ABSTRACT

LI, XINGYU. Key Material Factors of Digital Printing on Textiles. Case: Pigment on Woven Polyester. (Under the direction of Nancy Powell and Dr. Stephen Michielsen).

Improved prepared for digital printing base materials or substrate fabrics contribute to the final product's qualities in meeting end use performance requirements. This research seeks to determine the key factors (materials and processes) that affect digital printing on textiles' qualities and to improve substrate fabrics for digital printing enhancements. Polyester samples developed in the laboratories of the College of Textiles and commercially available fabrics were analyzed and printed with the MS-JP5 Evo digital printer.

Physical properties of the fabrics were evaluated for dry and wet crock fastness, tensile strength, tear strength, seam strength and clarity of printed test patterns. Best practices in preparing polyester woven fabric for direct digital printing were explored. A print clarity quantitative test method was created. Funded by a multi-national retail corporation, this study in basecloth factors impacting digital printing will contribute to the quality and efficiency of digital printing as an innovative advance in manufacturing.

Following the analysis stage, industry interviews will be conducted in order to validate the contributing factors discovered in this research and reveal any new factors.

Key Material Factors of Digital Printing on Textiles. Case: Pigment on Woven Polyester

by
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DEDICATION

To my mother and father.

BIOGRAPHY

Xingyu Li came from Shanghai, China. She received an undergraduate degree in Textile Engineering from Donghua University, and then attended North Carolina State University in the fall of 2013. After completing her Master of Science degree in Textile Engineering, she decided to pursue a doctoral degree in Fiber and Polymer Science. Her research involved various key material factors of digital printing on textiles and was supported by the Walmart Innovation Fund.

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CHAPTER 1 INTRODUCTION

Improved substrate fabrics or prepared for digital printing base materials contribute to the final product's qualities in meeting end use performance requirements. This research seeks to determine the factors (materials and processes) that affect digitally printed textiles' quality and to improve substrate fabrics for digital printing enhancements.

1.1 Background

There are three main markets for printed goods: Apparel, including greige goods printing and made-up garment printing; interior fabrics such as bed linens, upholstery and window treatments; and technical textiles, which differ from the two previously mentioned categories; the print is added to the fabric for added performance rather than for decoration. In addition to these three categories printing is used for carpet and automotive interiors, labels for garments and for signage [47].

Over 80% of these printed textile productions are screen printed [30]. Since the textile print market is a swiftly changing market strongly affected by fashion trends, digital inkjet printing, a developing technology, stands out due to its capacity for quick response to changing trends and its faster and cost effective sampling process [47]. It is foreseen that the traditional flat and rotary screen printing and roller printing techniques may be superseded by digital printing technologies [30].

Digital technology has evolved printing to a process of customized, quick turn-around, short production runs, while meeting high performance standards, especially for durability of materials in extreme conditions. Providing these advantages to the market is a challenge for manufacturers along the value chain, both in the chemistry, machinery and processing. Digital printing is positioned to address these demands but the selection of substrate fabrics appropriate to the application requirements may be a strong component determining finished quality and efficient processing.

Competitive products in home furnishings and the technical and industrial fabrics' markets use flat woven fabrics to meet the demanding performance and aesthetic expectations of the consumer. Many of the woven fabrics manufactured to meet industry and retail corporations' specifications, are imported fabrics woven with a combination of spun and filament polyester yarns, approximately 54-58" in width. There are multiple facilities for weaving synthetic flat woven materials in the southeastern region of the U.S. in small and large-scale production plants, especially in support of the home furnishings market and the technical and industrial fabrics' markets centered in the Carolina's.

To meet the requirement of the expanding digital textile print market, it's critical to understand which factors impact the finished products and to improve substrate fabrics specifically for digital printing.

In order to understand the existing product value and examine the factors affecting digitally printed textile products, the "voice of the customer" for furnishings fabric product was determined and organized in Table 1.1 according to the supply chain links. This initial list was based on published research and discussions with multinational retail corporation personnel, and industry experts.

