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Hybrid printing on fibre-based packaging

Performance, Quality and Market

Marcus Rehberger

Doctoral Thesis 2010

Royal Institute of Technology
School of Computer Science and Communication
Department of Media Technology and Graphic Arts
SE-100 44 Stockholm, Sweden

Hybrid printing on fibre-based packaging
Performance, Quality and Market

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Dr. Astrid Odeberg Glasenapp (Innventia AB, Stockholm Sweden)
Opponent: Prof. Gunter Hübner (Hochschule der Medien, Stuttgart, Germany)
Examination Committee: Prof. Ulrike Herzau-Gerhardt (HTWK, Leipzig, Germany)
Prof. Lennart Stolpe (Säffle, Sweden)
Docent Magnus Lestelius (Karlstads University, Karlstad, Sweden)

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To family and friends –
font of my life

Achim Hasenacker
✝ June 13, 2009

Abstract

Variable data will play a decisive role in the future of packaging and product promotion. Variable data printing (VDP) is a technique whereby certain information can be altered in an otherwise static layout with the help of a digital printing system, and in the packaging industry a wide range of applications is possible. Inkjet printing, due to its non-impact printing (NIP) principle, is the most suitable technology to use when applying variable data on packaging and to offer customized and even personalized prints for the industry and the end-consumer (van Daele, 2005).

The aim of the work described in this thesis was to evaluate the practicability of attaining high quality variable data print (VDP) at high speed. The thesis is divided into three major parts. Part one focussed on the surface topography of corrugated board and applicable analytical methods to describe the printability of the substrate. In the second part the performance of inkjet on corrugated board liners printed at high speed was investigated and how to achieve maximum printing resolution. The final part of the thesis is devoted to a market survey of variable data printing on the North American and European markets.

Part 1 concentrated on corrugated board as substrate and its pre-conditions regarding surface topography before the printing operation. Most critical for the quality are print defects such as mottling, gloss and stripiness, all of which occur in the printing of corrugated board. Stripiness is especially critical because it is one of the most disturbing print defects on corrugated board since it is periodical and more easily perceived than random print defects (Netz, 1996). Part 1 revealed that there is a difference in surface micro-roughness between the regions on the peak line of the fluting and the regions in the valley between two peaks of the corrugation which leads to glossy lines on the peak areas.

The aim of the second part was to assess the practicability of attaining high quality VDP at high speed on a variety of liners for corrugated board production. The trial was conducted on a Kodak Versamark DP5240 press in Örnsköldsvik, Sweden, in cooperation with the Mid-Sweden University - Digital Printing Centre (DPC). Nine different substrates were printed at speeds between 0.5 and 5 m/s. The results revealed that the paper type rather than the printing speed has the greatest influence on the print quality. Speed, however, is the most important technical factor for inline implementation of inkjet.

To obtain a picture of the industries' view of variable data print on fibre-based packaging, a market survey was initiated and was addressed to people in the development, marketing and decision-making sectors of the packaging and printing industry, including manufacturers of machinery, producers of packaging and prints, and print buyers. The goal was to draw an overview map covering the people's view of their market, trends in their fields and how they envision the future of VDP on fibre-based packaging. The conclusion was that inkjet technology has to prove itself first and to increase its technical capability, and the printing industry will then start investing more in this technology and in applications such as VDP.

Keywords: packaging, corrugated board, surface topography, print quality, variable data printing, hybrid printing, flexography, inkjet, print quality, market survey

Preface

'J'imagine' – As a little boy, I possessed a book about the Apollo missions and it was filled with photos from spaceflights to the moon. But one picture always captured my attention – the one with the moon's silhouette and the mighty earth in the background. This photo made me feel very small but it also showed me what mankind can achieve. 'Der Wille versetzt Berge' means that we can achieve everything by having a strong will, even though many times in my life I have had moments where I have questioned myself, but I never gave up. Defending my work and receiving the title of 'Doctor of Technology' is one of those moments I could not imagine achieving, but when I leave the room I shall look up to the sky and realize that I am one step closer, and one day I will be there and see it with my own eyes.

Three great influencers and supervisors of my thesis are Dr. Astrid Odeberg Glasenapp (Innventia[1]), Prof. Nils Enlund (KTH[2]) and Dr. Per-Åke Johansson (Innventia[1]). Astrid did a fantastic job to keep me coming back to Stockholm, and I enjoyed every single day working with her. The one who kept me moving and supported me as soon as I needed him was Nils. Thank you for taking me as a doktorand. The last supervisor I want to thank is PÅJ – my mentor, because he always took his time to answer even my dumbest questions.

I also want to express my great gratitude to Innventia AB[1] (formerly STFI-Packforsk) which accepted me as a PhD student, and all its employees with whom I enjoyed working so much and with whom I shared so many exciting experiences. Moreover I want to thank my bosses at Innventia, Bo Lindskog and Kennert Johansson, as well as Torben Jacobsson, for being so supportive.

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Last but not least, I have to thank all my new colleagues in the Printing and Pre-Press group at Tetra Pak[5] in Lund and especially my new bosses Robert Jeppsson and Sverker Olsson as well as Anders Stokholm, for giving me the time and freedom to properly finish my thesis.

---

[1] Innventia AB, Stockholm, Sweden
[2] KTH Royal Institute of Technology, Stockholm
[3] QIGC –The Québec Institute of Graphic Communications, Montréal, Canada
[4] Mid Sweden University, Örnsköldsvik, Sweden
[5] Tetra Pak Packaging Solutions AB, Lund, Sweden

In the end, there are also my friends, my precious font, who were always here when I needed them, such as having a coffee break with me, discussing stuff about my hobbies or just going for a beer sometimes. But there is also one person carrying the greatest burden from all of them, the woman who let me go to Canada, surviving endless hours of me being unresponsive and being in bad 'thesis writing' moods. Thank you, Barbara, for bearing and supporting me.

Aber auch meinen Eltern, Regina und Toni, und meiner Schwester, Stephanie alias deGloa, möchte ich Danken, Ihr habt mich geprägt und nur durch eure Unterstützung konnte ich soweit kommen.

Malmö, Sweden, October 2010

Rehberger

Marcus Rehberger

List of papers

Paper I

Rehberger, M., Odeberg Glasenapp, A., Johansson, P.-Å. and Gällstedt, M. (2006) *Topographical micro changes of corrugated board liners induced by heat treatment and their effect on flexographic print quality.* In Advances in Printing and Media Technology: Proceedings of the 33rd International Research Conference of Iarigai, Leipzig, Germany.

Paper II

Rehberger, M., Odeberg Glasenapp, A. and Johansson, P.-Å. (2007) *Topographical micro-changes on corrugated board liners - A comparison between laboratory and full-scale effects*. In 59th Annual Technical Conference of TAGA, Pittsburgh, Pennsylvania, USA.

Paper III

Rehberger, M., Odeberg Glasenapp, A. and Johansson, P.-Å. (2007) *Corrugated board production and its micro-scale impacts on the liner's topography*. In VIIIth Seminar in Graphic Arts, Pardubice, Czech Republic.

Paper IV

Rehberger, M., Odeberg Glasenapp, A. and Örtegren, J. (2010) *VDP on packaging – elementary velocity study on inkjet-printed papers for corrugated board production*. In 62nd Annual Technical Conference of TAGA, San Diego, California, USA.

Paper V

Rehberger, M., Odeberg Glasenapp, A., Xiaofan, Z. (2010) *VDP Quality aspects on fibre based packaging – an elementary print quality study on corrugated board.* Submitted to Journal of Print and Media Technology Research

Paper VI

Rehberger, M., Vigne, V. (2010) *A market survey about Variable Data Print (VDP) on fibre-based packaging in North America and Europe.* In Advances in Printing and Media Technology: Proceedings of the 37th International Research Conference of Iarigai, Montréal, Canada.

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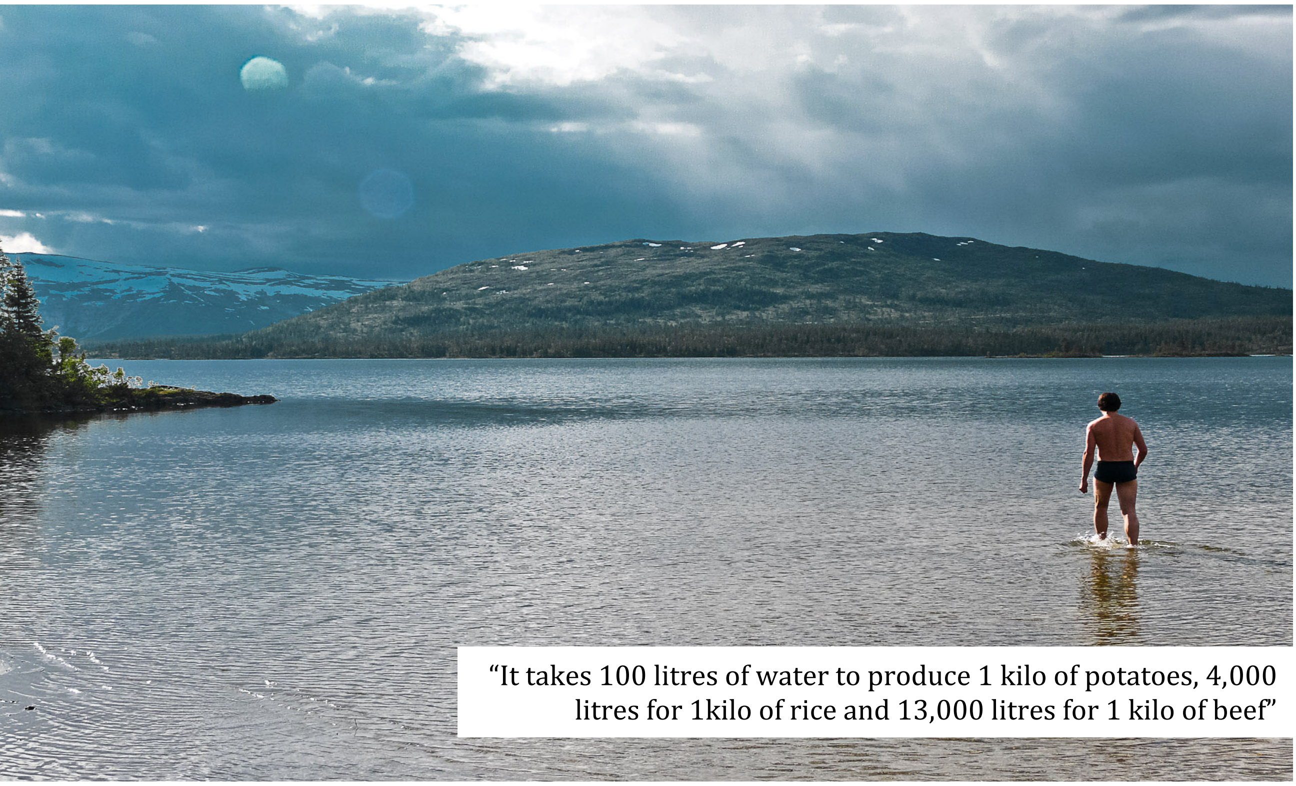
1

INTRODUCTION



“It takes 100 litres of water to produce 1 kilo of potatoes, 4,000 litres for 1kilo of rice and 13,000 litres for 1 kilo of beef”

1.1. Background

The packaging industry is one of the largest industries world-wide. Its turnover in 2008 with packaging container sales was US$ 500 billion with an estimated packaging machinery sales of US$ 25 billion (Anon, 2008b). Fibre-based packaging materials, such as carton and corrugated board, have a very diverse and continuously growing range of applications, e.g. wine packed in carton boxes. These have great advantages compared to other packaging materials, because its level of environmental sustainability is very high, it has a rather low packaging to product weight ratio, and it still offers great protection against external impacts (Anon, 1996; Hobbs, 2005).

Fibre-based packaging is not only a protective layer against impacts from the environment but also a medium for the exchange of information between product and consumer (Gordon, 2010b; Netz, 1996). The supreme goal of package printing is to catch the attention of the customer until she decides to buy the product (Calver, 2004; Meyers et al., 1998; Paine, 1992). Some rules need to be fulfilled to achieve these tasks: the package needs to be informative but easily structured addressing the buyer directly. Meyers and Lubliner (1998) state in their book "The marketers guide to successful package design" that for the consumer "the package is the product", but now - more than 10 years later - more products are on the market and the competition between the products has become more decisive (Gordon, 2010a). It is therefore becoming more difficult to catch the attention of the end-consumer. Despite the great effort made by the sales companies to advertise their products through several media channels, e.g. television and placards, the majority of all purchases are the result of in-store decisions (Ambrose et al., 2003; Calver, 2004; Meyers et al., 1998; Paine, 1992; Shimp, 2008). Abmad (1982) suggested that the role of packaging providing point-of-sale (POS) advertisement makes the packaging design very important. The industry has a continuous demand for new features to advertise their products and to make them an eye-catcher in contrast to their competing products. New printing techniques and technologies may therefore offer great new features to make the product outstanding.

In package printing, the flexographic technique has developed as the most applicable method because of its soft printing form which adapts to the substrate surface and is thus capable of printing uneven and rough surfaces such as corrugated board and cardboard. It has developed into a very sophisticated printing process and is very well capable of meeting today's offset print-quality demand, and thin-plate technology, kiss-impression and computer-to-plate (CtP) are important inventions (Bodwell, 2006; Hallberg Hofstrand, 2006; Jansen, 1999; Neumann, 1998; Taylor, 1992; Zeinert, 2010).

Flexography, despite its very high class print, is a technique to print only static information. In contrast, high quality digital printing is the new emerging printing technology entering the package printing industry which offers variable data print (VDP) and can thus alter the printed information for each individual copy. Using this technology, the industry would be able to print variable information with a regional or seasonal content, local languages, bar codes or anything else that could be customized on a package. This technique would enhance direct marketing with packaging because it would become more advanced and better available, especially for small or medium-sized businesses.

The next step in the use of VDP would be to print personalized data to address each customer directly in order to approach her personal interests. Personalized print is, however, less applicable at the POS, because information about the buying customer is not usually available. Companies such as Amazon.com possess the required data about their customers and can thus advertise products of interest to the customer. In addition personalized vouchers could be added to attract greater attention and to increase the chance of a second purchase.

The goal of digital printing in package printing should not, however, be to substitute the conventional printing but rather to complement it and to increase the value of the package and hence the product. Both printing methods can be used at the same time. The conventional printing will print the major part with the static image/ information at a low price level, and the digital printing will add the variable image/ information. The costs for the VDP, such as inkjet, will also be low, because only a small part will be printed with it. This idea, to combine two different printing techniques, is called 'hybrid printing', and the elements involved combine to offer completely new possibilities (Viström et al., 2006). To use hybrid printing in existing package converting lines puts further demands on the technology, such as speed, reliability and rigidness.

1.2. Research Objective

The objective of the work described in this dissertation is to investigate the printing performance of two combined printing methods, flexography and inkjet. Hybrid printing demands that both printing methods are capable of printing with similar quality on the same substrate at high speed. The aim was to detect problems in the printing material and/or printing method which might influence the print quality. The study was extended with a survey of the North American and European markets to obtain views of the printing and packaging industries regarding variable data printing and hybrid printing.

1.3. Thesis Structure

The dissertation is divided into three major parts, where the first part focuses on the surface topography of corrugated board and applicable analytical methods to describe the printability of the substrate. Possible impacts of the production process on the surface topography are also taken into consideration. Printing tests were performed with flexography and inkjet to detect major factors influencing the print quality (Papers I-III). The acquired data were a prerequisite for continuing to study the hybrid implementation of inkjet printing into the printing and converting of fibre-based packaging.

In the second part of the dissertation the performance of inkjet on corrugated board liners at high speed and the maximum printing resolution were investigated (Papers IV-V). The data were summarized separately and divided into a speed (Paper IV) and a substrate comparison (Paper V).

The final part of the thesis is devoted to a survey regarding variable data printing on the North American and European markets (Paper VI).

The three parts are presented and discussed separately and the following structure is maintained in the various chapters:

- Part one – Surface topography and printing pre-tests (Papers I-III)
- Part two – Inkjet high-speed test (Papers IV-V)
- Part three – Market survey of VDP (Paper VI)

2

THEORETICAL FOUNDATION

“Over 50% of grain traded around the world is used for animal feed or biofuels”

2.1. The packaging material

The history of fibre-based packaging started in 1817 when the first paperboard was produced in England, and the first folding box was shipped in the 1860's. Corrugated board was invented later. Corrugated paper was first developed in 1871 by Albert L. Jones, when Henry Jones acquired his patents to use it for the protection of glass bottles. In 1874, Oliver Long modified it to produce a single faced corrugated material (one liner, one fluting), and in 1895 the first continuous corrugator was developed. During the first part of the 20th century until the late 1950's, the corrugated board industry was struggling but then the breakthrough began, and the prestige of corrugated board has increased ever since (Laakso et al., 2003).

Today, fibre-based packaging is a premier packaging material. Not only has the usage and acceptance of corrugated board increased in the packaging industry, but also the awareness of its ecological and economic advantages (Laakso et al., 2003). Fibre-based packaging is used as a packaging material in almost all branches. Its suitability as a packaging material is due to the typical corrugated board properties such as a high bending stiffness combined with a relatively high compression strength and low specific weight (Meyer, 1999).

2.1.1. Corrugated board

Standard corrugated board consists of three layers, an inner liner, a fluting layer and an outer liner. These layers are linked by glue bonding at each tip of the fluting medium. Numerous combinations of liners and fluting medium are conceivable (Table 1). For higher resistance and strength, several liners and fluting layers are glued together to create a multilayer corrugated board in which a combination of different flute-geometries is often used (Table 2). In general, corrugated board is divided into different classes according to its geometry / wavelength and height of the fluting (Laakso et al., 2003; Meyer, 1999).

Table 1 Overview of the different types of corrugated boards.

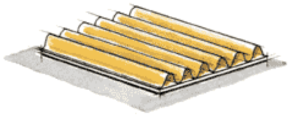
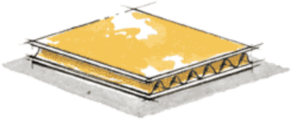
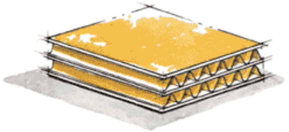
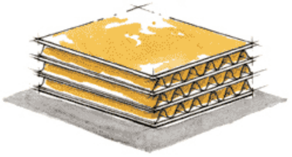
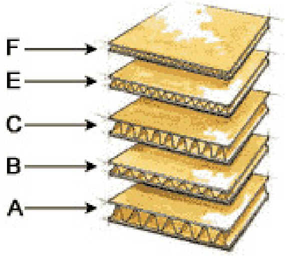
Single-faced corrugated board consists of two layers: A liner facing and fluting medium, glued together at the flute tips.	
Single-wall (double-faced) corrugated board consists of three layers: two liners (outer and inner liner) and an intermediate fluting medium. The liners are glued onto the corrugated medium at the flute tips.	
Double-wall corrugated board consists of five layers, three liners, outer liner (print), centre and inner liner, and two fluting media.	
Triple-wall corrugated board (triplex) consists altogether of seven layers, two liners outside, three fluting media and two liners in between.	

Table 2 Overview of the different flute types

Flute	Pitch	Height
F	2,4mm	0,75mm
E	3,2mm	1,22mm
C	7,95mm	3,5mm
B	6,5mm	2,5mm
A	8,9mm	4,6mm



In corrugated board production, Kraftliner (consisting mainly of sulphate cellulose) or Testliner (including waste paper and having lower strength properties) is used. Kraftliner can be manufactured according to the demands for visual appearance, and can be made of natural brown or bleached pulp (Bradatsch et al., 2002; Laakso et al., 2003). In order to give better print quality, corrugated board liners sometimes are coated to give higher whiteness, smoothness and gloss, and one or more layers of coating are usually applied. The coating consists of mineral pigments, e.g. china clay, calcium carbonate or titanium dioxide, giving the coating its white colour. A latex binder (styrene-butadiene emulsion) and a co-binder (starch or carboxymethyl cellulose, CMC) are added to give the coating the required mechanical strength. Additional components can be added such as optical brightening agents, preservatives and lubricant agents (Endres, 2006; Kirwan, 2005).

2.1.2. Paper-to-metal friction

Many variables drive the corrugator and create many different problems, e.g. warping, washboarding and poor bonding. A further factor can be friction which influences the paper topography and in consequence the print quality. Since this affects the outer liner, the printing side, the problem cannot arise before the outer liner enters the production process, i.e. behind the reel stand and just before the pre-heater and the double-backer. The conditions which occur in the double-backer are far from optimal for papers or paper coatings. Hot plates with temperatures up to 200 °C combined with a pressure load from the top are needed to cure the glue and to ensure proper bonding (Mensing, 2006; Pinnington, 2003). In addition, paper-metal friction occurs, because the board is pulled over heated steel plates. The double-backer section may have the strongest impact on the paper surface (cf. Odeberg Glasenapp, 2004c).

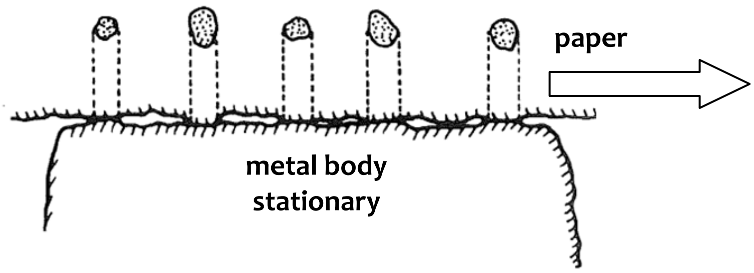


Figure 1 Schematic illustration of paper-metal contact, showing a large apparent area and smaller real areas of contact (schematics: Persson, 2000)

Friction is basically independent of surface roughness and surface contact area. However, in the case of paper-to-metal friction, the friction increases with increasing metal surface roughness (Back, 1991). The harder rough particles of metal are grinding or even ploughing into the softer paper material.

