could be verified and improved with real process data.

Furthermore, the work should be continued by developing a closed-loop control for the glue unit and the double facer. The control could utilize preheaters in glue unit, a moisturizer in the top and a bottom side and the pressure shoes in double facer. The moisturizers enable controlling moisture in cross direction, while other actuators can control only in the machine direction.

The case corrugator has similar temperature and moisture measurements after the preheaters in glue unit than in the single facer. In addition, there are moisture measurements at the end of the two bridges. The bridge measurements could be feedforwarded for the control. After the double facer, a scanner measures moisture and temperature from both top and bottom side in MD and CD. The scanner enables also measuring the total moisture of the corrugated board and additionally, a warp measurement measures the flatness of the produced board.

The objectives of the control are similar but a bit more complicated than in single facer: provide a temperature suitable for glueing and bonding, at the same time producing the board into suitable moisture level, and keeping the warp in the target. In practice, this will lead to a need for MPC (Model Predictive Control) type MIMO-control strategy.

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APPENDIX A: TRIAL PLAN

Table 10. *Liner test schedule.*

	Test point #	Machine speed m/min	Internal preheater wrap arm position %	External preheater wrap arm position %
Trial 1	1.1	250	55	0
	1.2	250	80	0
	1.3	250	30	0
	1.4	250	55	0
	1.5	250	55	0
	1.6	250	55	20
	1.7	250	0	80
	1.8	200	0	80
Trial 2	2.1	150	60	0
	2.2	150	80	0
	2.3	150	25	0
	2.4	150	55	0
	2.5	150	55	30
	2.6	150	55	70
	2.7	150	5	70
	2.8	180	5	70
	2.9	255	5	70
Trial 3	3.1	250	55	0
	3.2	250	80	0
	3.3	250	35	0
	3,4	250	55	0
	3.5	250	55	30
	3.6	250	55	80
	3.7	250	5	80
	3.8	205	5	80
	3.9	205	55	0
	3.10	205	80	0
	3.11	205	35	0
	3.12	205	55	0
	3.13	205	55	25
	3.14	205	55	75
	3.15	205	5	75
	3.16	250	5	75
Trial 4	4.1	200	25	0
	4.2	200	85	0
	4.3	200	25	0
	4.4	200	25	40
	4.5	200	25	80
	4.6	200	5	80
	4.7	200	15	0
	4.8	150	15	0
	4.9	150	90	0
	4.10	150	25	0
	4.11	150	25	45
	4.12	150	25	85
	4.13	150	5	85

Table 11. *Fluting test schedule.*

	Test point #	Machine speed m/min	External preheater wrap arm position %
Trial 1	-	-	-
Trial 2	-	-	-
Trial 3	3.1	250	30
	3.2	250	80
	3.3	250	30
	3,4	250	80
	3.5	250	25
	3.6	250	85
	3.7	205	85
	3.8	205	25
	3.9	205	55
	3.10	250	55
Trial 4	4.1	200	10
	4.2	200	75
	4.3	200	15
	4.4	150	15
	4.5	150	75
	4.6	150	10