Table 1.1 Analysis of Customer Needs

Customers	Durable	Affordable Low Price	Attractive Fashionable	Choice of styles	Stain Resistant	Water Resistant	Mold & Mildew resistant	Available for several seasons	Custom Order on line/website	Production Available in Stores	Cost
Multinational Retail Corporation	●	●	●	●	●	●	●	●	○	●	●
Supplier	●	●	○	°	○	○	○	○	○	●	●
Retail Consumers	●	●	●	●	○	○	○	●	○	●	➢
Other Retailers	●	●	●	●	○	○	○	○	○	●	●
INTERNAL											
Print	➢	➢	➢	○	➢	○	➢	➢	➢	➢	●
Cut & Sew	➢	➢	➢	○	➢	➢	➢	➢	➢	➢	●

Legend	
●	Very Important
○	Somewhat Important
➢	Not Important

The initial information gathered revealed that the product development team has several different "customers" to satisfy. The end consumer will have perceptions of the value of the product in meeting their needs, regardless of the manufacturing processes. The multinational retail corporation will have corporate goals and expectations from their supplier of the finished goods. The manufacturer will have requirements based on their production processes and the parameters of the raw materials suppliers.

An understanding of the priorities for each of these three major customers is helpful in determining how to approach the development of the optimum print substrate and would include competitive benchmarking and industry standards. The initial requirements were listed and the relationship to the engineering actions to fulfill the expectations were considered. For example, to meet the requirements of each of the supply chain participants and the consumer, durability is an important factor which is affected by fabric weight, fabric construction, pick level, yarn quality and so on.

Figure 1.1 is a cause and effect diagram which introduces many of the factors which will affect the print quality.