Figure 1 illustrates the contact between a paper and a metal plate. The small circles above the paper show the real contact area in contrast to the 'apparent' contact area, which is defined by the dimensions of the objects. The friction coefficient is thus very dependent on the difference in hardness between the two gliding objects and not only the roughness or smoothness of the surfaces (Persson, 2000). Paper-to-metal friction is a factor in corrugated board production which influences the paper surface topography and thus the print quality.

2.1.3. Surface topography

Thompson (2004) states that "one of the most important factors affecting print quality is the surface structure of the paper, generally referred to as surface smoothness or roughness". The surface roughness / smoothness depends on the formation of the paper and the paper structure is very dependent on the fibre morphology and treatment during stock preparation, as well as on the forming characteristics of the paper machine.

Several technologies are available to measure, characterize and show a paper surface structure. Surface topography is usually characterized by its roughness / smoothness value, and the air-leak methods are currently the most frequently used techniques (Barros, 2006). The Bendtsen and Print-Surf (PPS) methods are commonly used in the pulp and paper industry, but Kuparinen (2005) says that the Bendtsen method performs better on rough papers, whereas PPS is better suited to smooth papers. Papers I – IV include both sorts of papers and different techniques were therefore necessary to characterize the surface topography of the paper samples.

Test methods such as Atomic Force Microscopy (AFM) and Confocal Laser Scanning Microscopy (CLSM) scan the surface on an atomic- and nano-scale and they are described in detail by Barros (2006). In Papers I – III both methods were used.

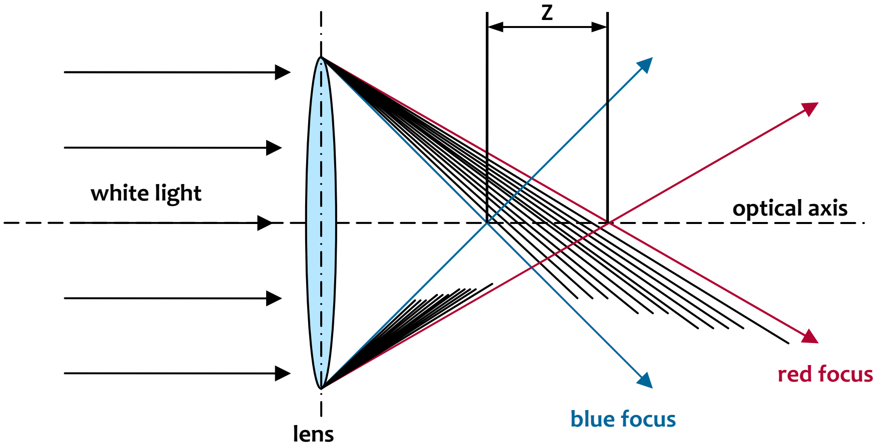


Figure 2 The principle of the FRT topography meter MicroProf (Source: © FRT GmbH)

The FRT MicroProf$^{©}$ is a non-contact method giving surface height profiles indicating roughness and waviness on a macro- and micro-scale. Its principle is based on chromatic aberration when white light is split into different colours focused on different heights. The light reflected by the surface is analyzed and the data are computed into a topographical image. Roughness and contour measurements can be made in x- and y-directions and the data can be shown in 2D and 3D images. The topography sensor works with a very high Z resolution (3 nm) and a working range of ±150 µm. The X-Y resolution is 2 µm, limited by the lateral resolution of the sensor. The affiliated software delivers 2D and 3D evaluated data, complying with the DIN and ISO standards for the evaluation of lines and roughness.

2.1.4. Surface reflection

Reflection is the change in direction of a ray of light when it strikes a mirroring surface (Figure 3). The incident light beam I_I and the specularly reflected light beam I_R lie in the same plane. Refraction of the light beam I_T occurs in the same plane, but the refraction angle θ_t is dependent on the difference in refraction indices of the medium (n_2) and the air (n_1) (Snell's law):

$$\frac{sin\theta_i}{sin\theta_t} = \frac{n_2}{n_1} \qquad (1)$$

where θ_i = incident angle of the light beam
θ_t = refraction angle of the light beam
n_x = refractive index of both media (unitless).

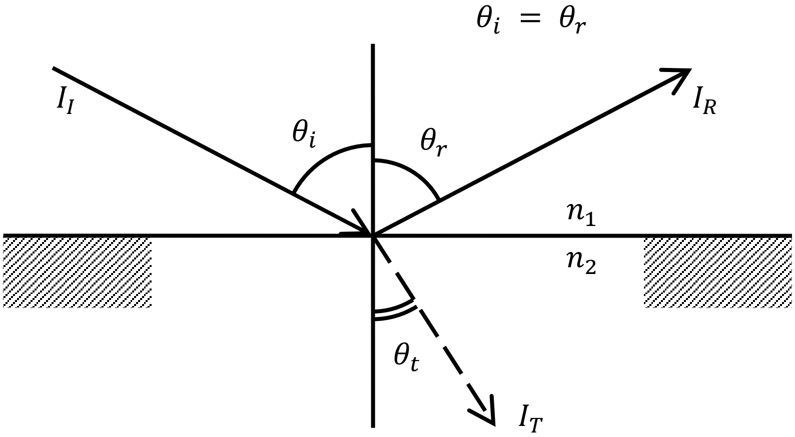


Figure 3 *A ray striking the interface between two media is split into a reflected part and a refracted part (Louman, 1983) the reflection angle θ_r is equal to the incident angle θ_i; the refraction angle θ_t is calculated with the formula above.*

The reflection is described by the Fresnel equations in conjunction with light reflexion on non-metallic surfaces:

$$R_0 = \frac{I_I}{I_R} = \frac{\rho_s + \rho_p}{2} \qquad (2)$$

where R_0 = reflectance
I_I = incident ray

I_R = reflected ray
ρ_s = $\left[\frac{sin(\theta_i-\theta_t)}{sin(\theta_i+\theta_t)}\right]^2$ polarised perpendicular to the plane
ρ_p = $\left[\frac{tan(\theta_i-\theta_t)}{tan(\theta_i+\theta_t)}\right]^2$ polarised parallel to the plane.

As Louman (1983) indicates, these equations are valid only for perfectly plane and closed surfaces. Paper surfaces are never perfectly plane. Furthermore, as Bennett (1999) states, the surface is assumed to be opaque. Effects such as light transmission into the material, scattering by material defects, or reflection from the back surface, are neglected. In addition it is assumed that the reflection angle is exactly equal to the incidence angle. The following equation is adapted for rough surfaces and inclined incidence of light (Bennett et al., 1999; P.-Å. Johansson, 1999; Louman, 1983).

$$\frac{R_S}{R_0} = \left[-\left(\frac{4\pi\sigma cos\theta_i}{\lambda}\right)^2\right] \tag{3}$$

where R_S = specular reflectance of a rough sample
R_0 = specular reflectance of a perfectly plane surface
σ = rms surface roughness (R_q)
θ_i = angle of incidence
λ = incident wavelength.

With this reflectance formula, the way in which the reflection is dependent on the incident angle and on the roughness can be calculated. In the case of corrugated board, the following equation can be used to derive the contrast k between the gloss from the peak and valley of the liner surface.

$$k = \left[\frac{[R_S/R_0]_{peak}}{[R_S/R_0]_{valley}}\right] \tag{4}$$

where k = contrast in reflectivity between peak and valley.

Gloss is a perceived phenomenon related to the specular reflectivity of a surface. In terms of print quality, this is a major factor affecting human perception (Béland et al., 2000; Lindberg, 2004; Lindstrand, 2002). The contrast value k is a measure of the difference between two different surface regions. The higher the value of k the higher is the gloss contrast and thus the visual disturbance.

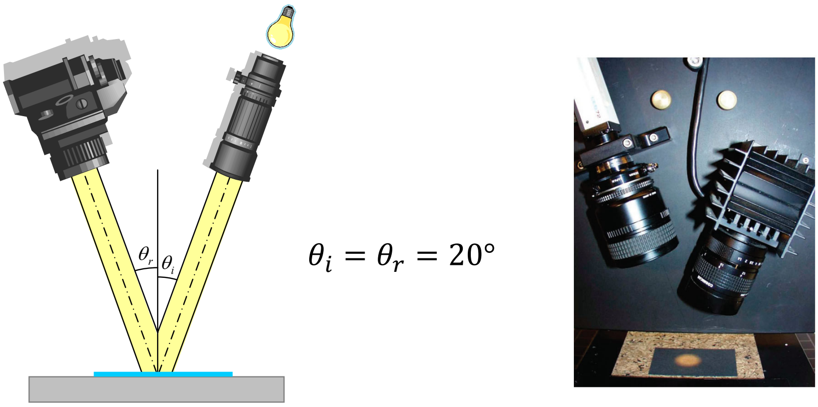


Figure 4 Construction of STFI-MicroGloss meter *(P.-Å. Johansson et al., 2004).*

The effect of gloss on unprinted or printed surfaces can be measured with the STFI-MicroGloss meter (P.-Å. Johansson et al., 2004), which captures images from the sample using illumination and camera angles of 20°/20° (Figure 4). The programme is able to make single images or a matrix of images. A single image has a size of 13x13 mm and the stitching process is performed with Adobe® Photoshop®.

2.1.5. Water absorbency

A paper is built-up as a network of fibres creating voids, formed as a multitude of small channels and pores into which liquids may be drawn by capillary forces. The rate at which the liquid is drawn into a paper is dependent on the bulk of the paper, the relationship between the surface energy of the material and the surface tension, and the viscosity of the liquid. The absorption behaviour of a paper can be defined by the number and size of the pores. A bulky paper usually tends to be open, with large pores, and absorbs the pigment of an ink along with its carrier, especially if the ink has a very low viscosity (flexography). A calendered paper having very fine pores, on the other hand, usually absorbs only the ink carrier. As Thompson (2004) describes: "the degree of absorption of an ink into its substrate is of utmost importance in printing since it is the contrast created between the ink and the paper that conveys the message, be it simple text or multicolour images". This means that the more absorptive the paper is, the less is the amount of ink left on the surface to absorb light and consequently more information is lost.

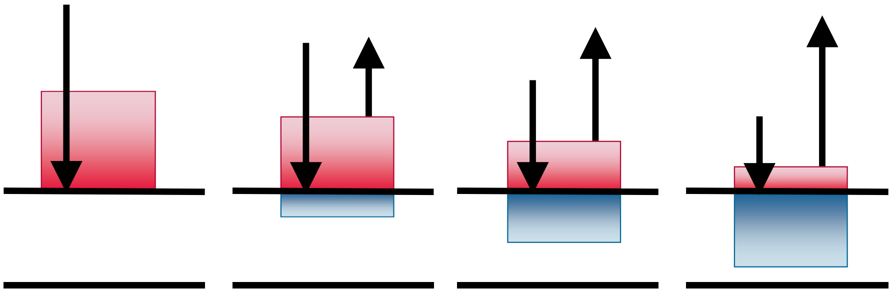


Figure 5 The loss of print quality due to ink absorption; decreasing optical density with increasing absorbency of paper (left to right) (B. Thompson, 2004).

For example, a printed black dot on a white paper (Figure 5) is perceived to be black when the paper is less absorptive and the drop stays on top of the surface (left dot). As the paper becomes more absorptive, the printed dot will become more grey and lose its brightness (right dot), because only a small proportion of white light is then absorbed, the rest being reflected back into the eye. Coloured ink printed on papers with similar whiteness values but different absorbencies may even be perceived as being different in colour. A disadvantage of low absorptivity can be that the ink spreads on top of the surface and this has a profound effect on dot gain. Nevertheless coated paper usually produces a better print quality, because uncoated papers always give a lower print density due to their greater ink absorption, with a resulting loss of gloss, saturation and brightness (B. Thompson, 2004).

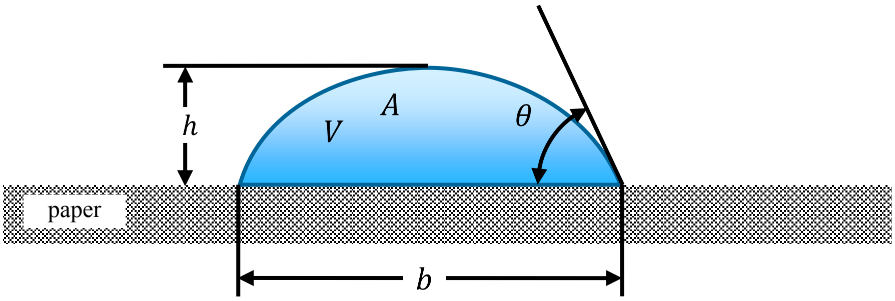


Figure 6 *Diagram of the drop on the paper surface during the wetting process; drop base b and drop height h are measured and contact angle θ and drop area A are calculated from these values.*

The DAT-1100 by Fibro System AB, Sweden is a dynamic contact angle tester measuring the wetting behaviour when a de-ionized drop of water with a volume of 4 µl (adjustable) is placed on the sample surface. The apparatus is equipped with a CCD camera to capture images of the drop during the wetting process with a maximum frequency of 1000 Hz. The program measures the drop base b and drop height h and calculates from these two values the contact angle θ, drop volume V and drop area A over the set time range (Figure 6).

2.2. The production of corrugated board

2.2.1. Corrugator

The processes for producing corrugated board are similar for all types, and most corrugators are at least capable of producing double-wall corrugated board. Depending on the type to be produced, steps are included or skipped. As shown in Figure 7, the process starts with the single-facer (a) where the fluting medium (1) is corrugated (2), glue is applied on the flute tips (3) and the fluting is brought into contact with the outer liner (4) by an impression roller. Newer machines are equipped with a pressure belt instead of an impression roller to ensure a more even but lower pressure distribution over a longer period. The single-faced board (6) is then forwarded to the next corrugator unit to complete the corrugated board.

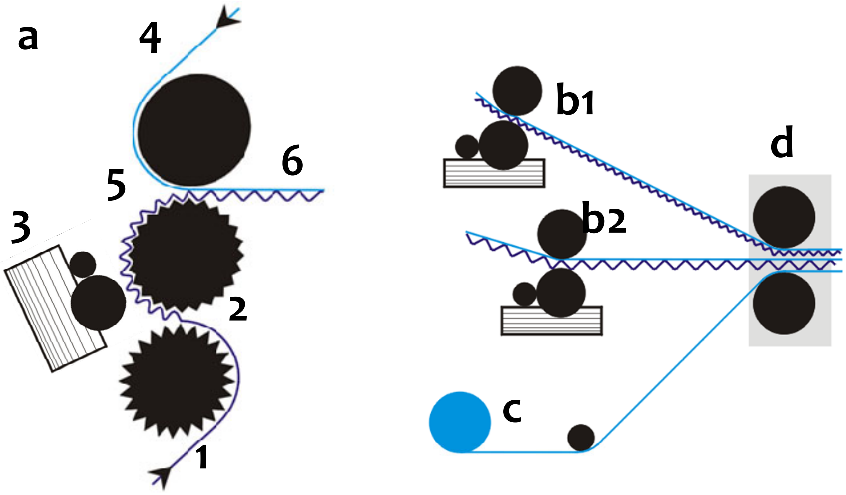


Figure 7 *The principle of corrugated board production (schematics © www.young-package.com)*

Two single-faced boards are shown on the right side of Figure 7 and two single-facers (a) are necessary to achieve this. To produce a triplex corrugated board three single-facers are required. Before combining the single-faced boards with the pre-heated outer liner (c) in the double backer (d), glue needs to be applied on the fluting tips (b1 and b2). In the double-backer, all the layers are pulled through by a conveyor belt, and the board is at the same time subjected to pressure and heat to cure the glue (Figure 8 bottom). Polster (2006) describes the double-backer as the Achilles heel of the corrugator when pushing for good bonding at high speed. After the double-backer, the board is shear-cut, slit, scored and cross-cut. At the end of the corrugator, the boards are stacked before being sent to the converting line.

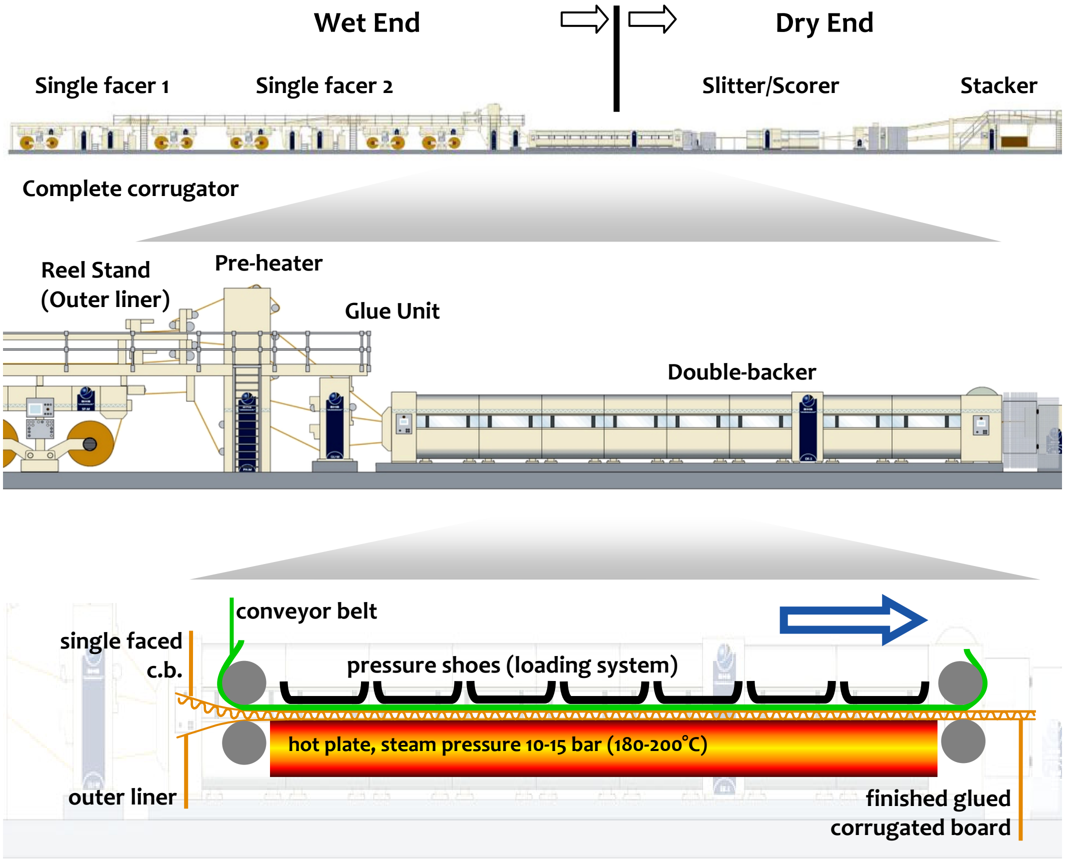

Wet End
Dry End
Single facer 1
Single facer 2
Slitter/Scorer
Stacker
Complete corrugator
Reel Stand (Outer liner)
Pre-heater
Glue Unit
Double-backer
conveyor belt
single faced c.b.
pressure shoes (loading system)
hot plate, steam pressure 10-15 bar (180-200°C)
outer liner
finished glued corrugated board

Figure 8 *Overview of the corrugator; top: complete corrugator; middle: from reel stand outer liner till end of double-backer; bottom: double-backer (schematics: © BHS-Corrugated)*

Figure 8 shows at the bottom a schematic view of the double backer to demonstrate the extreme conditions for the paper, hot plates with a temperature up to 200 °C and pressure. A more detailed explanation of why this matter is important in a printability context is provided in chapter '2.1.3 Surface topography'.

2.2.2. Converting

The converting line of a corrugated board production line combines several production steps until the final packaging product is finished. The customer decides how the final product is converted. The choices range from a simple plain sheet to a printed, die-cut and folded-glued ready packaging. Figure 9 shows that the printing machine is the first process unit in the line. In the packaging industry and especially in corrugated board post-printing, flexography is the only feasible printing method, because the flexible printing forme can adapt to the uneven surface of the corrugated board.