APPENDIX B: TRIAL TEST RESULTS

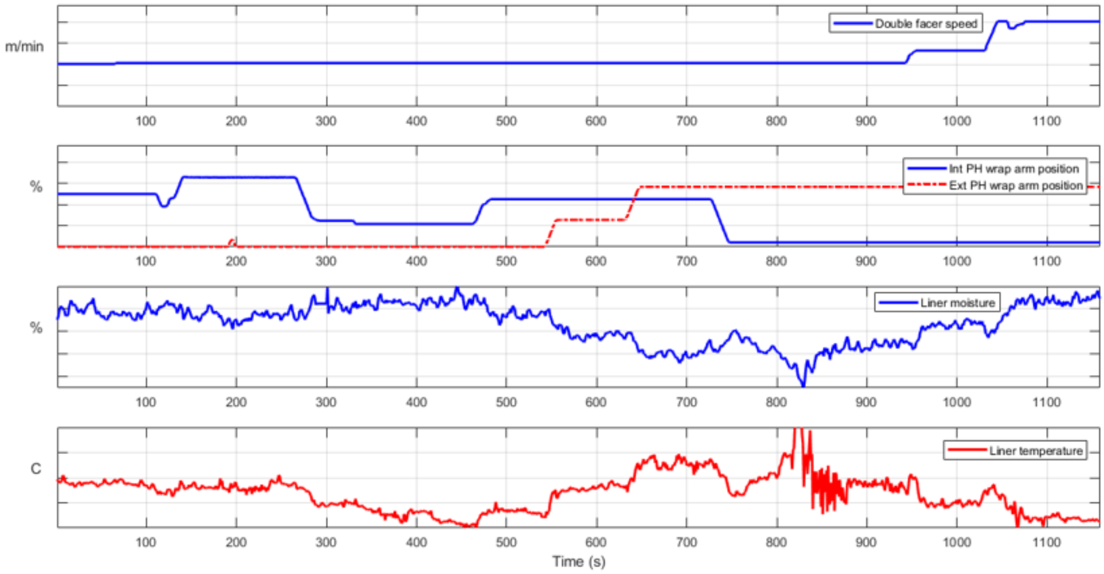

Figure 29. *Trial 2, midweight liner (DS130).*

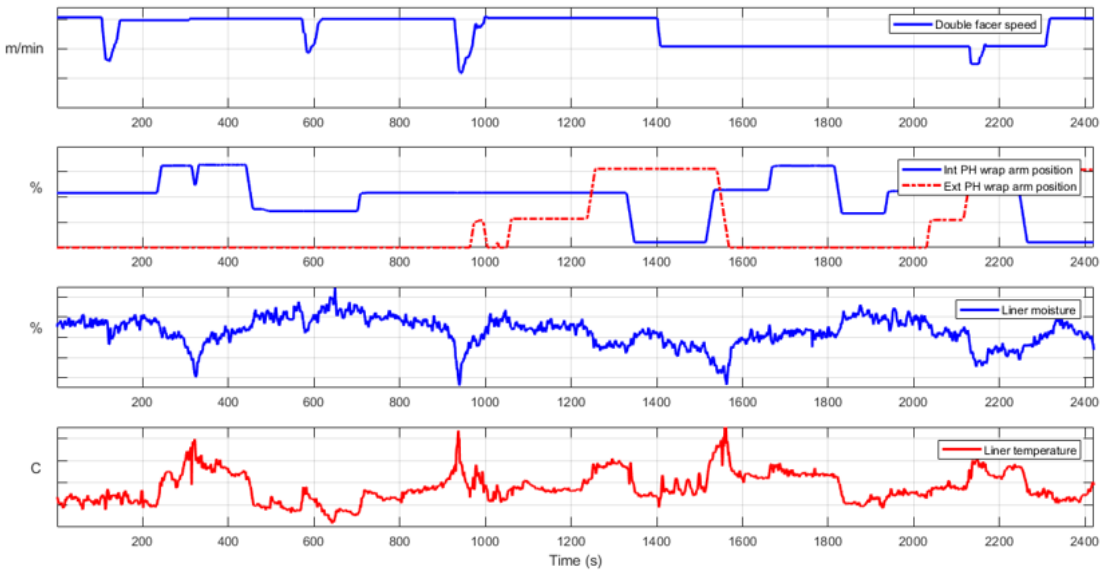

Figure 30. *Trial 3, midweight liner (DS130).*