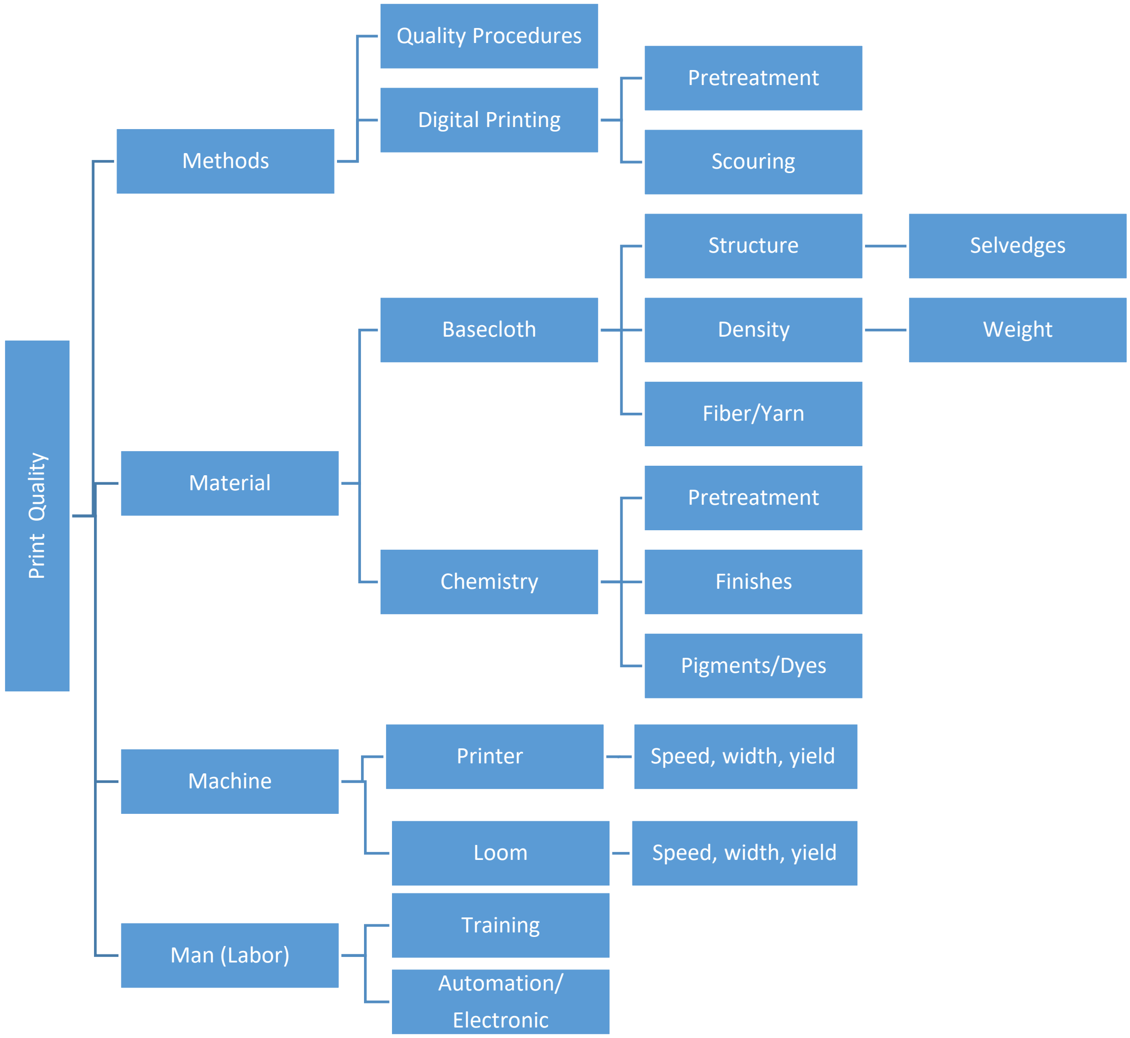


Figure 1.1 Cause and Effect diagram considering factors affecting print quality for a digitally printed home furnishings product

An environmental scan of the domestic suppliers of raw materials, fabric formation/weavers, and finishers was conducted. Observation and discussions with treatment chemists, dyestuff and ink producers, printers and fiber and yarn producers, and weavers provided a better understanding of requirements, processing methods and sources for current materials, issues and practices in digital printing substrates, particularly woven polyester.

CHAPTER 2 LITERATURE REVIEW

A digital printer can print on a wide range of substrates such as paper, plastic, canvas etc. Optimizing the print substrates, specifically in the requirements for digital printing, are essential to the finished quality of the product.

To improve the substrate for digital printing, especially polyester woven fabric, it’s critical to understand yarn and fabric formation. The following literature review will explain fiber and yarn’s contribution to woven fabric, and key factors of materials and processes that affect the qualities of digitally printed textiles.

2.1 Yarn and fabric formation

2.1.1 Polyester Fiber

According to research published in 2004 by DuPont, cotton is the most commonly printed substrate (48% of printing production), following by cotton/polyester blends (19%), polyester (15%), and viscose (13%). From a worldwide perspective, other substrates such as polyamide, polyacrylic, wool and silk, play just a minor role [28].

Much has been written about cotton substrates for all types of printing. However, a relative gap in the literature exists concerning polyester substrates for printing, especially for digital inkjet printing. As polyester is the second most used fiber after cotton and far ahead of other synthetics in various applications, especially for home furnishings and upholstery, it is critical to understand the characteristics of polyester substrates for digital inkjet printing.

Polyester yarn was studied in this research because of its availability, relatively inexpensive price, excellent UV degradation resistance, good abrasion resistance, high tear strength, resistance to mildew, low water absorbency, cleans easily, crease resistance [52], etc.

The continuous growth in production of polyester textile fibers in the world is due to this quality and the attractive performance properties to a significant degree [8]. Its very low moisture absorbency, resilience and good dimensional stability are additional qualities that are better than other man-made fibers.

Polyester is used in the manufacture of many products, including home furnishings, industrial fabrics, automotive and clothing. Polyester has several advantages over traditional fabrics such as cotton. It's very stable and strong and does not absorb moisture, but does absorb oil; this quality makes polyester the perfect fabric for the application of water-, soil-, and fire-resistant finishes. Its low absorbency also makes it naturally resistant to stains. Polyester fabric is also easy to dye, and not damaged by mildew. All these properties make polyester an appropriate base fabric for printing for high performance applications.

Polyester fibers were first produced in a series of stages: first by polymerization and collection of polymer chips, then by melt extrusion to produce unoriented fiber, followed by drawing to orient the structure. The main variable was the degree of orientation, though subtle changes could be achieved by heat treatments. Advances in engineering led to a progressive integration of the steps[8]. Polymer is fed directly to extrusion and drawing occurred before wind-up. A more significant change was the use of high wind-up speeds, which led to crystallization by tilting the competition between molecular alignment due to attenuation of the molten thread line and randomization by relaxation [8].

Shrinkage of Polyester Fibers

Shrinkage is generally defined as an irreversible shortening of fiber length. Fibers tend to shrink by the effect of raised temperatures in the atmosphere, in water or in another medium. Shrinkage in fibers, yarns and fabrics can be determined by a great number of different factors in which the changes in length after contraction are measured under defined conditions [7].

An entropic retraction is caused by shrinkage or shrinkage stress. When the internal energy of an oriented polymer is released by a rise in ambient temperature, polymer molecules tend to relax the orientation by retracting from an ordered, extended conformation to a disordered, random coil. This eventually produces a change of length or contraction force [16].