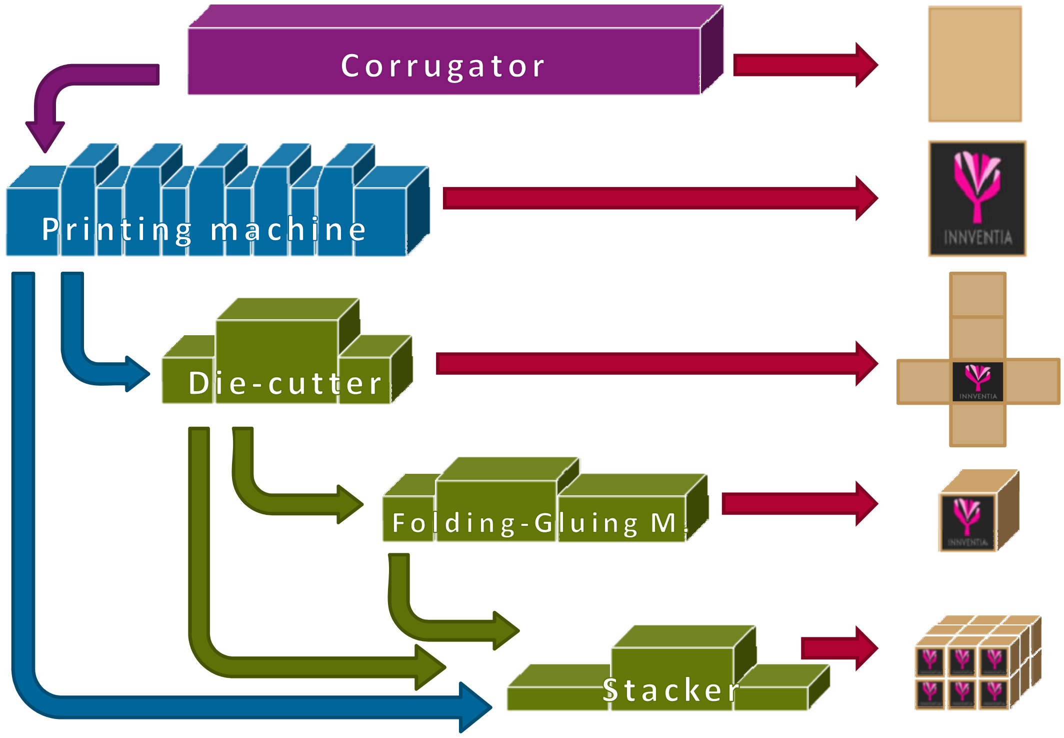

Corrugator
Printing machine
Die-cutter
Folding-Gluing M.
Stacker
INNVENTIA

Figure 9 *The converting line of a corrugated board production facility; the blue and green arrows indicate the different choices of the final product*

Die-cutting (Figure 10) is the process which determines the shape of the board before folding and gluing. It developed from die-cutting leather in the early 20th century and is nowadays available in two designs, flatbed and rotary presses. The rotary press can be located in-line, which in corrugated board converting means that is connected to the printing machine.

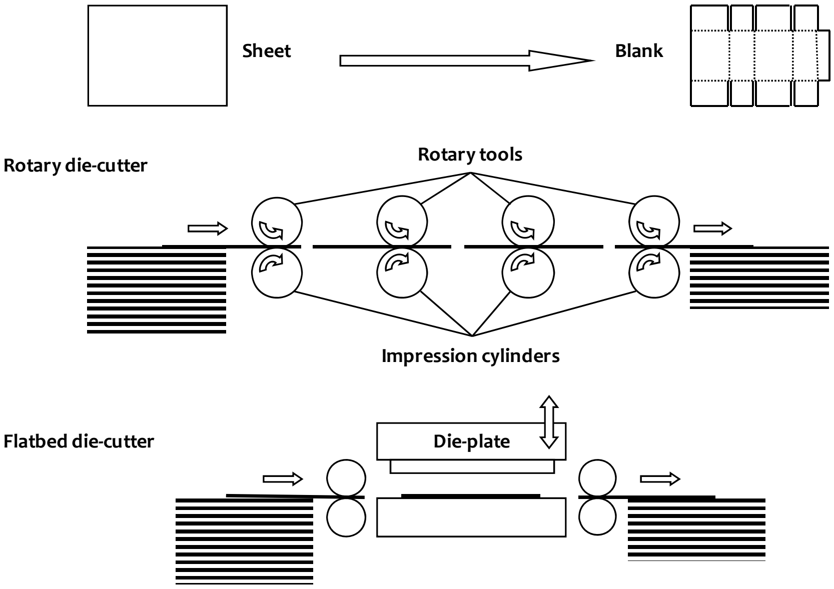

Sheet
Blank
Rotary die-cutter
Rotary tools
Impression cylinders
Flatbed die-cutter
Die-plate

Figure 10 *Schematics of a rotary die-cutter (top) and flatbed die-cutter (bottom)*

The principle of the rotary die-cutter is similar to that of a printing machine, because it has several rotary cutting and scoring cylinders (Figure 10). The flatbed die-cutter is equipped only with one cutting / scoring tool which makes it cheaper to run with regard to tool-preparation and changeover time. This version is however slower since only one sheet at a time can be fed into the machine.

The folder-gluer, as the name implies, applies glue to the board and folds the carton together. This machine needs to be versatile, because it has to handle a large number of packaging shapes, and this also affects the speed of the machine. The stacker, in combination with a feeder, is a unit which is a part of every converting machine. Before the packages leave the site they need to be stacked and palletized. The complete converting line can contain additional machines and some of these units can be combined into a single machine. The structure of the converting line is therefore very dependent on the product which the packaging producer is producing.

2.2.3. Flexographic printing

All conventional printing methods have nowadays been developed into very sophisticated printing machines. Flexographic printing is the predominant printing method in the packaging industry and especially on corrugated board due to the printing plate's ability to print on uneven surfaces. Historically, flexography can be traced back to letterpress which was the prime printing method for printing books. Both have the same principle of raised elements onto which the ink is applied and from which the ink is transferred to the substrate, but flexography uses low viscosity inks, flexible printing forms and a lower pressure. At the beginning of the 1990's, many boxes were still unprinted and more than two-thirds of the printing was single colour printing. The development continued and in recent years it has become one of the most important printing techniques beside offset and gravure printing (Casatelli et al., 1996; Kipphan, 2001; Meyer, 1999).

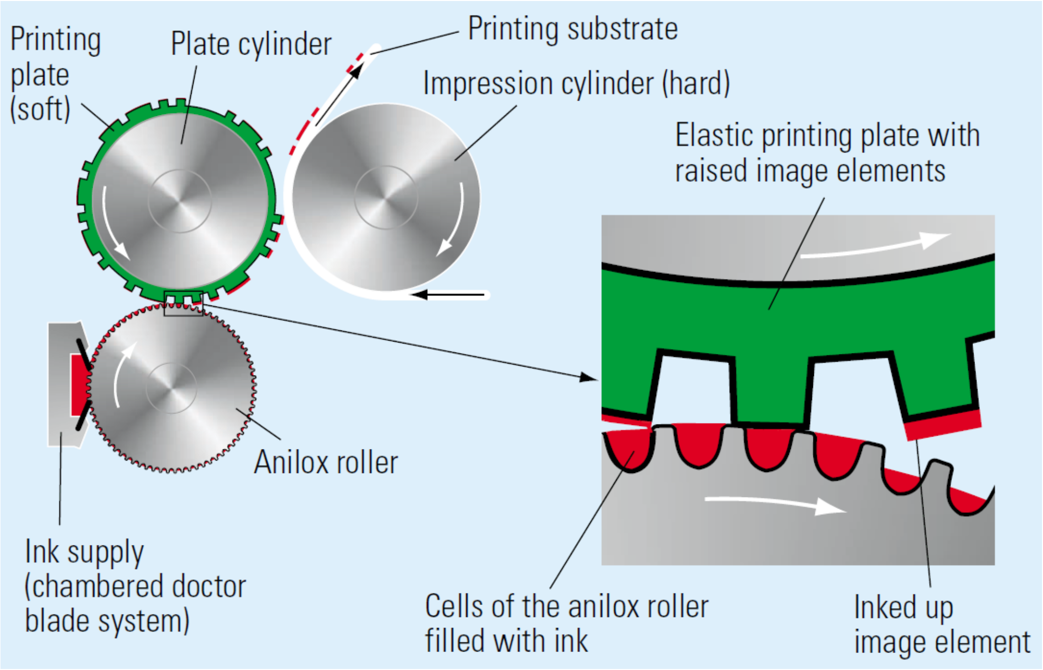

Printing plate (soft)
Plate cylinder
Printing substrate
Impression cylinder (hard)
Elastic printing plate with raised image elements
Anilox roller
Ink supply (chambered doctor blade system)
Cells of the anilox roller filled with ink
Inked up image element

Figure 11 *Printing process of a flexographic printing unit (schematics: Kipphan, 2001)*

Flexographic printing units can be built with two different inking versions, either a fountain roller or a doctor blade system. Both inking versions fulfil the same function of supplying the anilox roller with a defined amount of ink, but the fountain roller is an open system whereas the doctor blade is a closed system providing better ink stability. Figure 11 shows an inking unit with doctor blade and it can be seen that the anilox roller has cells carrying the ink from the inking unit to the plate cylinder. In the nip, where the two meet, the ink is transferred from the cells onto the raised image elements of the printing plate. The plate cylinder with the inked image elements meets the printing substrate and transfers the ink and thus the image. Depending on the ink type, different kinds of heaters follow to cure the ink (Kipphan, 2001; Meyer, 1999).

2.3. Hybrid printing

In some industry sectors, it is common to use hybrid systems to enhance the product or production process. In general, a hybrid technique is a combination of two different technologies or processes (Kipphan, 2001; Viström et al., 2006). In hybrid technology, the elements involved combine to offer completely new possibilities. In printing, this leads to the logical conclusion to combine different printing technologies in a single print. This could mean combining a conventional printing system such as flexography with an inkjet system. Personalization and variable data printing are the new marketing tools in medium mass production and niche products (Eccles, 2008; Starck, 2008) and, as mentioned in the introduction, this variable data could consist of regional or seasonal contents, local languages, bar codes or anything else that could be customized on packaging (Haak, 2006).

Lindqvist et al. (2010) describes the idea of using hybrid technology on packaging where the integration of printed and electronic media can require a hybrid print solution. Variable 2D codes printed on packaging could be read with a mobile phone that downloads the requested information from the internet (Heilmann, 2009). A more advanced way to use hybrid print is to apply it on printed displays. The printing of Organic Light Emitting Diodes (OLED), for example, requires three different printing methods and the process is very demanding in terms of technology (Kopola, 2009).

New market trend reports show that an increasing amount of newspaper and magazine printers are using hybrid printing techniques (Anon, 2009; Eccles, 2009; Kearns, 2010). Print runs are becoming shorter, personalisation and print-on-demand have added value, and people's need for instantaneous information is growing. Digital printing, however, is efficient and cost effective only up to a certain point where conventional printing methods become cheaper on a per-sheet basis (Viström et al., 2007). Hybrid printing is therefore seen as the most profitable solution to accomplish efficiency, low cost and personalisation (Kearns, 2010). It is only necessary to show printers how to maximise the potential of digital technology and to ensure that the staff understand the technology and what it can do (Anon, 2009).

Efficiency and cost are the keywords for a printer to be competitive (Anon, 2003a) and hybrid printing has to fulfil the same requirements to be successful. Figure 12 from Viström (2008) shows in a financial context the important driving forces and limiting factors to customise information on a packaging with hybrid printing. For a printer, cost reduction is the essential factor when investing in new techniques and machinery. Hybrid printing, however, will decrease the costs to only a minor part and may even increase them as indicated in Figure 12, but hybrid printing has other advantages. It will increase the revenue by adding precious value to the packaging. A printer is therefore challenged to risk investments and higher operating costs. The expedient utilisation of the hybrid system is a further mandatory factor; otherwise the full profitability of the technique cannot be retrieved. With successful utilisation revenues can be expected from marketing advantages as well as from an enlarged reachable market and better delivery services.

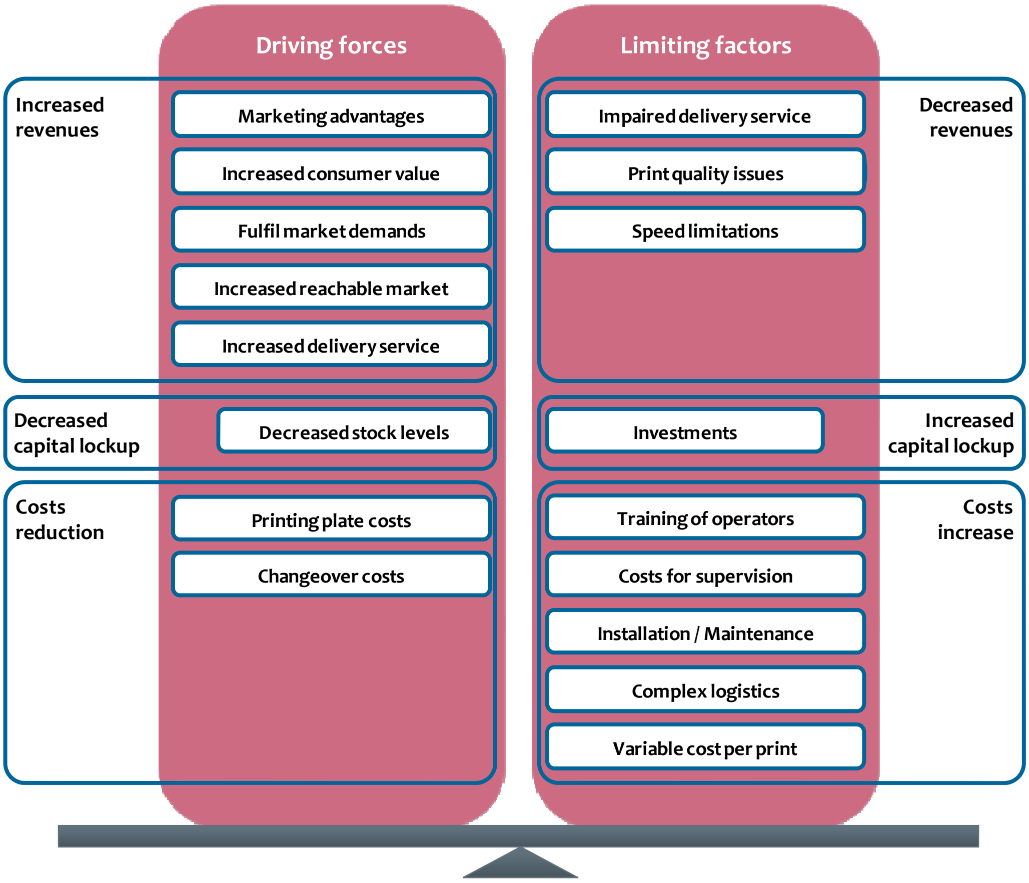

Driving forces
Limiting factors
Increased revenues
Marketing advantages
Increased consumer value
Fulfil market demands
Increased reachable market
Increased delivery service
Impaired delivery service
Print quality issues
Speed limitations
Decreased revenues
Decreased capital lockup
Decreased stock levels
Investments
Increased capital lockup
Costs reduction
Printing plate costs
Changeover costs
Training of operators
Costs for supervision
Installation / Maintenance
Complex logistics
Variable cost per print
Costs increase

Figure 12 *Financial view on potential driving forces and limiting factors in the customisation of information on packaging using a hybrid printing solution (Viström, 2008).*

Technical and structural issues, in addition to the financial aspects, are also of importance. Viström (2004a) presents a list of factors (Table 3) which should be considered in order to achieve high productivity with a high-speed inkjet printing unit incorporated into the converting line. The print speed and print quality factors in the left column are considered in the present thesis, but all the items in both columns are factors need to be considered if a hybrid printing unit is to be run successful. Very important are the reliability, the operator qualifications and the preventive maintenance.

Table 3 List of critical factors to be considered for an in-line implementation of an inkjet unit in the converting line (Viström, 2004a).

Productivity-related factors in high-speed inkjet printing:	**Critical factors in the converting line:**
Print speed	Start-up time
Reliability	Reliability
Print quality demands	Sufficient overcapacity
Operator qualifications	Operator qualifications
Preventive maintenance	System for removal misprints
Correct climate	Number of different substrates
Supervision	

2.3.1. Variable data printing

Variable data printing (VDP) is already in existence in the case of newspaper and magazine delivery, where the main content is printed in offset and the address of each subscriber with inkjet (Dante et al., 2000; Stack, 2003). To achieve VDP, the printer needs a database containing the variable content. Customer relationship management (CRM) systems are today the source of these databases, and they are an important feature of the strategy to manage a company’s interactions with the customer, clients and sales prospects. The databases hold customer demographics, buying patterns, and preferences (Kita, 2003). The overall goals are to find, attract, and win new clients, nurture and retain those the company already has, entice former clients back into the fold, and reduce the costs of marketing and client service (E. Thompson, 2009).

CRM systems basically have three phases to support the relationship between a business and its customers: 1. Customer Acquisition, to attract the customer for the first purchase; 2. Customer Retention, to satisfy and persuade the customer to return and to buy for a second time (2nd purchase); 3. Customer Extension, to guarantee customer loyalty. The 'growth' describes the expansion of first purchase customers from the three contextual factors: marketing orientation, innovative IT and value creation. Marketing orientation means that the organisation focuses on the needs of customers, so that not only the actual, tangible product is supplied to him but also core products and augmented products as well as warranty and customer service. The value creation process aims to enhance customer value and thus shareholder value. An efficient and innovative information technology system focussing on the needs of the customer closes the CRM circle (Figure 13).

CRM software records consumer behaviour and their transactions. Large databases store data on individuals and groups of individuals. In some ways, CRM means that an organisation is dealing with many segments each containing one person, since every consumer displays different purchasing habits and preferences. Organisations then try to market products and services to them based upon similar buyer behaviour seen on other individuals. A well-known example is Amazon.com, which tells customer X about “customers that viewed/bought the same product also bought the following products...” (O'Brien et al., 2009)

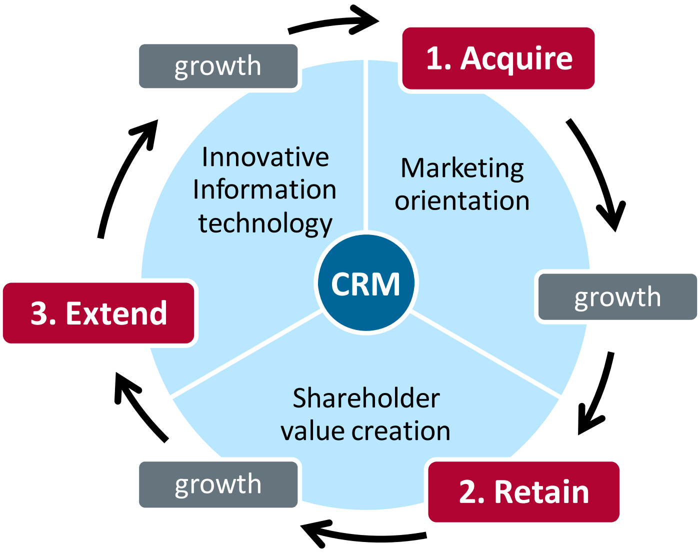

1. Acquire
growth
2. Retain
growth
3. Extend
growth
Marketing orientation
Shareholder value creation
Innovative Information technology
CRM

Figure 13 *Business strategy based on the three-phase CRM model (based on a figure from www.marketingteacher.com)*

Variable data printing is the tool needed to further enhance CRM. Figure 14 shows one way to put printed personalized data on a package in practice. The package could contain customer-related advertising connected with discounts to retain and extend existing customers as well as acquire new customers. The business model in Figure 14 is only one alternative, because products can be received directly from the product owner, via post-order or at the local shop. Sub-contractors, retailers and wholesalers could also benefit from variable data printing.

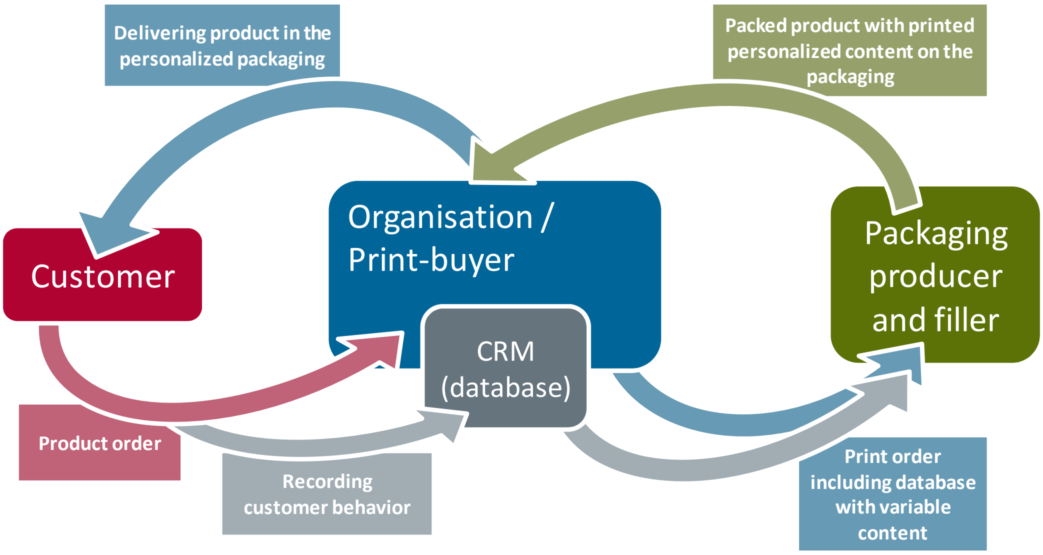

Delivering product in the personalized packaging
Packed product with printed personalized content on the packaging
Customer
Organisation / Print-buyer
Packaging producer and filler
CRM (database)
Product order
Recording customer behavior
Print order including database with variable content

Figure 14 *Product order and delivery with personalized print on the package.*

Today, CRM systems are present everywhere in the market, but the use of variable data printing in the packaging industry is very rare. The complexity of the workflow with customized / personalized print may restrain the industry from investing in VDP. Nevertheless, in contrast to personalized printing customized printing does not require any customer information; a database with random information is sufficient to achieve VDP. Personalized print, however, will be the successor due to its concept of directly addressing the customer. A feasibility study by Agfa shows an example with the name of the customer printed in high quality into the static image (Figure 15). There is no doubt that digital printing is capable of achieving VDP on a packaging and that it will manage to print in high quality, but the question is whether it can achieve this at high speeds implemented in the converting process.