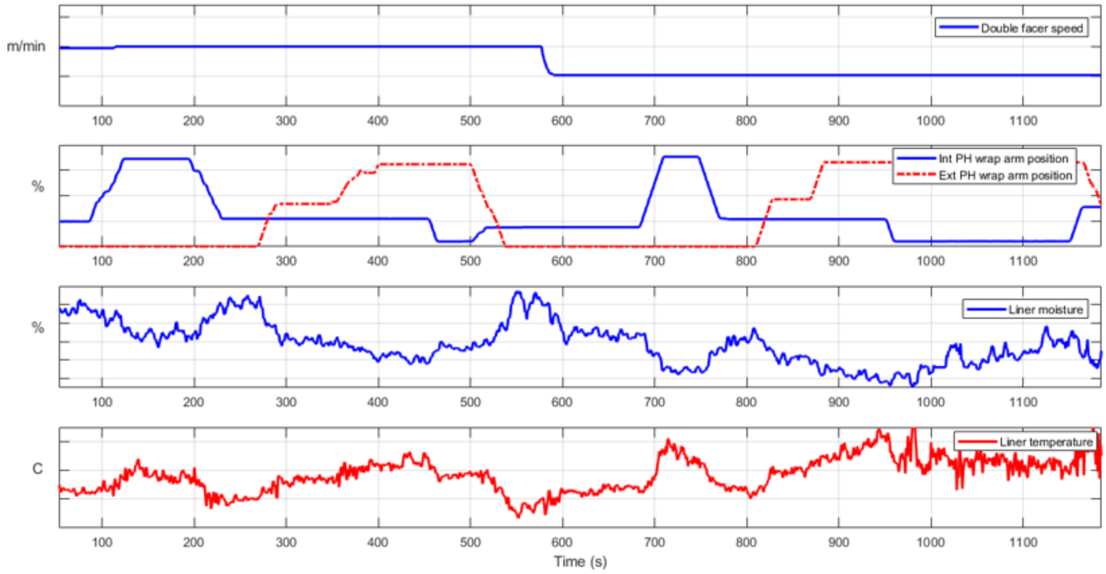

Figure 31. *Trial 4, light-weight recycled liner (SM85).*

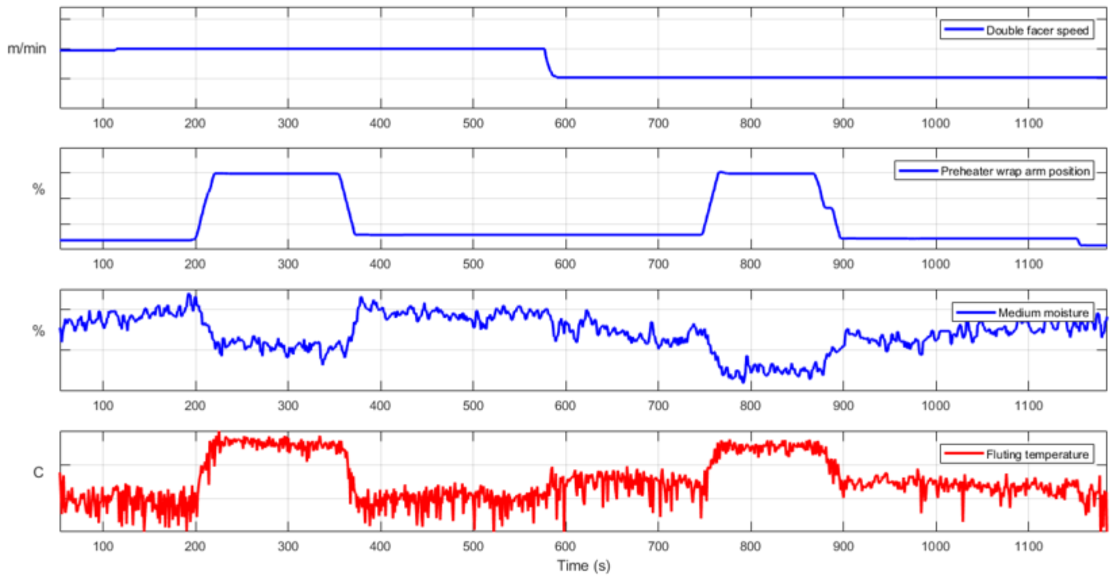

Figure 32. *Trial 4, medium fluting (SM85).*