In polyester fibers two basic contraction mechanisms leading to macroscopic shrinkage can be distinguished: amorphous and crystalline contractions. The amorphous phase in drawn polyester fibers that have not yet been thermally treated comprises more than 90% of the volume. Amorphous phase consists of a "frozen" physical network with chain entanglements forming knots in it. When heated above the glass transition temperature (for amorphous polyester it is about 70°C in a dry condition and 50 °C when wet), the mobility of the physical network is released. The result is an amorphous contraction in which the individual chains in the network take up a steric configuration which is energetically the most convenient for them. But simultaneously crystallization takes place [17] . Oriented polyester fibers have half-time of crystallization shorter than 0.01 s. Complete shrinkage is therefore obtained by shock heating only.

"Amorphous" shrinkage takes place only partially in semicrystalline polyester fibers. The amount of shrinkage is determined by the orientation in the amorphous phase and the mean relative molecular mass of the polymer. Amorphous shrinkage can occur at low temperatures, which less than 100°C only [17].

Excessive shrinkage of textiles containing synthetic fibers may be removed by heat-setting. By this means the crystalline phase is "improved" by recrystallization, which is connected with conformation changes to the chain in amorphous regions under defined external geometrical proportions. According to Shrinkage Rate of Polyester for Membrane Applications, “when the fiber is allowed to shrink during heat-setting, there are no external constraints to structural reorganization and a significant part of the residual stresses present in the non-heated drawn yarns relax. When the polyester is held at a constant length, a shrinkage force develops and only a part of the residual stresses is able to relax through limited structural reorganization. In oriented polyester yarns shrinkage is a function of the product of amorphous volume fraction and amorphous orientation factor” [17] .

2.1.2 Yarn Characteristics

Yarn is a basic component in a woven fabric, which contributes to the characteristics of the basecloth for digital inkjet printing. Yarns are classified into staple fiber yarn and filament yarn.

Staple Fiber Yarn

Staple, or spun, yarn is produced from short-length fibers called staple [11]. Man-made fibers, such as polyester, can be cut into short lengths and spun together to create staple spun yarns.

Staple yarn can be classified into three kinds of yarns by the types of spinning.

1. Ring Spinning

Ring spinning is currently the most widely used yarn production method. Initially developed in America in the 1830s, its popularity has survived the emergence of much faster spinning technologies. In addition to the superior yarn quality, ring spinning is extremely versatile. It is capable of producing yarns with wide ranges of linear density and twist from a great variety of fiber materials. It is also used for doubling and twisting multifold and cabled yarns [11].

2. Air-Jet spinning

DuPont first introduced air-jet spinning technology in 1963, but it has only been made commercially successful by Murata since 1980. DuPont used only one jet, which produced a low strength yarn. The Murata system has two opposing air-jets, which improves the yarn strength [11].

3. Open-end spinning

During the 1960s, open-end spinning was one of the new methods proposed to overcome speed and power consumption problems in the ring spinning method for yarn spinning technology. This method separates the yarn twisting action and winding action, and rotates the package winding action at the relatively low winding speed, which can create yarn without using a spindle [14].

Filament Yarn

A filament yarn is made from one or more continuous strands called filaments where each component filament runs the whole length of the yarn. Those yarns composed of one filament are called monofilament yarns, and those containing more filaments are known as multifilament yarns [11].

A higher filament count will typically increase cost, bulk, apparent thickness, snagging potential, potential warmth, and provide a more absorbent surface and more similarity to spun yarn.

Texturing is a process which can modify flat continuous yarn to give bulk and additional stretch to filament yarns, and meanwhile can add more cost, apparent thickness, increase snagging potential and potential warmth and provide a more absorbent surface [11].

Sizing

In the textile industry, yarns such as cotton and spun polyester are frequently sized before warping and converting into woven fabrics. It is an essential process to coat warp yarns with size to bind the fibers of yarns to reduce fluff or hairiness so that yarns may be strong and resist the mechanical stress in the weaving process, and maintain or improve weaving efficiency.

The sizing process consists of depositing an amount of size onto the yarn sufficient to affect the desired results. Yarns are sized in order to increase their tensile strength and to reduce the yarn-to-metal coefficient of friction as well. A stronger yarn is desirable in order to minimize breakage in subsequent textile operations especially as a warp yarn in weaving. A low strength results in breakage which causes interruption of the weaving operation, reduces efficiency and increases costs, also affect the resulting quality of the fabric. A low yarn-to-metal coefficient of friction is desirable in order to minimize yarn and machine wear [9].