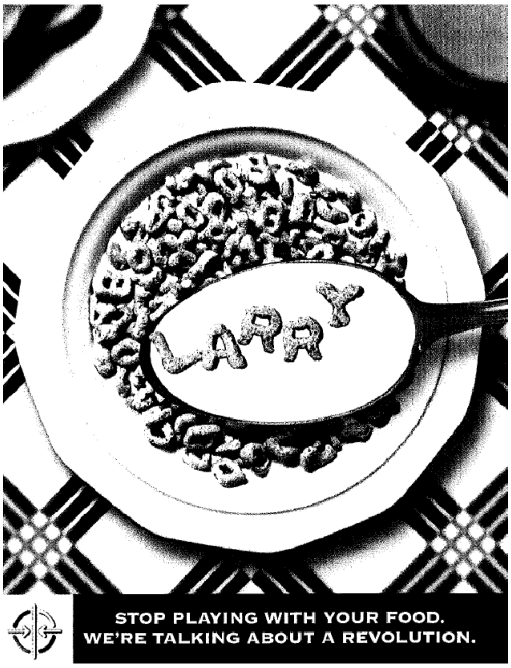

LARRY
STOP PLAYING WITH YOUR FOOD.
WE'RE TALKING ABOUT A REVOLUTION.

Figure 15 *VDP project by AGFA (Bober, 2003)*

2.3.2. Inkjet printing

Inkjet printing, of all digital printing techniques, is the best printing technique to add variable data to a static layout on corrugated board (Aboody, 2005; Viström, 2004b). It is a non-impact-printing method (NIP) and it works computer-to-print (CTP). This makes it a versatile printing method, able to print on any substrate regardless of its thickness (Moncarey et al., 2003).

Inkjet printing heads are nowadays very sophisticated and with continuing development will soon be capable of meeting the requirements of high printing speed combined with high print quality and multi-colour printing (Birkenshaw, 2006; Stack, 2003). Thermal inkjet (TIJ) and piezo inkjet (PIJ) already show very good progress in print quality compared to conventional printing systems, but the lack of speed is still a critical factor. Both systems are widely used in wide- and grand-format printers, bar-coding and mailing applications (Anon, 2008a; Lynn, 2009). Lynn (2009) says of continuous inkjet (CIJ), on the other hand, that it is capable of printing at high speed and that it dominates small character marking. An ongoing study at Innventia AB aims to increase the printing speed of a PIJ up to 150 m/min by using multiple single-pass heads, but a single CIJ single-pass head is capable of reaching 300 m/min. In the following text the digital / inkjet technology referred to is therefore CIJ.

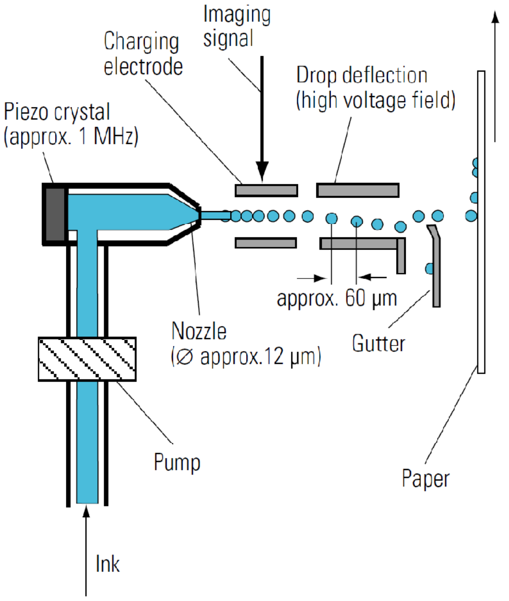


Figure 16 *Principle of continuous inkjet (Kipphan, 2001)*

The basic functioning principle of a CIJ printing head (Figure 16) is that a piezo crystal is continuously generating droplets. An electrode determines whether the image signal charges or does not charge the drops. The charged drops are then deflected into the gutter and returned into the ink system. All other drops continue their flight to the substrate and form the image. This technique enables drops to be fired at a very high frequency.

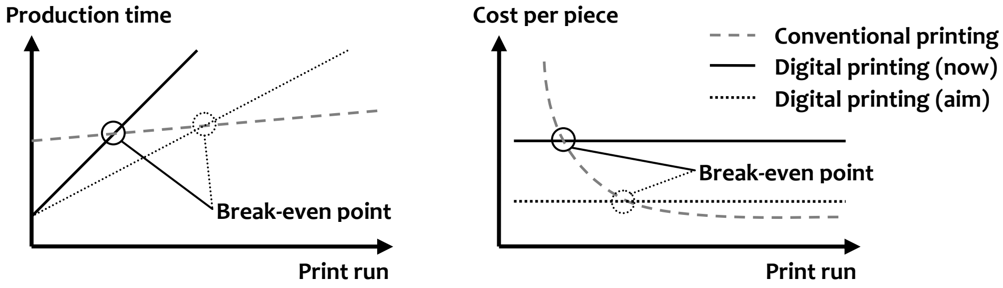


Figure 17 *Left: Compared to conventional printing digital printing has a very low start-up time but the printing speed is limited (Kipphan, 2001); Right: the digital printing has a constant price per printed piece, but conventional has high initial printing costs which decrease with longer print runs (based on Mejtoft, 2008).*

Compared to conventional printing the start-up time for digital printing from sending the file to the first printed sheet is extremely short and therefore very cost efficient (Figure 17, left figure). The relatively low printing speed of inkjet, on the other hand, reduces its fast start-up advantage in long print runs. According to Stack (2003), inkjet printing heads will become faster and therefore the performance will shift towards the dotted line and cost-effective long print-runs will be possible. A similar trend is expected with the cost per piece comparison. Nowadays the costs are very high but steady for digital printing and, in contrast to conventional printing, only the initial costs are high due to the time and cost of the pre-press process (Figure 17, right figure). When inkjet becomes faster and the equipment and the materials become cheaper, inkjet will at least approximate the dotted line, and long print runs with additional capability to produced customized prints will then be possible.

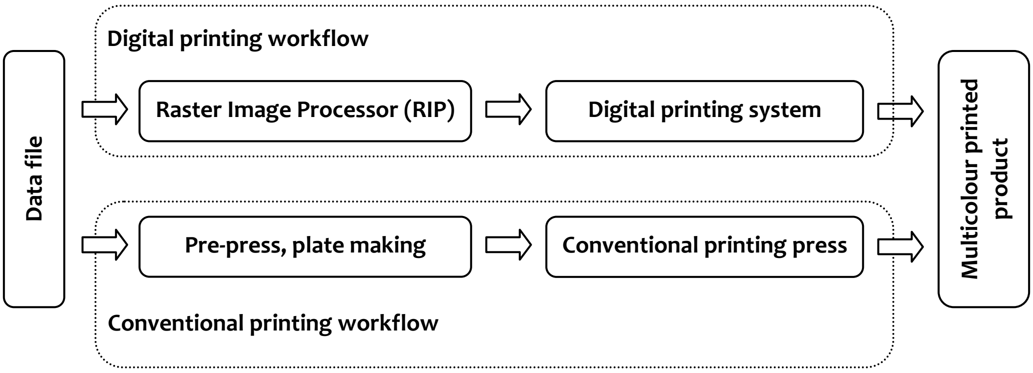

Digital printing workflow
Data file
Raster Image Processor (RIP)
Digital printing system
Pre-press, plate making
Conventional printing press
Conventional printing workflow
Multicolour printed product

Figure 18 *Comparison between a digital and conventional printing production workflow (Kipphan, 2001).*

In Figure 18, both the digital and conventional printing workflows are illustrated and both have a similar workflow. The process begins with a ready image file for the pre-press / raster-image-processor (RIP). In the pre-press department of conventional printing, the information from the data file can be transferred to the printing plate with the older analogue method or with the digital computer-to-plate (CtP) technique (Kipphan, 2001). This process exceeds a time frame of 30 minutes and an additional time of 10 to 30 minutes has to be added from the start-up until the first correct printed sheet leaves the printing machine. A digital printing workflow requires only minutes to process the file in the RIP, send it to the printing machine, start-up the printing machine and adjust the printing until the correct printing production can start. A time difference of 30-60 minutes or more can occur when comparing the two workflows. This advantage of digital printing methods is that they are the perfect printing method for short print runs, and can also implement customized segments into the print.

2.3.3. The implementation of inkjet in the converting process

Inkjet printing on packaging is already a common method and it has been developed mainly from printed displays or case coding and bar coding on fibre-based boards (Anon, 2003b; Dante et al., 2000; Haines, 2005; McLoone, 2007; Polischuk, 2006). Common uses are cinema displays or in-store displays for product promotion. None of these are mass-produced and in most cases inkjet is chosen because of its ability to print larger dimensions and its flexibility for customizing prints (Hunter, 2001). These wide-format off-line inkjet units are however ineffective in terms of extra production steps; such units unnecessarily increase cost and time consumption in mass production. To successfully use the inkjet technology in mass production, the keyword is: in-line inkjet printing units, where an inkjet unit is assimilated into the converting process of a packaging production line. Possible locations for integration could be the conventional printing unit, the die-cutter, the folder-gluer or the product-filling machine.

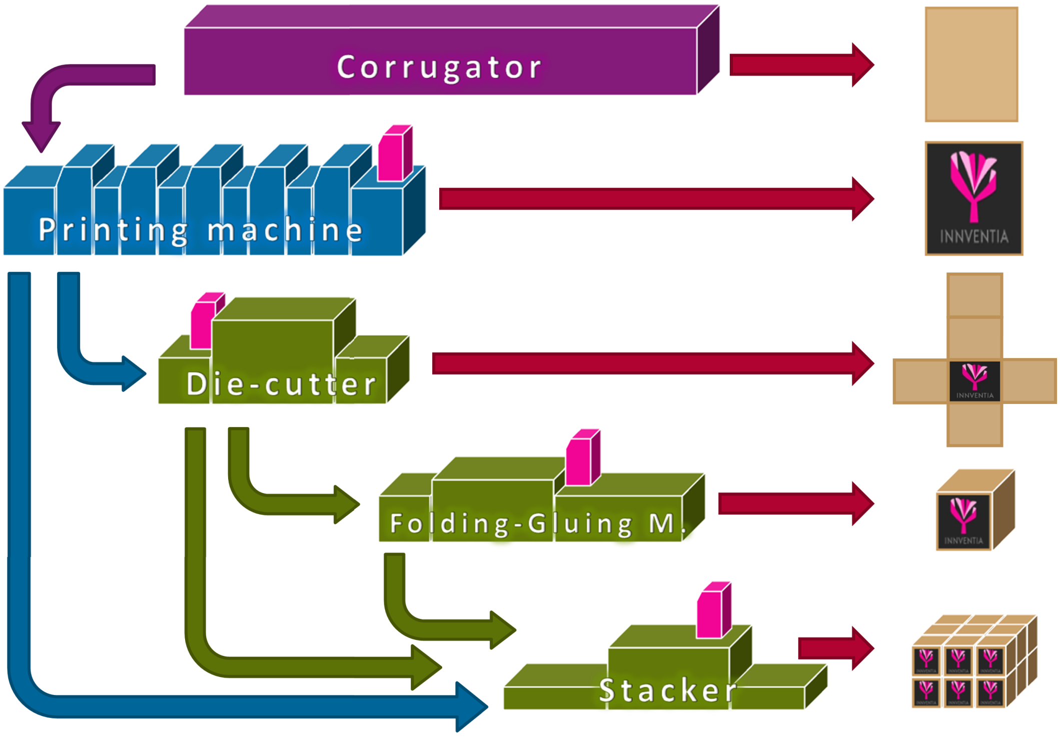

Corrugator
Printing machine
Die-cutter
Folding-Gluing M.
Stacker
INNVENTIA

Figure 19 The converting line of a corrugated board production facility with possible locations for inkjet printing units

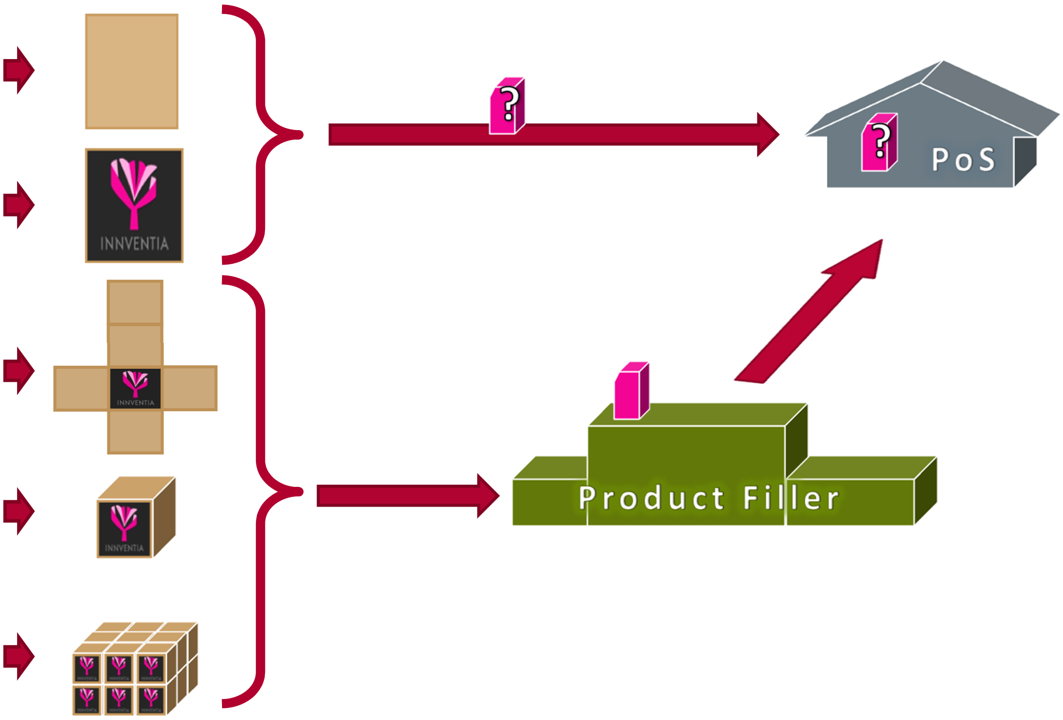

?
PoS
Product Filler
INNVENTIA

Figure 20 Further examples showing where inkjet could be implemented in the distribution line

Digital printing units for the packaging industry must therefore have the capability of being implemented in-line in the converting process (Figure 19). Existing or new converting machines can be equipped only if the digital printing unit fulfils the following requirements:

- easy-to-integrate design
- high-speed printing
- easy to maintain and
- fail-proof

These are the most important, but it would be also an advantage to locate the unit as close as possible to the end of the converting line to minimize the waste production in the case of false print. To continue this thought, the printing unit should be located at the latest possible location: the distribution or point-of-sale (POS) (Figure 20). At these locations, the printing faces other difficulties and a versatile unit able to print on different packages with different sizes, different surfaces and different shapes would be necessary, but high-speeds would not be required. Nevertheless, a large number of printing units would be required. One step closer to the production line, fewer printing units with better performance can be installed. The filling machines run at a high speed and are located at the end of the production / distribution line. Nevertheless, even here the digital printing unit would be confronted with relatively different shapes and substrates, but it would be done under controlled conditions, waste production due to false print could be minimized drastically, and better performing digital printing units can be installed enabling better print quality.

2.4. Print quality

The first part of this thesis discusses print quality issues generated from the production of corrugated board. Impacts on the surface topography of the liner, especially in the tip area of the corrugation, were examined. Besides topographical analysis, the print quality was also measured. In Part 2 of this thesis, liners were printed on a high-speed inkjet rig and similar print evaluations as in Part 1 were applied.

2.4.1. Corrugated board stripiness

The type and surface properties of the corrugated board substrate determine the print quality (Barros, 2006; Jansen et al., 2002; Sheng et al., 2000). Print density, print uniformity, print gloss and image fidelity are some regular corrugated board printing defects (Zang et al., 1995), but a further printing defect is dominating the research field, viz. streaked prints. Numerous investigations have been performed to minimize these. The problem is related to the construction of corrugated board, where the substructure is an undulated fluting medium. This layer is responsible for the stiffness of the board and is covered with two liners. The inner liner is normally inside the box and the outer liner is printed. Stripiness / streakiness is one of the most disturbing print defects on corrugated board, since it is periodical and more easily perceived than random print defects (Netz, 1996).

If pressure is applied on the plane surface of the corrugated board, deflections appear between the wave-tips. This surface structure looks like a washboard and it typically appears in the final print as darker and brighter lines at the same frequency as the fluting (Figure 21) (Barros, 2006; Cusdin, 2000; Hallberg Hofstrand, 2006; Zang et al., 1995). Pressure variations occur during the production of the board, when the single-faced board is combined with the outer liner. A conveyor belt on the top applies pressure on the board which is pressed against a hot plate with the outer liner (Mensing et al., 2003; Pinnington, 2003). At the positions where this outer liner is linked with the undulated liner, an overpressure occurs and these areas are therefore affected to a higher degree by grinding effects. Surface roughness changes may be the consequence. Previous investigations (Odeberg Glasenapp, 2004c) revealed surface roughness changes between the original raw paper and the treated surface in the corrugator (Odeberg-Glasenapp, 2004).Stripiness was examined with several test methods as explained in Papers I – III.

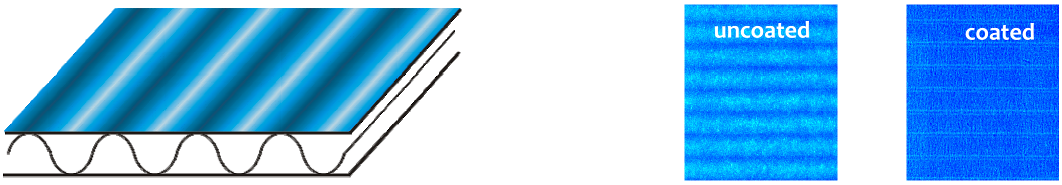


Figure 21 *Left: streakiness of a solid print area in theory; right: examples of flexo printed corrugated board with streakiness.*

2.4.2. Optical print density

The optical print density is calculated as the logarithm of the ratio of the reflectivity of the unprinted base paper to the reflectance factor of the printed substrate.

$$D = log\frac{R_\infty}{R} \qquad (5)$$

where D = density
R_∞ = reflectance factor of the blank substrate
R = reflectance factor of the printed area

A densitometer is calibrated with an unprinted reference for which the density $D = 0$. Increasing ink-film thickness reduces the reflection and the density increases (Brehm, 1992).

2.4.3. Colour measurement, CIE-L*a*b*

L^* is the lightness of a colour and can be between 100% (white) and 0% (black). In the a^*b^* coordinate system the a^* axis represents the red / green component and the b^* axis the yellow / blue component (Pauler, 2002). Knowledge of the exact colour values is not always the most important feature; a significant factor is the colour difference between a reference and a sample. For this reason, CIE introduced together with the $L^*a^*b^*$-space in 1976, the ΔE value. The higher the ΔE-value, the greater is the difference between two colours:

$$\Delta E_{ab} = \sqrt{(\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2})} \qquad (6)$$

where ΔE_{ab} = colour difference between sample 1 and 2
ΔL^* = $L_1^* - L_2^*$
Δa^* = $a_1^* - a_2^*$
Δb^* = $b_1^* - b_2^*$

2.4.4. Line raggedness

Line raggedness, i.e. the quality of the edge / contour of a printed line, is an important factor in the visual readability of small text fonts and the technical readability of barcodes. Figure 22 shows a 1 px line in the lateral and longitudinal directions, the target diameter of the dots and examples of dots deviating in area and position, factors which influence the shape of the edge and the raggedness of a line. The PrintSharp Tool (Innventia AB) is a software tool capable of determining line raggedness and line thickness by analysing the scanned image of a line, as indicated in Figure 22. The tool first seeks the contour line l_c by scanning inwards pixel by pixel from the image border (I_t and I_b) and calculates the median ($\bar{a}$ and $\bar{b}$) of both edges of the line. The tool has a built-in algorithm which determines the optimal threshold, taking into account the background noise of the paper.

The raggedness can then be calculated in two different ways. Raggedness-1 (R_1) given by Equation (7) is the ratio of the actual contour length (l_c) to the length of the straight line (l_s). The perfect contour is a straight edge having $R_1 = 1$.

$$R_1 = l_c / l_s \qquad (7)$$

where R_1 = raggedness-1; the relative excess contour length in relation to a straight line

l_c = length of contour line [µm];

l_s = length of straight line [µm]; distance between the image borders I_l and I_r

Raggedness-2 (R_2), given by Equation (8), is the standard deviation, and is analogous to the R_q (root mean square) surface roughness. The distances s_i between the mean line and the associated contour line are determined and the standard deviation R_2 is calculated. In this study, R_2 has been used as a measure of the line raggedness.

$$R_2 = \sqrt{\frac{1}{n}\sum_{i=1}^{n} s_i^2} \qquad (8)$$

where R_2 = raggedness-2 [µm]; the standard deviation of the contour from the mean line

s_i = distance between mean line and contour line [µm] in *y*-direction; $\bar{a} \triangleq$ upper mean line and $\bar{b} \triangleq$ lower mean line

i = index number of distance points in *x*-direction;

n = total number of pixels in *x*-direction

A further module of the PrintSharp Tool calculates the line thickness (t_l), i.e. the distance between the medians ($\bar{a}$ and $\bar{b}$) of the line:

$$t_l = t_e - (t_{\bar{a}} + t_{\bar{b}}) \qquad (9)$$

where t_l = line thickness in [µm]; distance between the upper $\bar{a}$ and lower $\bar{b}$ mean line

t_e = distance in [µm] between the upper I_t and lower I_b image borders in *y*-direction

$t_{\bar{a}}$ = distance between the upper image border I_t and $\bar{a}$ in y-direction in [µm]

$t_{\bar{b}}$ = distance between the lower image border I_b and $\bar{b}$ in y-direction in [µm]

Lateral line

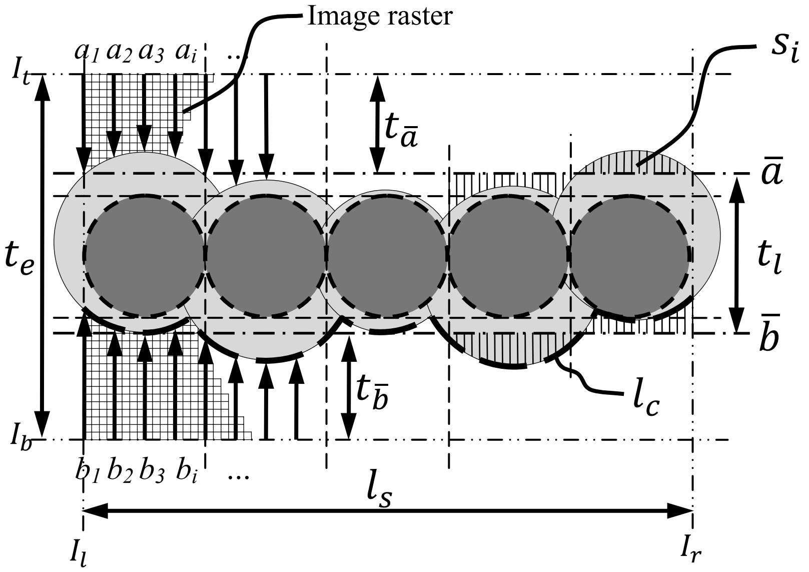


Image raster
I_t
a_1 a_2 a_3 a_i ...
s_i
$t_{\bar{a}}$
$\bar{a}$
t_e
t_l
$\bar{b}$
$t_{\bar{b}}$
l_c
I_b
b_1 b_2 b_3 b_i ...
l_s
I_l
I_r

Longitudinal line

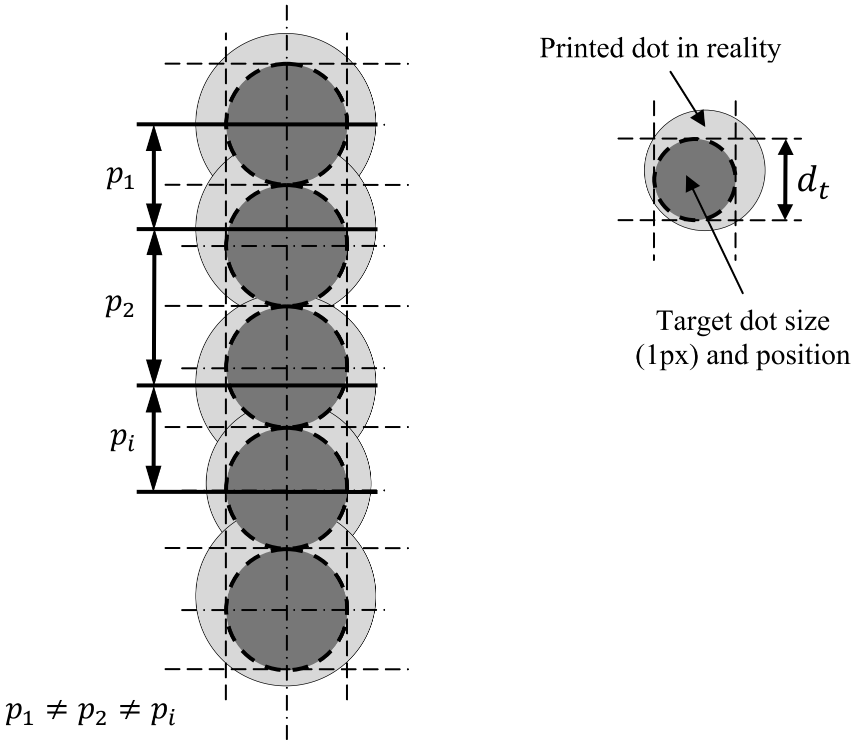

p_1
p_2
p_i
$p_1 \neq p_2 \neq p_i$
Printed dot in reality
d_t
Target dot size (1px) and position

Figure 22 *Diagram of two 1 px lines within an image raster and the top I_t, bottom I_b, left I_l and right I_r image borders. For the lateral line (left), the calculation of raggedness, line thickness and dot deviation in form and position from the target dot is shown. The longitudinal line (right) shows the dot deviation pi in the printing direction. The printed lines are scanned and rasterised as illustrated in the diagram.*

2.4.5. Print mottle and geometrical dot gain

Mottle is described by Johansson (1999) as optical inhomogeneity, an unevenness in optical density and print gloss. It appears in solid tones or smooth image regions. A flatbed-scanner-based analysis system is used, where the coarseness is determined by applying a bandpass analysis, and the result is then divided by the mean reflectance (Fahlcrantz et al., 2004). The software used, called STFI-Mottling Expert 1.0, can be run on any PC-System with almost any flatbed scanner.

To determine the average size of the printed dots, microscopy images in the 10 % gray tone area were taken. Images were captured by an optical microscope Zeiss Axioplan 2 using a dark field technique in reflected light, and analyzed using the ImagePro-Plus (Media Cybernetics, Inc., USA) commercial image analysis system. This program measures the diameter of the printed dot $d_p$at five different angles and calculates an average diameter. The diameter of the theoretical dot d_t is equivalent to the distance between the dots, which in the case of inkjet is the resolution of the print head (see Figure 22). From the two diameter values, the target dot diameter and the dot diameter in the print, the area coverage in the print is first calculated:

$$F_p = F_t \cdot \frac{A_p}{A_t} = F_t \cdot \frac{d_p^2}{d_t^2} \qquad (10)$$

where F_p = area coverage in the print [%]
F_t = target area coverage [%]
A_p = dot area in the print [μm^2]
A_t = target dot area [μm^2]
d_p = dot diameter in the print [µm]
d_t = target dot diameter [µm]

and the geometrical dot gain z_g is then calculated:

$$z_g = F_p - F_t \qquad (11)$$

where z_g = geometrical dot gain in [%]

3

FRAME OF REFERENCE

“Every year, 13 million hectares of forest disappear”

The study has been divided into three major parts as illustrated in Figure 23:

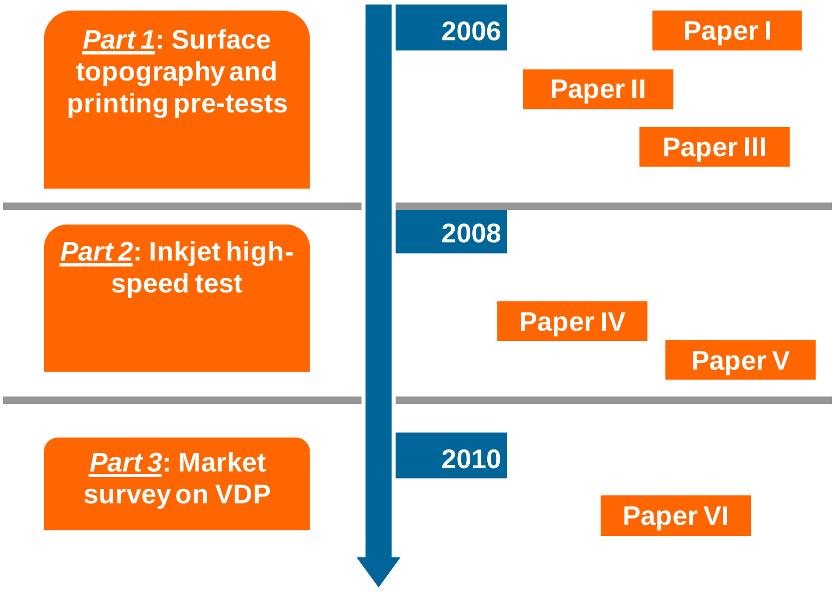

Part 1: Surface topography and printing pre-tests
Part 2: Inkjet high-speed test
Part 3: Market survey on VDP
2006
Paper I
Paper II
Paper III
2008
Paper IV
Paper V
2010
Paper VI

Figure 23 The three parts of the study presented in this thesis, the related Papers are shown on the right side

3.1. Part 1 – Surface topography and printing tests (Papers I-III)

The surface topography of a liner substrate contributes to a great degree to the print quality that can be achieved. Most critical in terms of quality are print defects like mottling, gloss and stripiness, of which all appear in the printing of corrugated board. Stripiness is especially critical because it is a defect directly caused by the corrugated board construction. A further cause can be found in the production process of corrugated board. Studies by Odeberg Glasenapp (2004c) revealed a difference in surface micro-roughness between the regions on the peak line of the liner and the regions in the valley between two peaks of the corrugation.

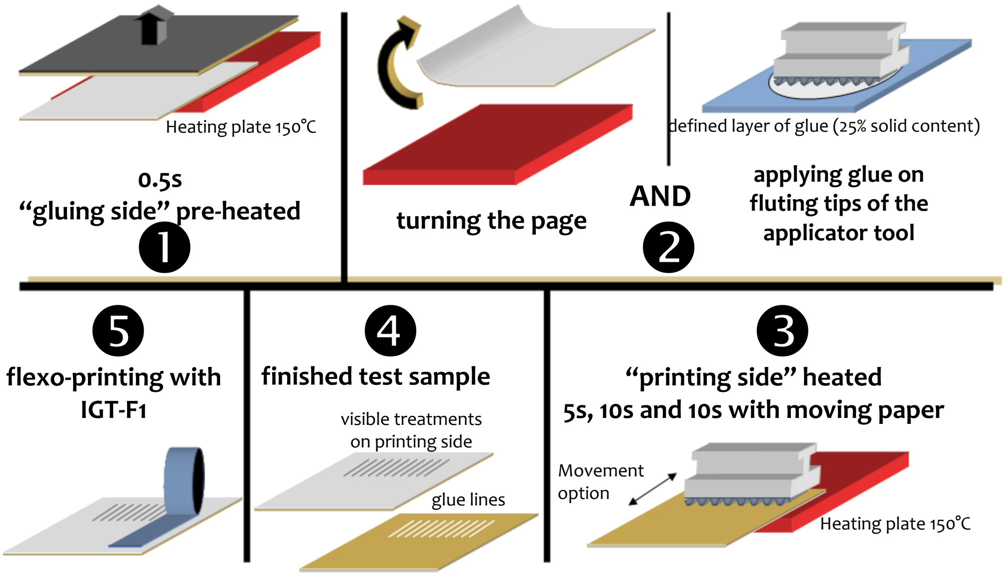

Heating plate 150°C
0.5s
"gluing side" pre-heated
❶
turning the page
AND
❷
defined layer of glue (25% solid content)
applying glue on fluting tips of the applicator tool
❺
flexo-printing with IGT-F1
❹
finished test sample
visible treatments on printing side
glue lines
❸
"printing side" heated
5s, 10s and 10s with moving paper
Movement option
Heating plate 150°C

Figure 24 Test procedure for producing differently treated samples in the laboratory.

Planning and performing tests on a full-scale corrugator can be very time-consuming and the results would be dependent on the daily production. Executing the tests on a laboratory scale instead is more flexible and changes can quickly be made in the test setup. Despite the advantages of laboratory tests, one disadvantage is that speed is a critical parameter. The top speed of actual corrugators can be 420 m/min and this can never be achieved on a laboratory scale. In addition, a laboratory trial would not produce corrugated board comparable to real sheets. Most important is to obtain an overview about which setting is the most significant. The data from the tests can be compared with data from the topographical tests and finally with the print results.

The laboratory trials are described in detail in Paper I. The tests reported in that paper focus on uncoated papers and further data for coated liners can be found in Paper II. The laboratory test (Figure 24) was set up to correspond to the procedures in a corrugator. These tests contain only the process steps from the reel stand of the liner to the end of the double-backer (Figure 8). In the laboratory test, the paper was pre-heated on the gluing side with a heating plate. After the sheet has been turned, it was loaded with a tool with a milled flute profile. This tool simulates the flute profile and the load from the double-backer top heating plates. In addition, glue was applied on the flute tips of the tool to include the possible influence of factors like moisture and evaporation. During step 3, one set of liners (10sM) was moved back and forth on the laboratory heating plate, whereas the other sets (10s, 5s), were kept stationary, in order to measure the difference between moved and unmoved paper on a hot plate. The chosen times on the heating plate were 5s (only unmoved) and 10s (both moved and unmoved). In a final step, chosen samples were printed with a laboratory flexographic printing machine.

In a further step, a full-scale test in a corrugator was performed in order to confirm the results of the laboratory test. The trials were divided into two parts, one for uncoated and one for coated grades. In Paper II, the trials and the corrugator settings are described in detail.

3.2. Part 2 – Inkjet high-speed test (Papers IV & V)

The “HybSpeed Printing” project was initiated to study the combination of a conventional printing process with inkjet printing. The aim of the project was to assess the practicability of attaining high quality VDP at high speed on a variety of packaging papers for corrugated board production.

The exploratory trials were conducted on a Kodak Versamark DP5240 in Örnsköldsvik, Sweden, in cooperation with the Mid-Sweden University - Digital Printing Centre (DPC). The DP 5240 is a CIJ and is capable of printing at a resolution of 240 x 240 dpi at a speed of 300 m/min. Nine different substrates, white top and pure white liner, single-coated, double-coated, kraftliner and testliner were printed at speeds between 0,5 and 5 m/s. The high speed printing test rig, illustrated in Figure 25, is designed as an endless belt system and paper samples can be attached to this belt.

The arrangement of a printing test requires not only a reasonable printing system but also a proper print layout. To assess the performance of the liner papers, the following print evaluations were chosen: line raggedness and thickness, area coverage, lightness, print mottle, print density and dot diameter. In addition, the absorbency, surface roughness and unprinted mottling of the paper were determined.

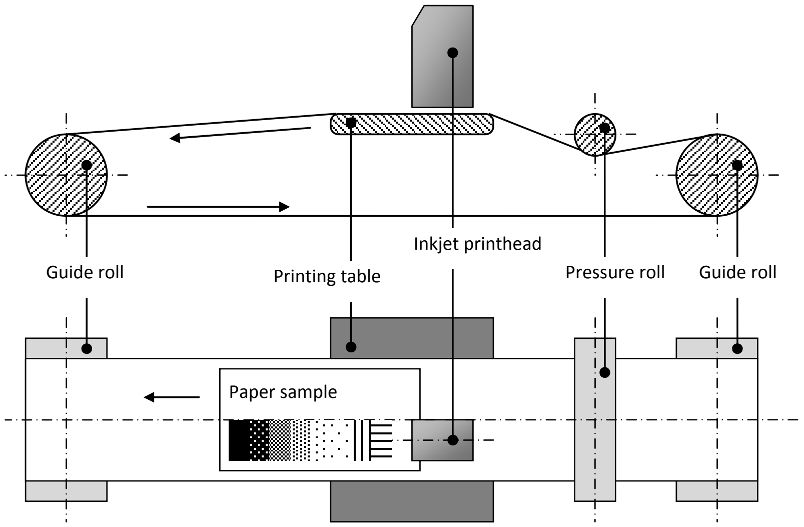

Guide roll
Printing table
Inkjet printhead
Pressure roll
Guide roll
Paper sample

Figure 25 *High speed inkjet printing test rig at DPC. Kodak Versamark DP5240 inkjet unit printing on paper samples mounted on an endless belt.*

The print layout is shown in Figure 26 and it includes lines of different thicknesses (1, 2, 3, 5, 7, 10 px), each line being printed three times in both the longitudinal and transverse directions. The text was printed in Times New Roman in 8, 10, 12, 18 and 36 px's. The second part of the print layout was the gray tone; two different modes were used in Adobe Photoshop CS2 to create the gray tone boxes, which are regular half-tone (HT) and diffused dither (DD). The stepping for both modes between the gray tones was 2 % between 0 % and 10 % and 10 % between 10 % and 100 % (see Figure 26).

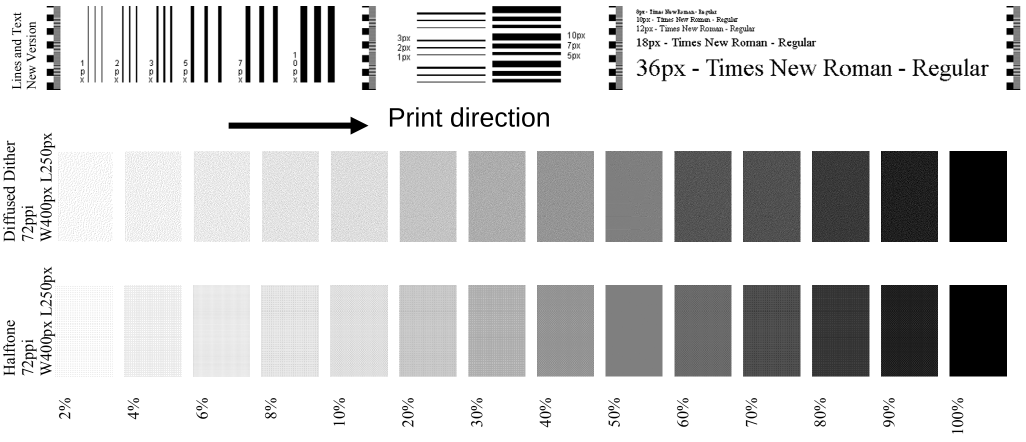
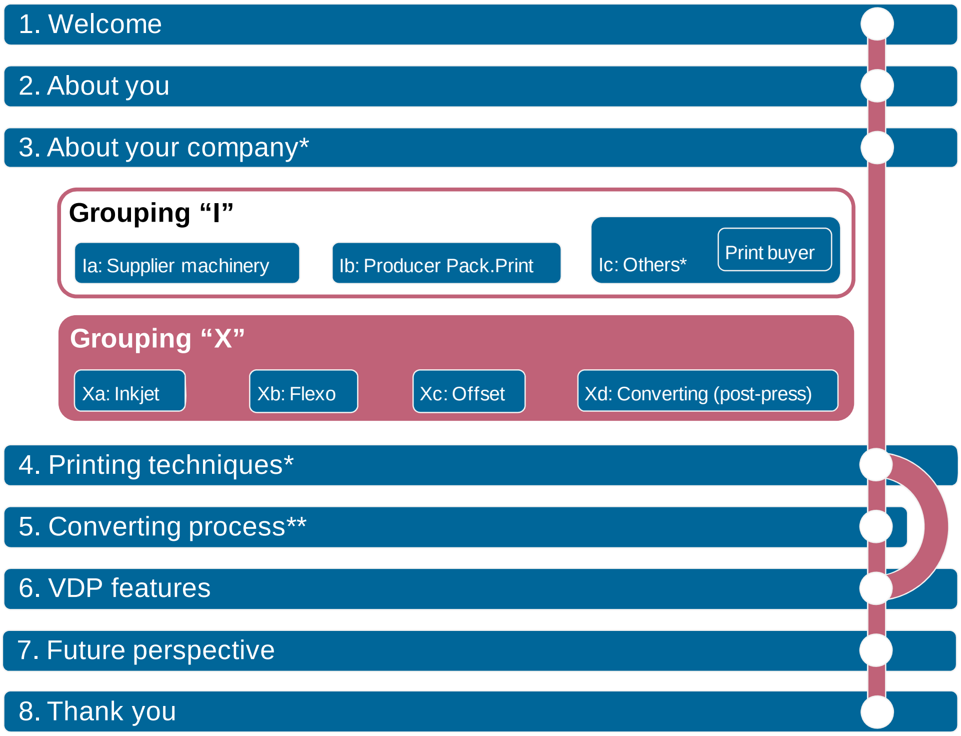

Lines and Text New Version
1 px
2 px
3 px
5 px
7 px
10 px
3px
2px
1px
10px
7px
5px
8px - Times New Roman - Regular
10px - Times New Roman - Regular
12px - Times New Roman - Regular
18px - Times New Roman - Regular
36px - Times New Roman - Regular
Print direction
Diffused Dither 72ppi W400px L250px
Halftone 72ppi W400px L250px
2%
4%
6%
8%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%

Figure 26 *Print layout; top: lines (1-10 px) and text (8-36 px), bottom: gray tones in halftone and diffused dither (generated with Adobe Photoshop; W400px = width 400px and L250px = length 250px)*

3.3. Part 3 – Market survey of VDP (Paper VI)

Inkjet printing is the most suitable technology with which to apply variable data on packaging and to offer customized and personalized prints for the industry and the end-consumer. To obtain a picture of the industries' view on variable data print on fibre-based packaging, a market survey was initiated and was addressed to people in the development, marketing and decision-making sectors of the packaging and printing industry, including manufacturers of machinery, producers of packaging and prints, and print buyers. The goal was to draw an overview map covering people's view on their market, trends in their fields and how they envision the future of VDP on fibre-based packaging.

The detailed aims of this survey were to identify (i) how familiar is the industry with VDP? (ii) what are the thoughts of the industry about this technology? (iii) which parameters are of prime interest for the people in the packaging sector regarding VDP features?, and (iv) what is possible today and in the near future?. The final report will be an aid for the industry to support machinery manufacturers in their development, converters in investing in the right inkjet machinery and print-buyers in the decision process regarding inkjet-printed VDP features.