Many types of sizing agents have been used. Polyvinyl alcohol is widely applied as a size for synthetic yarns such as polyamides (nylon); acrylic fibers such as polyacrylonitrile; and polyesters such as polyethylene terephthalate [9].

Although sizing is necessary and enhances performance quite well, it may interfere with subsequent finishing steps and must be removed, which is called desizing, before these finishing steps can be carried out. These subsequent finishing steps include bleaching, dyeing, printing, and permanent press finishes, etc. In this case, scouring, to remove the size on fabrics, is a very important process before printing. Scouring is a deep cleaning of fabrics to help provide good penetration and assure even color of digital inkjet printing.

2.1.3 Woven Fabric Formation

Weaving equipment

The looms manufacturing woven fabric are generally classified as shuttle and shuttleless looms. The shuttle loom weaves a fabric by passing the shuttle (bobbin wrapped with weft yarn) through the warp shed. The weaving steps are seen in Figure 2.1 below [12].

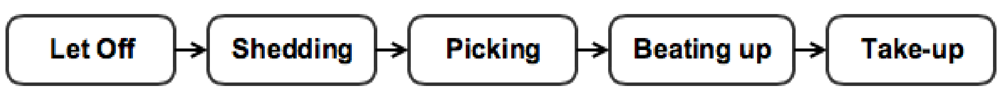


Figure 2.1 Weaving steps for a shuttle loom [12]

The warp sheet yarns are separated by raising one or more harnesses in a dobby loom for the shedding action, and the filling yarn is inserted by passing the shuttle though the shed in picking. Then, this weft yarn inserted across the warp sheet is beat up or pressed into the fell of the cloth using the reed in beating up as seen in Figure 2.2. In take-up, the fabric is wound onto the cloth or fabric beam. As the fabric is woven the warp is advanced by the let off of the warp beam.

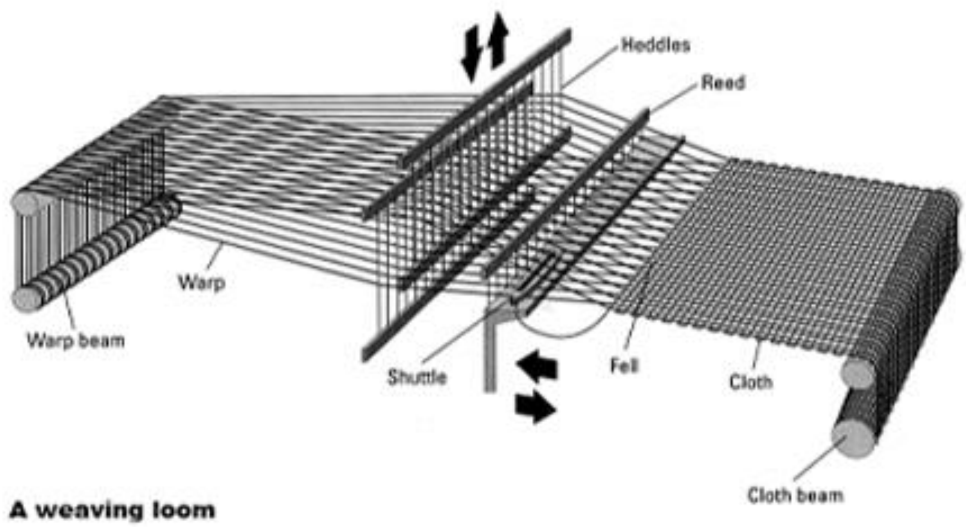


Figure 2.2 Weaving loom [48]

For the shuttle loom, four harnesses are the most commonly utilized to produce the basic woven fabric. However, this loom has limitations as a more complicated pattern could require more than six harnesses. In addition, the shuttle loom creates noise and has a relatively slow speed in production. For this reason, shuttleless looms which use an alternative method of filling insertion such as air-jet, rapier, and water-jet are currently more common for manufacturing woven fabric as described below [12]:

The air-jet loom passes the filling yarn through the shed using the air provided by a narrow jet of air. Thousands of meters of the filling yarn can be inserted per minute if the yarn is not bulky and heavy. And, 157 inches of warp width is available for weaving [12].

A rapier loom is a shuttleless weaving loom which has rigid or flexible sword-like carriers called rapiers which pass the yarn through the shed: it can insert the filling yarn up to 1,000 picks per minute. This loom mainly weaves basic cotton and fabrics using spun yarn.