1. Welcome
2. About you
3. About your company*
Grouping "I"
Ia: Supplier machinery
Ib: Producer Pack.Print
Ic: Others*
Print buyer
Grouping "X"
Xa: Inkjet
Xb: Flexo
Xc: Offset
Xd: Converting (post-press)
4. Printing techniques*
5. Converting process**
6. VDP features
7. Future perspective
8. Thank you

*Part includes a question which is mandatory to continue
**In part 4 is questioned the knowledge regarding the converting process of fibre-based packaging. Participants without this knowledge skipped part 5 and were directly forwarded to part 6

Figure 27 General structure of the questionnaire.

The questionnaire incorporated 20 questions and Figure 27 shows its general structure of the questionnaire.

Parts 2 and 3 included questions designed to assign each participant a place in the later analysis and more detailed statistical examination. The first grouping of participants *"I"* was related to the business area, whether the participant was a) a supplier of machinery, b) a producer of packaging print or c) other. In the grouping *"X"*, the relevant data was based on how large a percentage of the company's business was assigned to substrate, inkjet, flexography, offset, screen-print and converting (post-press). Part 4 sought to assess how familiar the participant was with printing techniques and his or her impression of inkjet within the conventional printing industry. Part 5 'Converting process' included technical questions regarding the implementation of inkjet, while part 6 discussed concrete VDP features. The final part discussed the future of inkjet, VDP and conventional print.

4

SUMMARY OF PART ONE – SURFACE TOPOGRAPHY

"20% of the world's population consumes 80% of its resources"

Trials in the laboratory and on a full-scale have been performed to clarify topographical effects on corrugated board liner during the production in the corrugator. The micro-scale changes in surface roughness were examined by a pivotal study. In both trials, it was possible to show evidence of the existence of surface impacts in the corrugated board production process. The results from the field test showed that the samples in the laboratory trials were treated too harshly. Therefore, only the uncoated grades were analyzed in the laboratory trial. On the other hand, the full-scale trial showed no effects on the uncoated grades and therefore only the coated grades were examined in this trial. The samples evaluated in the two trials showed conclusive results. The surface roughness in the peak area was less than that of the untreated reference and the valley area.

4.1. Laboratory Trials

The laboratory trials showed that the surface and the surface roughness were affected by heat, pressure and friction. There is no clear border between these factors; they are all interdependent. Figure 28 shows CLSM images of the liner with the untreated reference (left), the treated sample measured on the peak area (middle), and the valley area (right).

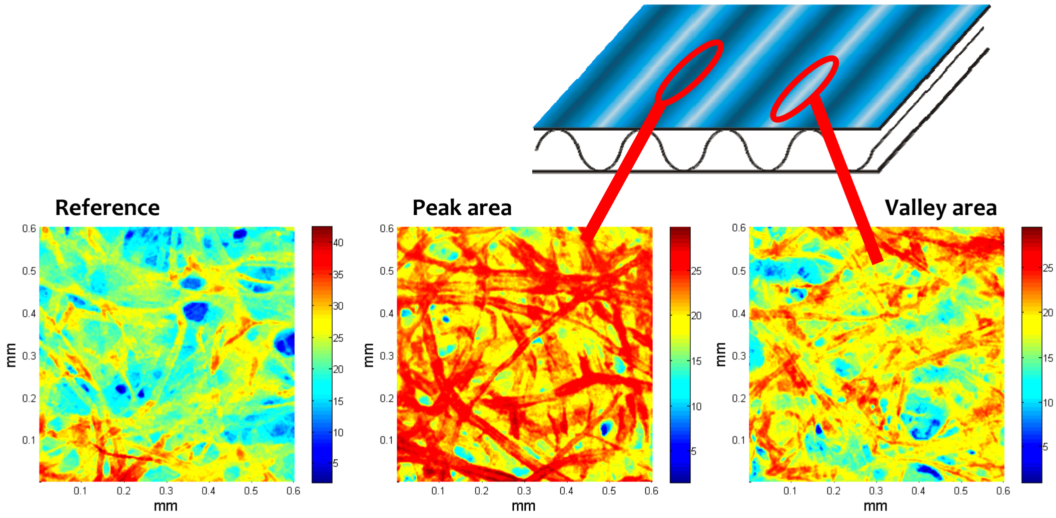


Figure 28 CLSM images from uncoated sample; left: reference; middle: on the peak; right: valley

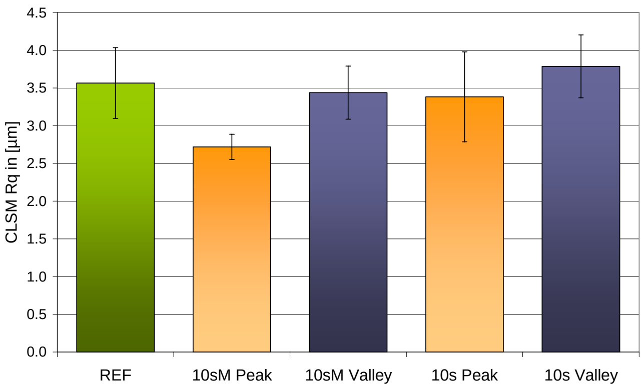


Figure 29 CLSM results from the uncoated sample including the non-treated reference, the 10sM samples and 10s samples.

The surface roughness results in Figure 29 include two different kinds of treatments on the uncoated sample, viz.: 10sM: 10 seconds treatment with paper movement on the heating plate, and 10s: 10 seconds treatment but no movement. The difference in surface roughness change between peak area and valley area is clearly visible especially for the paper moved on the heating plate (10sM), but also the unmoved sample (10s) shows a decreased roughness.

Surface changes can also be seen in the gloss measurements with the STFI-MicroGloss meter on the uncoated samples which show differences in the reflectance between peak and valley areas (Figure 30). Similar images were captured of the coated samples, but the samples showed signs of a harsh treatment that has led to a substantial change in the surface roughness. It was assumed that the top coating layer has been rubbed off, especially at the peak lines. The uncoated grades were, however, less affected by this treatment, which allows us to assume that the uncoated grades are more resistant to heat, pressure and friction.

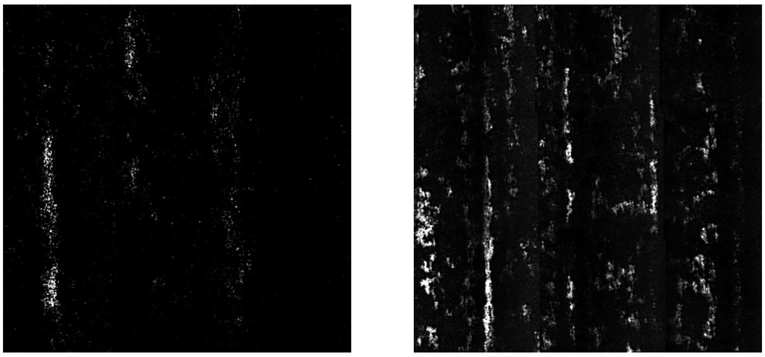


Figure 30 *Gloss of an uncoated (left) and coated sample (right); images taken with the STFI-MicroGloss meter*

The prints were made with flexographic printing. Even though the samples were only single liners without any fluting or second liner, the glue applied on the reverse side made the printing surface appear like a corrugated board surface with a washboarding effect. This washboarding may also have affected the print quality results in the laboratory trials. Stripiness and its background have been studied increasingly in the past few years by many researchers (Ian R. Chalmers, 1998; Cusdin, 2000; Hallberg Hofstrand, 2006; Holmvall, 2007; Netz, 1996; Odeberg Glasenapp, 2004a; Pedraza, 1993; Rehberger, 2004; Zang et al., 1995). Two effects of washboarding are differences in print density and colour. For this reason, the results of the print analysis should be examined with caution.

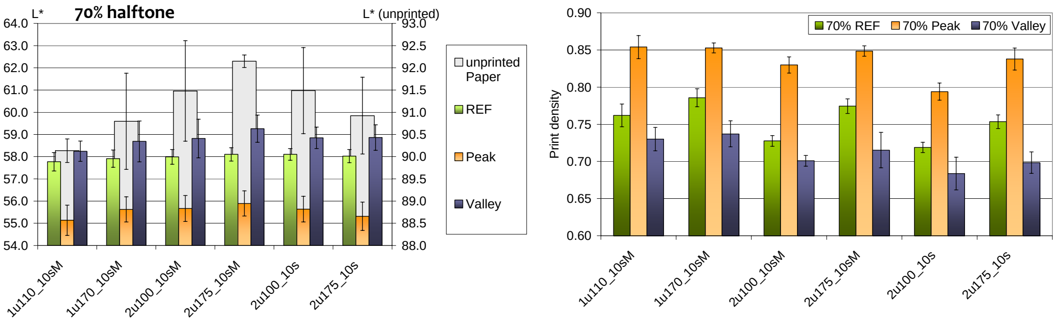


Figure 31 *Left: L***-values of the uncoated grades in 70% halftone; the bars at the front belong to the left-hand axis and the bar at the back to the right-hand axis*
Right: Density of the 70% halftone

The flexography print results in 70% halftone of six uncoated liners are shown in Figure 31. It was not clear whether or not the print density results were related to the surface roughness. Both the print density results and the lightness measurements suggest a difference in ink film transfer. Especially in halftone, the peak lines appeared darker and the print density showed higher values than in the valley regions. As reason for the difference between the valley and the reference can be assumed that during the printing the washboarding effect occurred and less ink was transferred into the valley regions. The question of whether the print analysis results were due to surface roughness changes or to washboarding effects could not be clarified in this study.

4.2. Full-Scale Trials

The process step responsible for changes in the paper surface is presumably located in the corrugated board production process. The most probable cause lies in the double-backer. Therefore, counteractive measures should be discussed. A. Johansson et al. (1991, 1995) state that friction is an important parameter affecting the paper surface. Back (1991) mentioned that a low coefficient of friction of paper against metal is desirable in the corrugator, i.e. that highly polished metal surfaces are important. Changes in the design of the hot plates in the double-backer can contribute to a lower friction coefficient and thus minimize the wear effect.

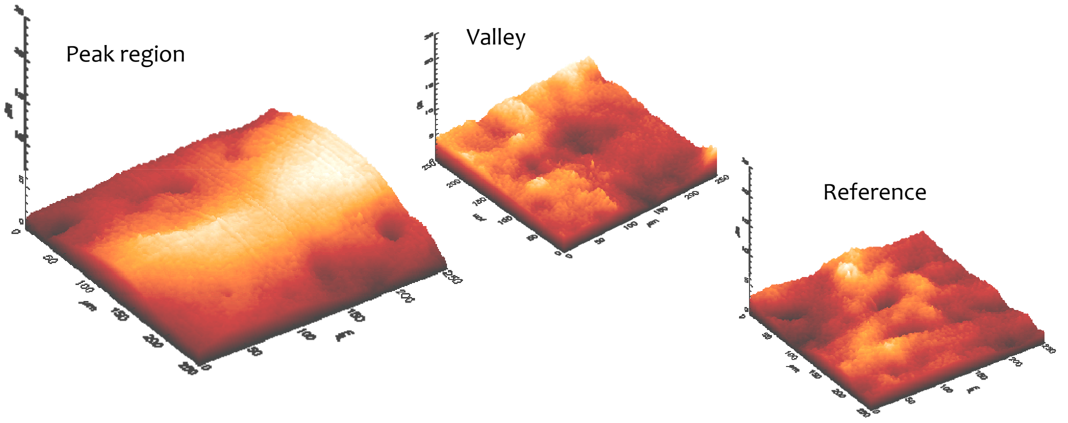


Figure 32 *FRT MicroProf images (250 x 250 µm, resolution of 1µm / pixel, 25 µm in z direction); left: peak area, the wavy structure of the liner is recognizable; middle: valley area; right: reference.*

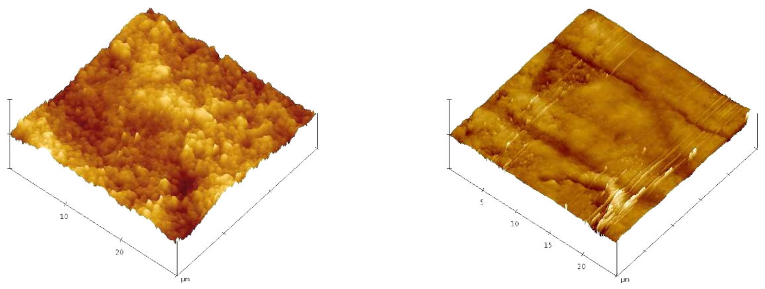


Figure 33 *AFM images; left: reference sample (30 x 30 µm, Rq= 139.76 nm), taken from the paper roll at the reel stand; right: treated sample (25 x 25 µm, Rq= 52.03 nm), peak-area on the liner; failures in the right hand image caused by problems during the measurements.*

To summarize the knowledge gained from this pilot trial, surface roughness changes on a micro-scale occur on the liner during the production of corrugated board. Since the STFI MicroGloss measurements revealed, that the uncoated samples did not show any gloss effect in the unprinted state, this series was excluded from further evaluation.

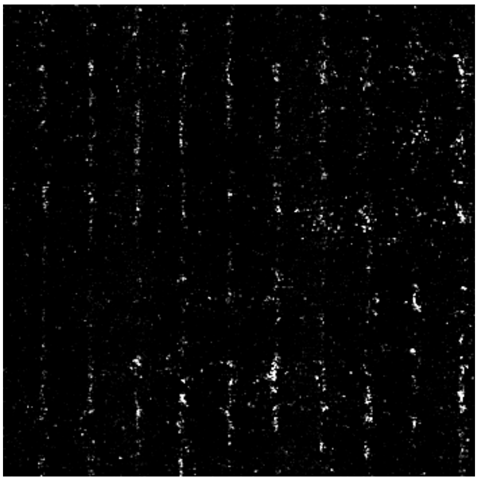


Figure 34 *Gloss image of a coated sample; captured with STFI MicroGloss meter.*

The coated samples, however, showed a very clear result. The gloss appearance of the unprinted sample is visible to the eye and can be measured with the STFI MicroGloss meter (Figure 34). This was supported by all the surface roughness measurements performed on the macro-, micro- and nano-scales, all of which gave the same result (Figure 35). The surface roughness along the peaks was lower than that of the reference and the valleys. The images from the measurements with FRT-MicroProf (Figure 32) and AFM (Figure 33) clearly show the difference in surface topography between the fluting peak and the valley between the peaks.

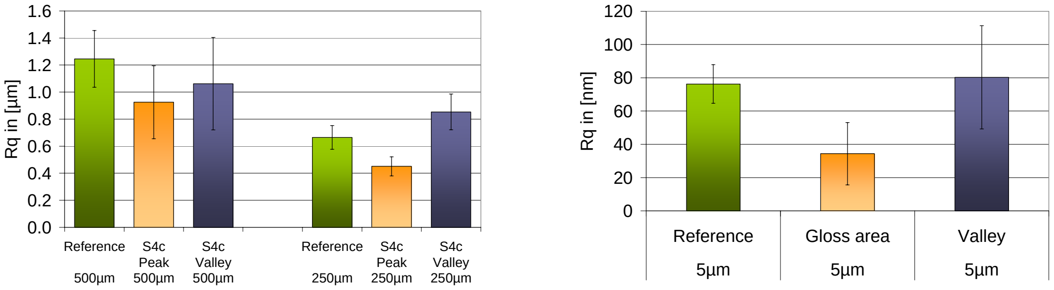


Figure 35 *FRT MicroProf (left) and AFM (right); the value below the sample indicates the length of the square measurement area. In all cases, the surface roughness is lower in the peak regions.*

It can be concluded that the coating layer is less resistant to heat, pressure and friction. The magnitude of the affected areas is then dependent on the corrugator settings.

The colour data were not as useful as expected. The L^*-values were surprisingly little influenced and the differences were even negligible (Figure 36) in spite of the differences found in the topographical measurements. It appears that the effects described in this thesis affect only the gloss appearance but not the lightness. In this respect, the results agree with the study performed by Odeberg

Glasenapp (2004c). The existence of surface roughness differences on a micro-scale between peaks and valleys is confirmed by several measurement methods.

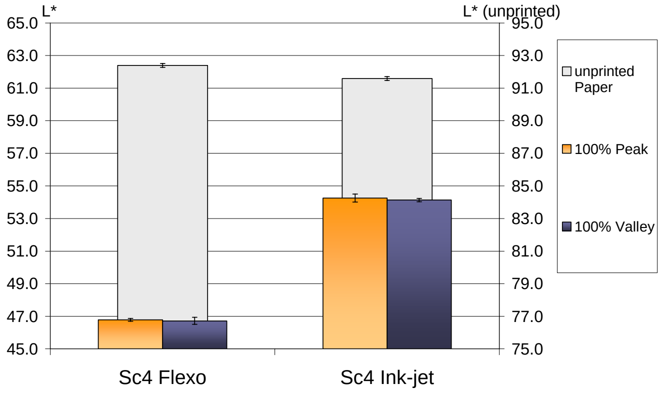
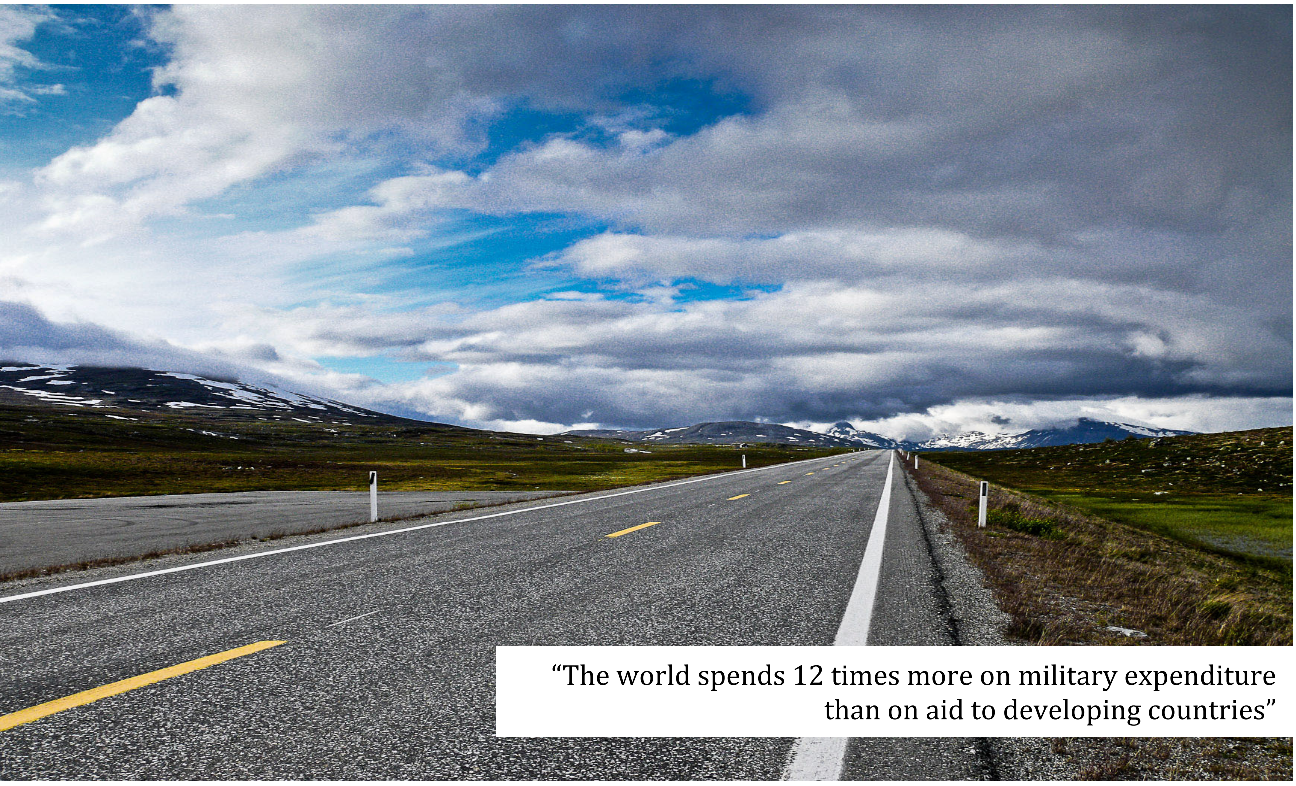


Figure 36 *Print analysis results: L*-values, the front bars belong to the left primary axis and the chart behind belongs to the right secondary axis.*

In both laboratory and full-scale trials with different types of substrates (coated and uncoated), the same trend was detected that the surface roughness is changing during the double-backing, but the print result was always affected less than expected. Flexo- and inkjet printing did not show any difference in print-lightness and therefore it can be expected that surface roughness changes will not lead to printed stripiness. Printing with flexography and inkjet on a corrugated board with washboarding effect, on the other hand, will lead to visual differences, because flexography is dependent on an even surface but inkjet is not or very little. The question remains how great the difference would be.

SUMMARY OF PART TWO – HIGH-SPEED INKJET TESTS

5



“The world spends 12 times more on military expenditure than on aid to developing countries”

The HybSpeed Printing project was initiated in order to study the combination of a conventional printing process with inkjet printing. The aim of the project was to assess the practicability of attaining high quality VDP at a high speed on a variety of liners for corrugated board production. The trials were conducted on a Kodak Versamark DP5240 in Örnsköldsvik, Sweden, in cooperation with the Mid-Sweden University - Digital Printing Centre (DPC).

The variety of packaging materials on the market is extremely large and the choice is based on purpose and price. The paper type is an important factor influencing the runnability of inkjet printing. Nine different types of liners were chosen as listed in Table 4. These were two white / white-top uncoated liners (N1, N2), three coated liners (N3, N4, N5), two kraftliners (N6, N7) and two testliners (N8, N9). The printing was carried out at three different speeds, low (0.5 m/s) medium (2 m/s) and high (5 m/s).

Table 4 Boards used in the high-speed inkjet test.

- Pure white, uncoated, 170 g/m^2 (N1)
- White top, uncoated, 175 g/m^2 (N2)
- Pure white, coated, 95 g/m^2 (N3)
- White top, single-coated, 170 g/m^2 (N4)
- White top, double-coated, 175 g/m^2 (N5)
- Kraftliner, uncoated, 186 g/m^2 (N6)
- Kraftliner, uncoated, 140 g/m^2 (N7)
- Testliner, uncoated, 140 g/m^2 (N8)
- Testliner, uncoated, 150 g/m^2 (N9)

5.1. Inkjet printing speed

The printing speed, regardless of liner properties, was the most important parameter to be studied in this trial, but the question remains whether inkjet print is capable of giving high quality at high speed, and of meeting the requirements for in-line implementation.

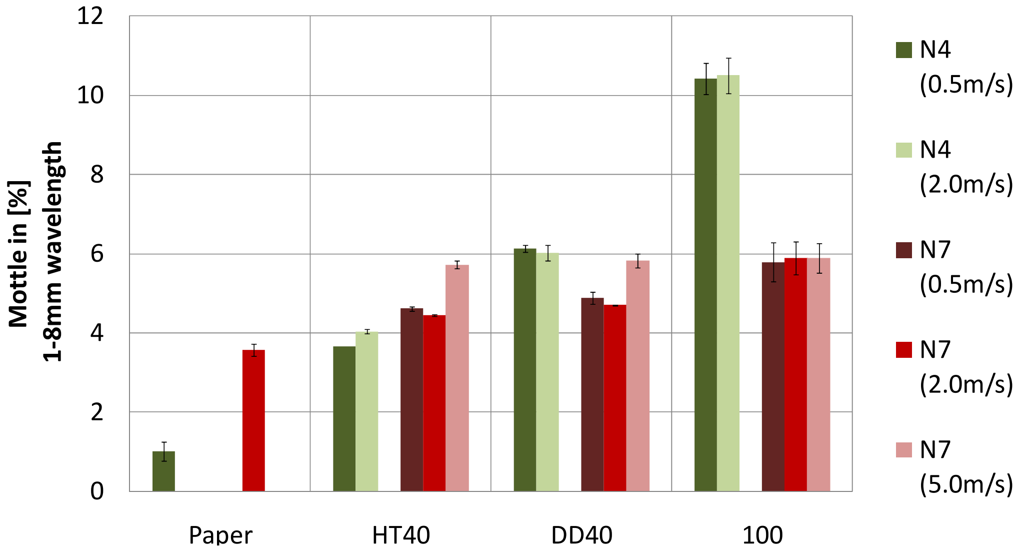


Figure 37 Paper and print mottle in the wavelength range of 1-8 mm measured on the unprinted paper, 40 % halftone (HT40), 40 % diffused dither (DD40) and on fulltone (100), for two different papers (N4 and N7) printed at different speeds.

The print mottle values, shown in Figure 37, for the uncoated N7 paper were influenced by speed and at the highest speed the mottle was significantly higher than at the low and medium speeds in the 40 % halftones. The high paper mottle of the N7 paper may have an influence on the print mottle in the 40% halftone since the values for N7 are higher than those for N4, but in the 100% fulltone this effect disappeared because the paper was covered with black ink. The speed had little influence on the mottle on the N4 paper, but in fulltone the mottle was much higher than on N7, probably because of an excess of applied ink. The fulltone area was overfilled by ink and formed locally brighter and darker spots which were clearly visible.

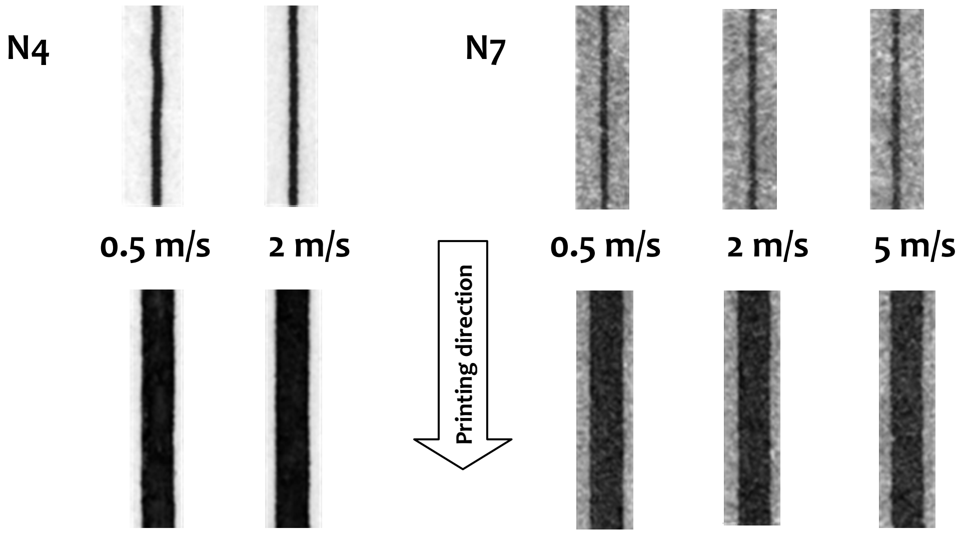


Figure 38 *Examples of longitudinal (LL) 1 px and 7 px lines printed on papers N4 and N7 at different speeds.*

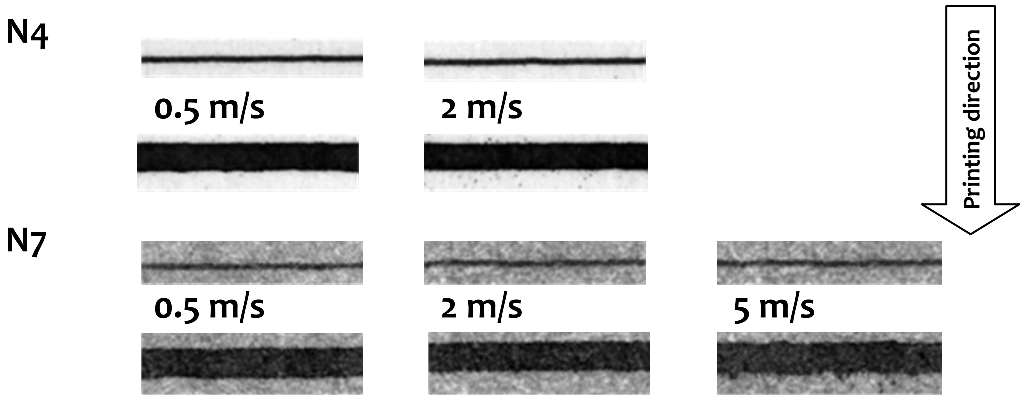


Figure 39 *Examples of lateral (LQ) 1 px and 7 px lines printed on N4 and N7 paper at different speeds.*

The edge sharpness evaluation was separated into longitudinal (LL; Figure 38) and lateral (LQ; Figure 39) lines with respect to the leading and trailing edges of the printed line. The leading edge of the LQ line, in particular, was very ragged and the high-speed sample in particular had severe break-outs (Figure 40). This may be because air was dragged along with the paper belt and because the resulting turbulence deflected the ink drop. In addition, the ink drop was forced into the pits between the paper fibres due to the high speed, and this caused these severe break-outs. It would be desirable to repeat this high-speed printing test and to use a high-speed camera to study the ink drop setting.

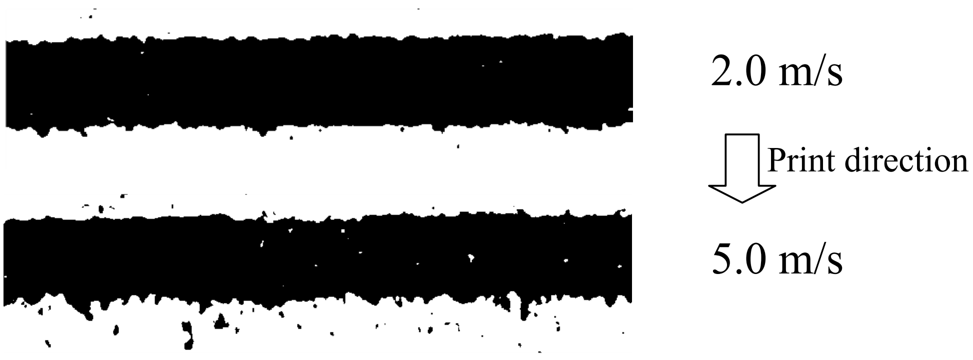


Figure 40 *B/W images from the 7 px lines printed on paper N7. The difference between the two speeds is clearly visible. The leading edge of the 5 m/s line is much more ragged than the 2 m/s line.*

The lateral printed lines are in general more wavy and ragged than the longitudinal lines, due to the principle of the printing system. A longitudinal line of e.g. 1 px is dependent only on the ink drops from a single nozzle, whereas a lateral line depends on several drops and all these drops have to strike the surface at the same time to produce a straight line. A slight deviation is sufficient for the line to become ragged and show a greater waviness. Figure 41 illustrates this effect, the longitudinal line being straight with a minor ragged edge and the lateral line being wavy and very ragged. Both the lines were scanned from the same paper sample and the same printing. This image was then processed into a B/W image to emphasize the edges of the lines.

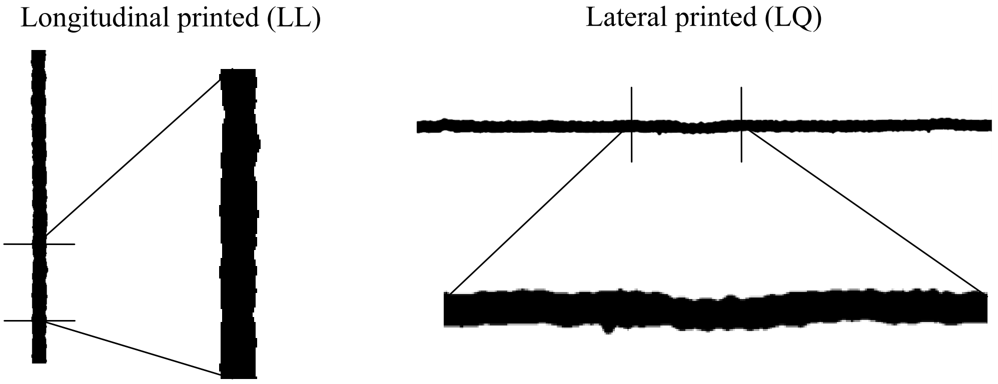


Figure 41 *B/W images of 1 px lines printed at the same speed, showing the difference in evenness / raggedness between longitudinal (LL) and lateral lines (LQ). The LL line is straight but slightly ragged. The LQ line is very ragged and also quite wavy.*

The print density was also affected by the printing speed but the difference between the two papers was greater, because the N4 liner showed a much higher print density than the N7 liner, but this was due to the wetting behaviour. In the results, it was assumed that the increase in dot diameter was a side effect, but this could not be confirmed because the drop size in fact decreased at high speed.

The LL lines showed a significant increase in line thickness with increasing speed, whereas the LQ lines, which should have been more affected, had an almost constant line thickness.

The quality of prints on fibre-based packaging boards is influenced by the printing speed and print mottle, print density and line sharpness are most affected. The effects of speed are visible, and at even higher speeds they might increase or new effects might emerge. This trial examined the runnability of inkjet on fibre-based packaging boards, but in a trial the practicality of printing bar codes, 2-D codes, should be studied or print quality should be assessed by a test panel.

All the print quality results in this study were, however, influenced more by the board properties than by the printing speed, which was expected considering the great difference between the two papers. The following chapter will therefore discuss the results for all nine board types.

5.2. Board grades

The printability and versatility of packaging boards was tested to see how different types and treatments influence the result. Surface roughness and wetting behaviour appeared to have the greatest influence on the print properties in high-speed inkjet printing. Nine papers were compared to see how the physical properties of the paper, e.g. surface roughness (Figure 42) and absorbency, influence the print quality.

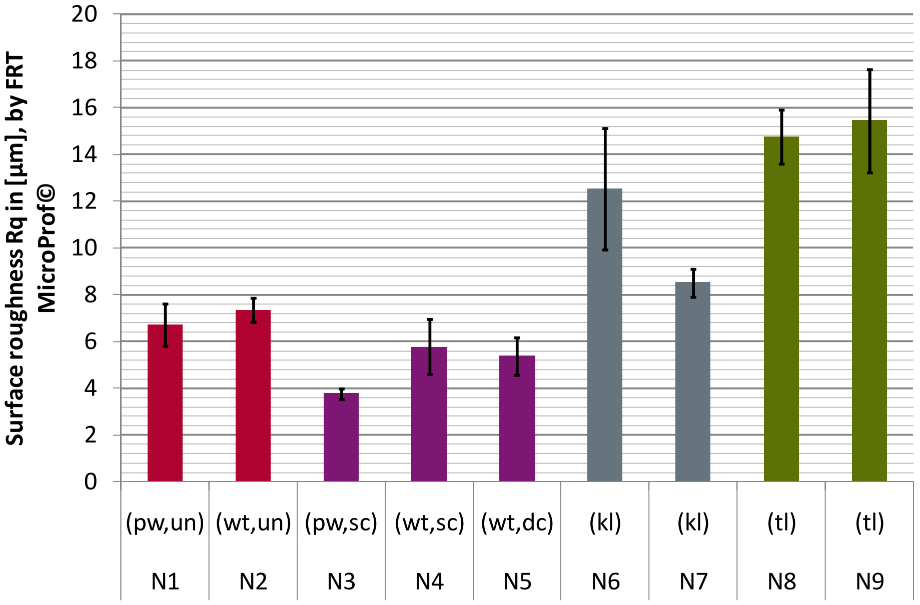


Figure 42 *Surface roughness values for all the papers in this test. Abbreviations pw= pure white, wt= white top, un= uncoated, sc= single coated, dc= double coated, kl=kraftliner and tl= testliner.*

The settings of the inkjet system were kept constant for all the papers, in order to make quantitative conclusions possible, but the consequence was that an excess of ink was transferred to the papers, causing very high print density values. Changes in the ink formulation and in the drop size would have been necessary to achieve optimal print quality on each paper.

The coated paper showed a higher print mottle (Figure 43) and larger dot diameter (Figure 44), but the printed dots and lines had perfectly sharp edges (Figure 45; N3-N5). The ink amount had less effect on the kraftliners and testliners, because these papers had a greater absorptivity, but the impact of the surface topography on the print was much greater. The uncoated white liners have been bleached and further treated to enhance print quality. In tests like line raggedness, they had almost the same quality as the coated papers, but in other tests the effect of the non-coated surface was evident.

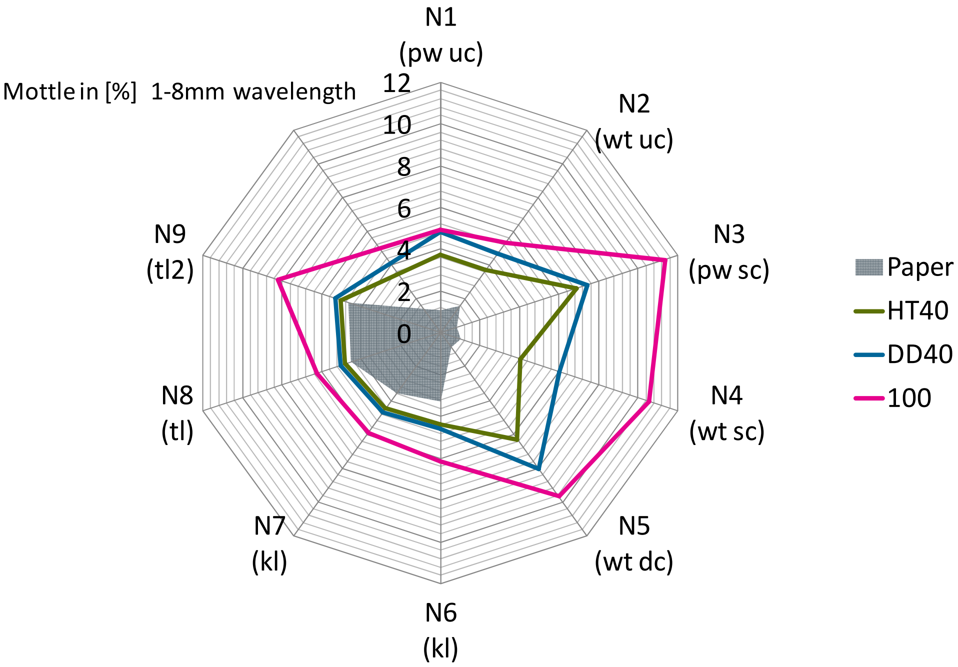


Figure 43 *Mottle in the wavelength range of 1-8 mm. Measurements on the plain paper, 40 % half-tone (HT40), 40 % diffused dither (DD40) and full-tone (100) areas.*

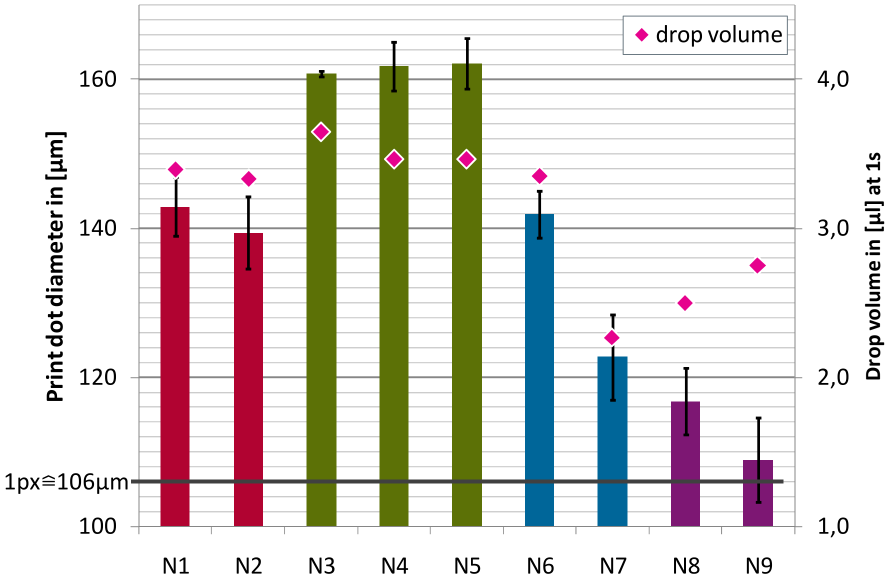


Figure 44 *Print dot diameter in the 10 % halftone area. The 1 px line indicates the target size of a single dot and the single points show the drop volume after 1 s in the absorbency test.*

Inkjet technology is in principle capable of achieving a quality similar to that given by conventional printing machines. The difficulty of achieving high resolution at high speeds is the only obstacle preventing inkjet technology from being used for high quality bulk production. Multiple single-pass heads including a very powerful RIP-system (raster image processor) would be necessary to achieve this (Haak, 2006), but such powerful systems are as yet available only for special purpose machines and they are too expensive for use in daily production.

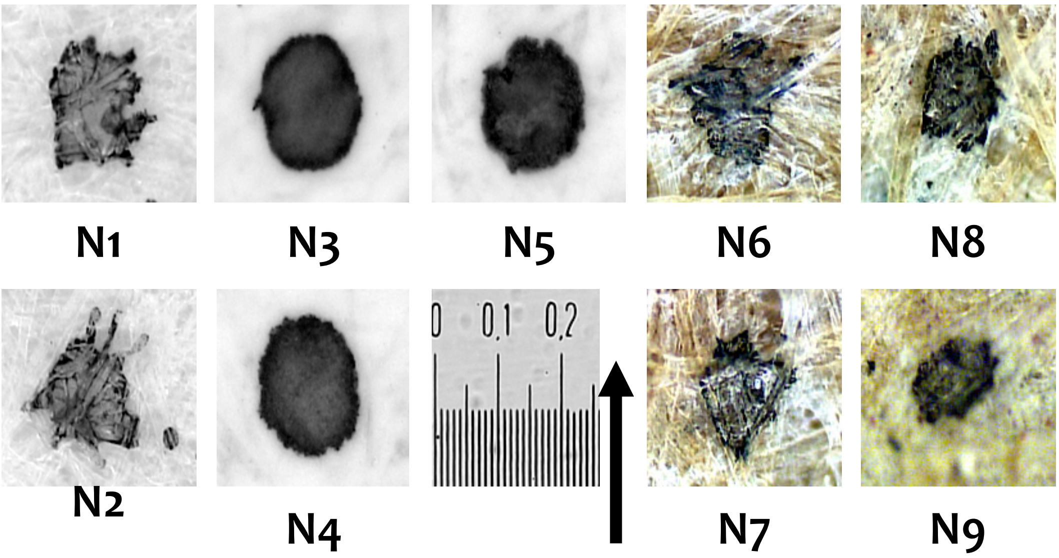


Figure 45 *Microscope images of single dots from the 10 % halftone on all the papers (image treated for better illustration). The arrow indicates the printing direction, which is the same as the paper fibre direction.*

SUMMARY OF PART THREE – MARKET SURVEY OF VDP

6

“5,000 people a day die because of dirty drinking water
1 billion people have no access to safe drinking water”

To show the possibilities of hybrid print in combination with printed VDP features on fibre-based packaging, a study entitled: “A market survey of Variable Data Print (VDP) on fibre-based packaging in North America and Europe.” was initiated. A questionnaire was made available in the internet to people in the development, marketing and decision-making sectors of the packaging industry (manufacturer, producer and print buyer). The goal was to draw an overview map covering people’s views on their market, trends in their fields and how they envision the future of VDP on fibre-based packaging. The complete structure of the survey, including the questions, is attached as an appendix.