Water-jet looms weave fabric using a high-pressure jet of water to insert the filling yarn across the warp yarn. Since this loom is manufacturing the fabric in a wet environment, water resistant sizing is required for the warp yarn. For this wet process, only hydrophobic nylon or polyester filament yarn is used. Additionally, the fabric width is limited in manufacturing with the water-jet loom.

Compared to the shuttle loom, the shuttleless loom increases manufacturing productivity and efficiency. In producing a basecloth for digital printing, the most appropriate loom needs to be selected with consideration of the loom’s capabilities related to preferred yarn and fabric construction types and required widths of fabrics.

Cam and Dobby shedding mechanisms

Cam and dobby shedding are the most commonly used mechanisms in weaving a fabric. These shedding mechanisms lift or lower the shaft or harnesses to create two layers of the warp yarns. For warp separation, the cam shedding utilizes the lifting plan to control harnesses. This cam shedding is simple to use, however, the number of harnesses controlled by cam shedding is limited. On the other hand, the dobby shedding can produce woven fabric with more complicated pattern designs. The characteristics of the cam and dobby shedding in Table 2.1 show their repeat length and number of harnesses. In cam shedding, the maximum practical number of filling picks is limited to 8 picks to the repeat.

Compared to cam shedding, dobby shedding provides much higher repeat lengths and uses a varied number of harnesses for manufacturing more complicated designs in woven fabric [1].

Table 2.1 Characteristics of cam and dobby shedding mechanism [1]

Shedding mechanisms	Repeat length	No. of harnesses
Cam:		
Positive cam motion	up to 8 picks	12
Negative cam motion		
Dobby:		
Positive mechanical dobby	6000 picks	28
Negative mechanical dobby	150 picks	19
Mechanical rotary dobby	4700 picks	28
Electronic negative dobby	6400 picks	16
Electronic rotary dobby	6400 picks	28

Weave structure (Fabric Construction)

Woven fabric is constructed through the interlacing of warp and weft yarns in two different directions: vertical direction for warp yarn and horizontal direction for weft yarn. There are three basic weave structures in woven fabric: plain, twill, and satin, as shown in Figure 2.3 images created by EAT DesignScope Victor® below.

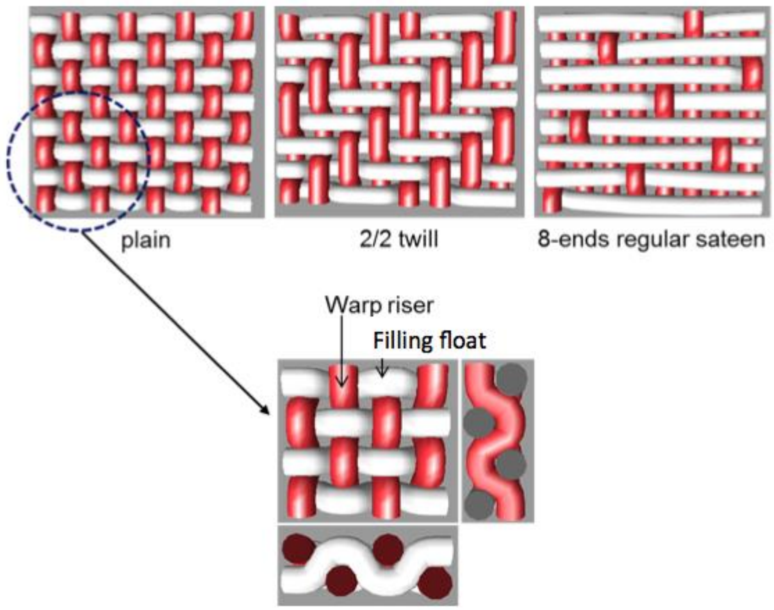


Figure 2.3 Basic weave structure simulations (EAT DesignScope Victor®)

When warp and weft yarns are interlaced, yarns deform into a wavy shape instead of a completely straight yarn. As a result, the actual length of yarns in the fabric is longer than fabric width and length. The shortening of yarn length in woven fabric is known as crimp [49]. Its calculation is:

Yarn Crimp% = $\frac{(Straigten\ yarn\ length - Yarn\ length\ in\ fabric)\times 100}{Fabric\ length}$

Crimp in woven fabric depends on yarn size, yarn density and fabric construction.

Warp crimp percentage is used to decide the required total length of yarn to be placed on to a warp beam to weave a specified length of fabric.

Each weave structure is determined by the float of a weft yarn passing over or under a warp yarn. These basic weave structures can be extended into the advanced weave structures such as basket, warp rib, weft rib, and 3/3, 1/4, or 3/1 twill [2, 4] Examples of advanced weave structures are shown in Figure 2.4.

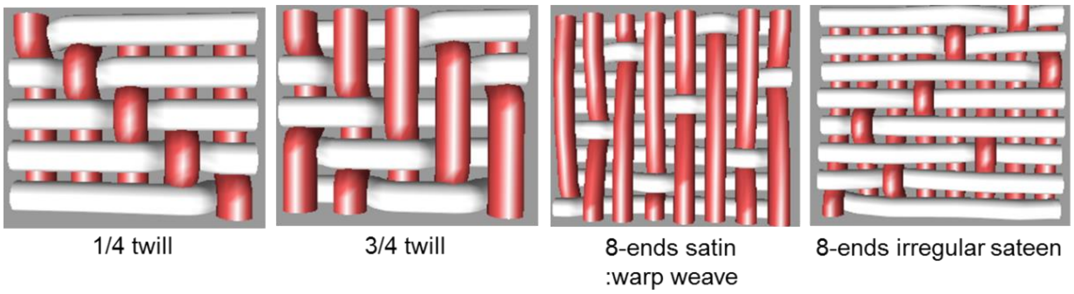


Figure 2.4 3D images of advanced weave structures (EAT DesignScope Victor®)

Plain weave or a derivation of plain weave provides an even, consistent surface for printing quality, meets the performance characteristics for digital inkjet printing, and is created through an efficient manufacturing process.

Fabric density & cover factor

The density of a woven fabric is determined by ends per inch (epi) and picks per inch (ppi) per unit length (inch or centimeter): vertical and horizontal directions respectively. The more warp or weft yarns are interlaced in a unit length of a weave structure, the resulting woven fabric will have a higher density. As the fabric density increases, the yarns will become more tightly packed. This fabric density is also characterized by the cover factor, K, which indicates the area covered by yarns relatively to the total area of woven fabric. The cover factor of woven fabric, K_F, is expressed using K_e and K_p. as seen in the equation below: [3]

$$K_F = K_e + K_p - \frac{K_e \cdot K_p}{28}$$

where,

$$K_F = 28C_F \tag{1}$$

$$K_e = 28C_e = 28\left(\frac{2R_e}{p_e}\right)$$

$$K_p = 28C_p = 28\left(\frac{2R_p}{p_p}\right)$$

The cover factor, K, with suffix e or p is the covered area by warp yarn (e) or weft yarn (p), which is characterized by warp or weft yarn diameter, $2R$, and warp or weft yarn spacing P. The cover factors of warp and weft yarns are also used as an indicator in determining woven fabric's weaveability as shown in the figure below [21].

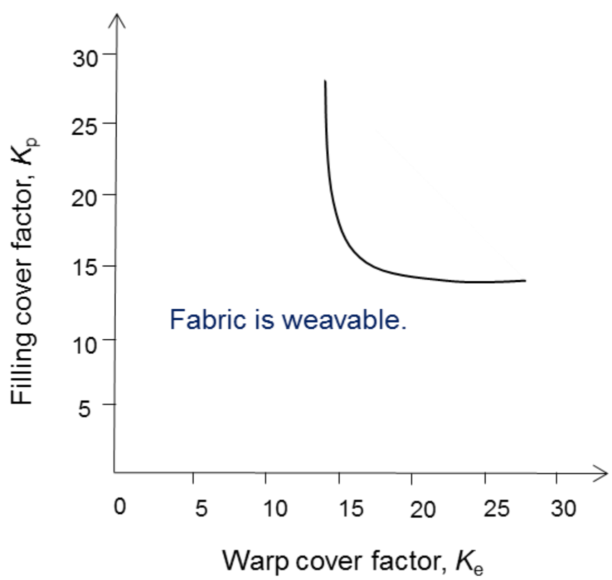


Figure 2.5 Peirce's graph for fabric's weaveability [21]

The fabric density and cover factor have a proportional relationship with fabric weight: the higher fabric density and cover factor will lead to higher fabric weight. This fabric density will be also affected by yarn size: the larger yarn will result in the higher fabric density for a given weave structure with the same epi and ppi. The fabric density, cover factor, and fabric weight as well as weave structure are interrelated in determining the woven properties such as air permeability, durability, and wet or dry crocking of a base cloth. These characteristics of woven fabrics also have impacts on digital inkjet printing on textiles. It will be studied in this research.