In all, 42 persons from both the European and North American printing and packaging markets participated in this survey. To focus on certain groups and to draw more realistic conclusions, the analysis was done on the total and on the material split into two groupings, where the grouping “I” included the groups “supplier of machinery”, “producer of packaging print” and “other”, and the grouping ”X” included “inkjet”, “flexo”, “offset” and “converting (post-press)”. The distribution in each grouping is listed in Table 5.

Table 5 Proportions of participants in each group

Total: 42 participants			
Grouping “I” (all 42 participants)		**Grouping “X” (34 out of 42)**	
Group “supplier machinery	33,3%	Group “inkjet”	26%
Group “producer packaging print”	33,3%	Group “flexo”	12%
Group “others”	33,3%	Group “offset”	26%
		Group “converting (post-press)”	17%

On most questions, all these groups more or less agreed about VDP with inkjet implemented in the converting process of fibre-based packaging. Some questions, however, were seen differently by some groups, mostly due to their business interest. A crucial element is to start thinking locally because, with increasing VDP opportunities, its application on primary and / or secondary packaging will also increase according to the participants (Figure 46). This result can be seen not only in the total, but also in both groupings.

A factor which was considered not to be significant was the de-inking of inkjet-printed substrates (Figure 46). Nowadays, all environmental issues are very fragile topics and worldwide all companies have to consider detrimental influences on the environment. In the printing business, conventional printed substrates, e.g. with mineral or vegetable-oil ink (offset) or solvent-based ink (gravure), are relatively easy to de-ink by flotation, but water-based inks as used in inkjet printing are not. Compared to conventional printed papers, the percentage of inkjet-printed papers is, however, very little and would not significantly influence the waste from the de-inking units. It can therefore be assumed that, for this reason, the participants did not consider this issue to be significant.

It was considered that the implementation of inkjet “in-line” in the converting process is an important task. Otherwise it will be impossible to achieve large quantities where the static part is printed with conventional printing and the variable data part with inkjet. It is only a matter of time before this can be realized; single-pass inkjet units now print fast enough with sufficiently high resolution to be implemented in-line.

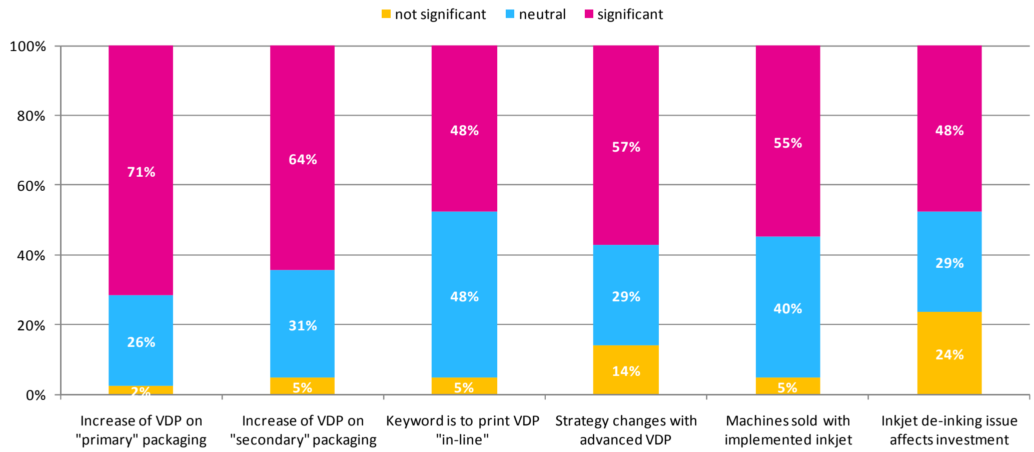


Figure 46 *The immediate future of inkjet and its applications (Table 6, question 7.1)*

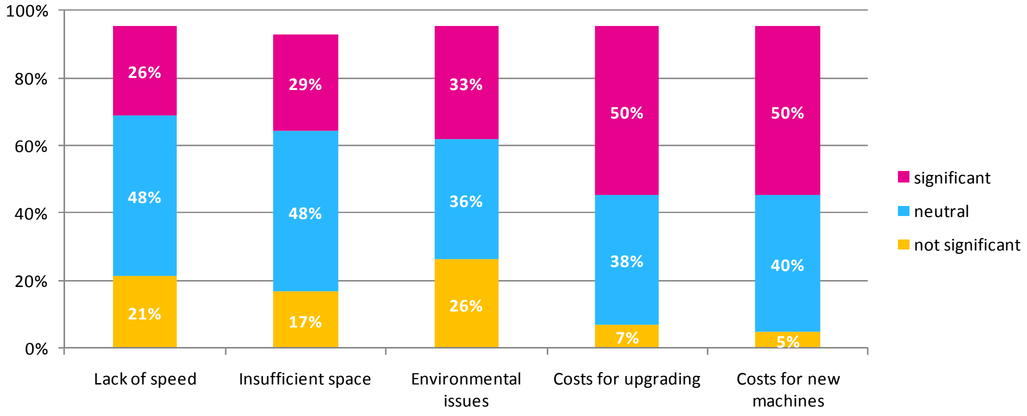


Figure 47 *The significance of technical and financial issues (Table 6, question 5.2).*

Costs are naturally a crucial factor, because investments in new machinery or upgrades of existing machinery are only made if the cost-benefit ratio is favourable. Upgrading existing machines is in most cases cheaper than investing in new machines and it is therefore important for inkjet to be an easy-to-integrate system (Figure 47).

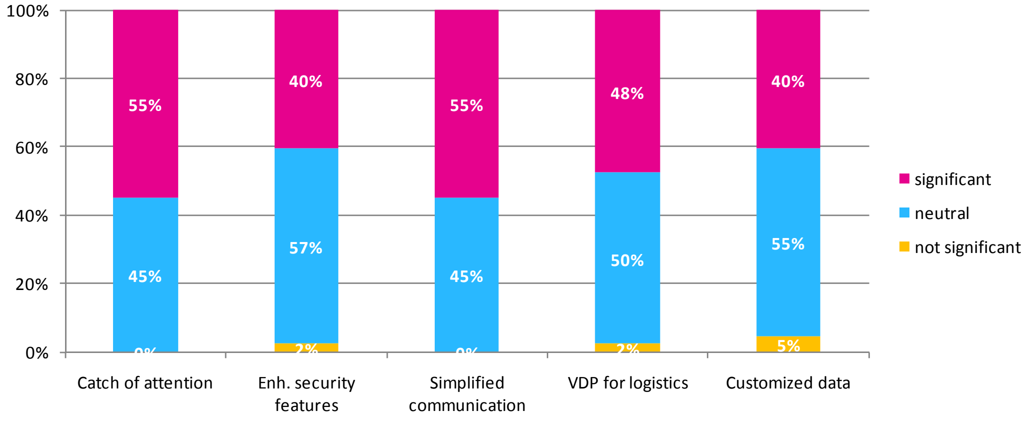


Figure 48 *The importance of practical VDP features (Table 6, question 6.1).*

The participants were also confronted with practical VDP features (Figure 48). Those considered most significant were catching the attention of the customer and simplifying the communication of information between product and consumer, providing as much information as possible in a short time period. Both shall persuade the consumer to buy this product and not the competing product next to it.

The VDP features mentioned and the future of inkjet and its applications were rated on average as being very significant, and all the participants were very positive regarding inkjet, its applications and VDP features. This was also true of each group in the grouping sections. It cannot be stated that the traditional printing industry with its conventional printing machines has a negative attitude. Inkjet technology must first prove itself and increase its technical capability, and the printing industry will then start investing more in this technology and its applications such as VDP.

7

CONCLUDING DISCUSSION

“Three quarters of fishing grounds are exhausted, depleted or in dangerous decline”

The “HybSpeed Printing” Project was a feasibility study to examine the combination of a conventional printing process with inkjet printing, in-line, in the converting process, and specifically to evaluate the practicability of attaining high quality variable data print (VDP) at high speed on a corrugated board substrate.

Tests in the laboratory and on a full-scale have been performed to study topographical effects on corrugated board liner during the production in the corrugator and their influence on the print quality. The micro-scale changes in surface roughness were examined and in both trials, it was possible to show evidence of the existence of surface impacts in the corrugated board production process. The surface roughness in the peak area was lower than the untreated reference and the valley area, in agreement with the study performed by Odeberg Glasenapp (2004b). The existence of surface roughness differences on a micro-scale between peaks and valleys was confirmed by several measurement methods.

The process step in the corrugator responsible for these changes in paper surface and thus causing paper-gloss is located in the double-backer. Therefore, counteractive measures should be discussed. Johansson et al. (1991, 1995) state that friction is an important parameter affecting the paper surface. Back (1991) mentioned that a low coefficient of friction of paper against metal is desirable in the corrugator, i.e. that highly polished metal surfaces are important. Changes in the design of the hot plates in the double-backer may contribute to a lower friction coefficient and so minimize the wear effect.

The change in surface roughness led to glossy stripes on the peak areas which were still visible after printing. Stripes in the print, whether they already exist on the surface of the substrate or are caused by the printing process, are one of the most disturbing print defects (Netz, 1996). Glossy stripes on the substrate shining through the print will, however, appear differently in flexo compared to inkjet.

The samples prepared in the laboratory showed print lightness and print density shifts. It was not possible to say whether these were due to surface roughness changes or to the washboarding effect. The coated samples in the full-scale test showed a paper-gloss effect, but after printing no colour change was detectable, only a minor print-gloss effect when viewing the samples at certain angles. This may be because the ink used was capable of forming an ink film layer on top of the surface of the paper, covering the micro-roughness of the matt regions and creating an almost homogeneous print-gloss appearance.

In both trials, laboratory and full-scale, on both substrate types, coated and uncoated, and using both printing methods, flexography and inkjet, the same trend was detected, but the print quality was affected less than expected. The difference between inkjet and flexography was, despite two different printing methods and two different ink types, very small and both showed the same trend in peak and valley areas.

The print defect due to the aspects of the production of the corrugated board will not affect the applicability of hybrid printing. Inkjet printing has an advantage compared to flexography, because it is non-impact technique and is therefore much less influenced by the corrugation of the board, and the print with inkjet will appear less stripy.

The second part of this thesis therefore focussed less on the surface topography changes due to the production processes and more on the substrate properties themselves. The high-speed printing set-up with the inkjet test-rig was used to test different liner grades, uncoated and coated, kraftliner and testliner, at different speeds. The results revealed that speed has an influence on the print quality, but that the print lightness (L^*) was not affected. Print mottle and print density showed slight differences at speeds up to 5 m/s, but at lower speeds the values were very similar. The feature most influenced by speed was the raggedness of the printed lines. At high speeds, the lateral printed lines in particular showed severe break-outs on the trailing edge. One explanation could be that the drop expelled from the inkjet head strikes the paper surface first with its tip and that, since the paper was moving at a speed of 5 m/s, the drop did not completely settle on the same spot. A testliner is, for example, very rough, and the ink drop is forced into the pits between the fibres, which act as channels for the ink.

The factor which has a far greater influence on print quality than speed is the paper type. Print mottle, print density and lightness L^* as well as area coverage and geometrical dot gain are very dependent on the surface roughness and absorbency characteristics of the paper. The high-speed test with a range of different papers was performed only with inkjet, but a similar outcome can be expected when printing the same papers with flexography. Speed, however, is the most important factor for in-line implementation of inkjet.

Both printing techniques seem to have similar prerequisites regarding the substrate and the effects on the print. Print differences, e.g. colour/ lightness shifts, which might appear in hybrid printing when using both printing techniques next to each other have not been examined in this thesis. Any continuation of the technical hybrid print study should examine this.

This study demonstrates that inkjet printing meets the requirements of hybrid printing with flexography on corrugated board. Inkjet printing units are available for use at the required speed and giving the required print resolution, and the development will continue towards better performance. The inkjet manufacturers together with the converting machinery producers will have to continue to examine the issues regarding the technical implementation of an inkjet unit. The aim of the inkjet print industry has to be: first to improve the printing performance in order to decrease the printing time and thus increase the printing speed and second to decrease costs per piece.

The position of the inkjet unit must be taken into account. The later an inkjet unit is implemented in the product packaging process the easier it is to minimize the waste production in the case of false printing and to achieve a faster reaction in the case of immediate changes. The latest possible location is the distribution or the point-of-sale (POS), but these locations are confronted with other troubles and an endless number of printing units would be required. The product-filling machines would be the best alternative to implement a digital printing unit.

The market survey showed that the printing industry has a great demand to be able to use variable data printing, but most of them are still waiting until the system has proved itself to be reliable and cost-effective. Many applications are thinkable, whether customized or personalized printing, where personalized printing requires the knowledge of the customer, and customized is only random printing. As soon as the printing industry starts using it, the initial costs for the units, the fixed costs and the variable costs will drop and more people will see the benefits of this technique.

8

FUTURE RESEARCH

“There may be at least 200 million climate refugees by 2050”

As been suggested in this thesis, more tests are required to examine the implementation of hybrid print in the converting process. A consideration of the following topics is suggested:

- Material study; flexographic ink, inkjet ink and paper
- Technology study; flexography and inkjet in hybrid printing
- Applicability study; implementation of an inkjet unit in the converting process

A greater focus on ink rheology and ink-substrate interaction could help towards understanding the effects when an ink-drop from the inkjet print-head strikes the surface. How do the absorbency characteristics of the paper influence the ink-drop setting? It would be also possible to record the behaviour during the setting with a high-speed camera from different angles to see how the ink drop spreads on the surface structure. The surface topography should also be examined before considering the ink-drop setting.

The technical study could be continued to see the difference between flexographic printing and inkjet printing when they are combined in hybrid printing, by printing samples first with flexography and including an image printed with an inkjet unit. The speed factor should also be considered. A suitable printing layout must be designed to test the implementation of hybrid printed elements, and a test rig should be constructed for printing at high speed, where samples pre-printed in flexography can be mounted.

Finally, the implementation of an inkjet unit in the converting process should be examined. The converting machine should have a constant speed which should not exceed the limit of the inkjet printing unit. Most suitable would be the rotary or flat-bed die-cutter, because the corrugated board is then still flat and even and the machine speed is not too high.

The need for the customisation and personalisation of printed packaging products is undeniable. Hybrid printing is facing a bright future but before it can be applied in useful way a number of issues remain to be solved.

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List of abbreviations

AFM	Atomic Force Microscopy
CB:	Corrugated board
CCD:	Charge-coupled device
CIJ:	Continuous inkjet
CLSM	Confocal Laser Scanning Microscopy
CMC:	Carboxymethyl cellulose
CRM:	Customer relationship management
CtP:	Computer-to-plate
CTP:	Computer-to-print
DAT:	Dynamic Contact Angle Tester
DD:	Diffused dither
DD40:	40 % diffused dither
DPC:	Digital Printing Centre
DTP:	Desktop publishing
HT:	Halftone
HT40:	40 % regular half-tone
LL:	Longitudinally printed lines
LQ:	Laterally printed lines
NCS:	Natural Color System
NIP:	Non-impact printing
OLED:	Organic Light Emitting Diodes
PIC:	Printhead Interface Controller
PIJ:	Piezo inkjet
POS:	Point-of-Sale
PPS:	Parker Print Surf
R1:	Raggedness-1
R2:	Raggedness-2
RIP:	Raster-image-processor
TIJ:	Thermal inkjet
VDP:	Variable data printing

Appendix

1. Structure of questionnaire (Part 3)

Table 6 Detailed structure of questionnaire beginning with part 4, including the questions with answers or instructions

4. Printing techniques

4.1. How familiar are you with printing and converting techniques and its technical and/or economic state-of-the-art possibilities?

a) Not so familiar, b) Quite familiar, c) Very familiar

4.2. Conventional printing techniques are very well developed within packaging print on fiber-based packaging. What is your opinion: will the new emerging inkjet technology be a competitor to conventional printing systems or will it complement them in the future?

a) It will complement, b) A competitor, c) Both, it will complement but is a competitor, d) Neither of the above

5. Converting process

5.1. Several locations are possible to implement an inkjet unit "in-line" in the converting process. Could you mark the most applicable location(s), which is/are in your opinion easy upgradeable with an inkjet unit and would NOT impact the production process.**

a) Conventional printing machine
b) Die-cutter
c) Folding-gluing machine
d) Packer (stacking and packing of finished packages)
e) Other unit (Please specify "Other unit")
f) It is NOT possible to implement

5.2. Implementation of an inkjet unit in the converting process of corrugated board or cardboard could raise technical and/or financial issues. Such issues could stop your company to invest in VDP. Please rate the following issues:*

a) Lack of speed
b) Insufficient space for integration
c) Environmental issues (e.g. dust)
d) Costs for upgrading existing machinery
e) Costs for new machines equipped with inkjet units
f) Other Issue (Please specify "Other issue")

6. VDP features

6.1. Could you rate the importance of the following VDP features printed on fiber-based packaging?*

a) Catch of attention of a consumer at the Point of-Sale (e.g. promotion campaign)
b) Enhanced security features (e.g. pharmaceutical products)
c) Simplified communication of information between product and consumers (e.g. customized info on packaging)
d) Variable data for logistics and distribution
e) Customized data to target consumers directly (e.g. consumers name on packaging)

6.2. Do you have 1 or 2 concrete packaging example(s) in your mind, where VDP features could be printed with a hybrid process? (hybrid process = combination of a conventional printing process with inkjet)

Examples and/or descriptions of applications can be written in two textboxes (A and B).

7. Future perspective

7.1. Please rate the following statements regarding the near future of inkjet and its applications in the packaging print of fiber-based packaging:*

a) The usage of VDP features on "primary" packaging will increase quite a lot with increasing opportunities
b) The usage of VDP features on "secondary" packaging will increase quite a lot with increasing opportunities
c) The keyword is to print VDP features "inline" in the converting process rather than off-line
d) Your companies strategy will change with more advanced VDP features
e) Conventional printing and converting machines will be sold with implemented inkjet units to print VDP features, f) De-inking of inkjet printed materials is still an issue and it will affect your decision to invest in inkjet technology

*Question is built-up as a matrix where the matrix row is mentioned above and the rating is done as follows:

Not significant, Less significant, Neutral, Quite significant, Extremely significant, N/A

**Multiple choices possible

Included Papers

Author's contribution

The thesis contains six Papers, all written mainly by the author of this thesis. The planning, execution and evaluation of trials described in Papers I to V have been done to a great part by the author. The author presented Papers I to IV and VI at the respective conferences. Astrid Odeberg Glasenapp was supportive with proof-reading of all six papers and partly in the planning and analysis of the trials. Per-Åke Johansson assisted with the analysis in Papers I to III and with the proof-reading of the Papers I to V. Mikael Gällstedt was the third proof-reader of Paper I. Jonas Örtegren supported the test described in Papers IV and V, and proof-read of Paper IV. Zhang Xiaofan evaluated the samples and summarized the results described in Papers IV and V. Valériane Vigne was supportive in the preparation and evaluation of the questionnaire, and proof-read Paper VI.

Paper I

Rehberger, M., Odeberg Glasenapp, A., Johansson, P.-Å. and Gällstedt, M. (2006) *Topographical micro changes of corrugated board liners induced by heat treatment and their effect on flexographic print quality.* In Advances in Printing and Media Technology: Proceedings of the 33rd International Research Conference of Iarigai, Leipzig, Germany.

Paper II

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Paper III

Rehberger, M., Odeberg Glasenapp, A. and Johansson, P.-Å. (2007) *Corrugated board production and its micro-scale impacts on the liner's topography*. In VIIIth Seminar in Graphic Arts, Pardubice, Czech Republic.

Paper IV

Rehberger, M., Odeberg Glasenapp, A. and Örtegren, J. (2010) *VDP on packaging – elementary velocity study on inkjet-printed papers for corrugated board production*. In 62nd Annual Technical Conference of TAGA, San Diego, California, USA.

Paper V

Rehberger, M., Odeberg Glasenapp, A., Xiaofan, Z. (2010) *VDP Quality aspects on fibre based packaging – an elementary print quality study on corrugated board.* Submitted to Journal of Print and Media Technology Research

Paper VI

Rehberger, M., Vigne, V. (2010) *A market survey about Variable Data Print (VDP) on fibre-based packaging in North America and Europe.* In Advances in Printing and Media Technology: Proceedings of the 37th International Research Conference of Iarigai, Montréal, Canada.

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(Ashley et al., 2003; Barros et al., 2005; I. R. Chalmers, 1997; Christoffersson, 2004; Davis, 2010; Ek et al., 2009; Jeon et al., 2004; Järnström et al., 2006; Löfgren, 2006; McLoone, 2007; Mejtoft, 2006a, 2006b; Moss et al., 1993; Nicolay, 2008; Norberg, 2006; Olsmats, 2002; Rehberger, 2004; Rehberger, Glasenapp et al., 2010; Rehberger, Odeberg-Glasenapp et al., 2010; Rehberger et al., 2006; Rentzhog, 2004; Santos et al., 2004; Ström et al., 2003; Vikman, 2004; Zang et al., 2001)