2.1.4 Woven Fabric's Durability

Woven fabric's durability is impacted by fabric density, fabric weight, weave structure, yarn structure, and fiber properties. Especially, fabric density is critical in determining the woven fabric's strength through differing picks or ends per inch in a warp or weft direction. If the warp and weft yarns are interlaced more for a given weave structure, the fibers in the woven fabric will have higher fiber binding. This fiber binding effect will be important in increasing the tensile strength of woven fabric. Amongst basic weave structures such as plain, twill, or satin, a plain structure possesses the highest intersections of warp and weft yarns. The higher number of intersections in a plain weave structure creates more crimp in the warp yarns, contributing to the enhancement of the fiber binding effect. However, the fabric strength can be weakened by the warp crimp when the warp and weft yarns are too closely interlaced in a plain weave structure [24]. Therefore, it is important to determine an appropriate fabric density maximizing the woven fabric's tensile strength.

If the yarn is twisted, the fiber binding in a yarn structure can be enhanced. The yarn twist (tpi) and irregularity help the yarns to hold the neighboring yarn more effectively and strongly [24]. According to the study by Pail et al. [20], the fiber binding is a primary factor for the shear resistance of woven fabric. Also, this study explained the relation between yarn movement and shear strength. It is pointed out that the yarn movement in shearing deformation can cause low shear strength and greater breaking elongation even in the case that this woven fabric shows high strength and low breaking elongation in tensile strength. This means that strong fiber binding should be considered most importantly in yarn formation to enhance the fabric's durability in regards to the physical and mechanical properties of woven fabric. It would also be critical in the durability of a substrate and in particular in printing for ink/disperse dye penetration and image clarity, leading to the quality and appearance of the final printed product. On the other hand, tear strength of woven fabric is related to yarn's mobility for a given weave structure. When a woven fabric is distorted as seen in Figure 2.6, yarn slips and is moved to the Del Zone. And, as the yarn increases in the Del zone, the tear strength of the woven fabric will become stronger. In a weave structure, loosely constructed woven fabric will obtain higher yarn mobility through creating larger spaces between yarns where the yarns can easily move around. Thus, twill or sateen weave structure shows higher tear strength than plain because twill or sateen has longer float lengths compared to plain, and this long float length increases the yarn's mobility in the low intersection of warp and weft yarns [23, 24].

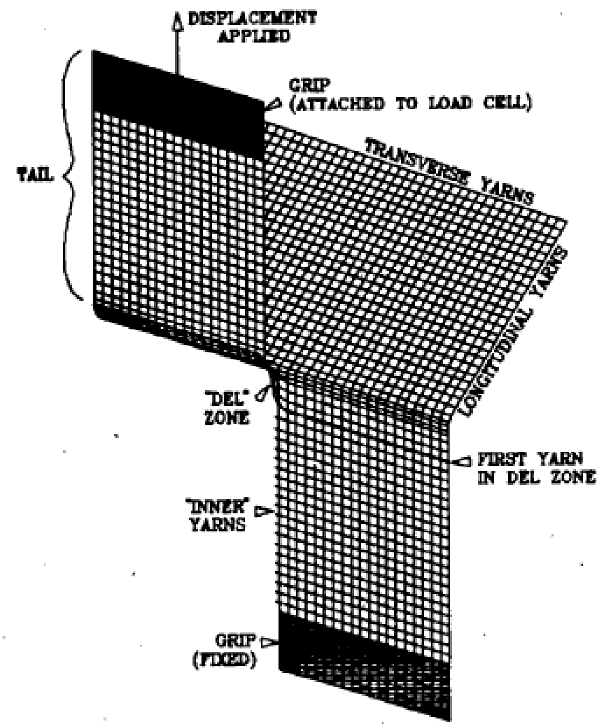


Figure 2.6 Schematic of woven fabric's tear testing [24]

2.2 Digital Inkjet Printing on Textiles

In the previous section, fiber, yarn and fabric formation were reviewed. Each of these technologies have been advanced by digitization. Traditional printing advances will be addressed in this section as electronic control of processes will have major impacts on manufacturing.

"Digital printing on textiles, also known as inkjet printing, is a generic technology that primarily uses, but not limited to, dye formulated as "ink". Digital printing is highly adaptable, both within what it can do as a technology as well as the uses to which this generic technology can be applied. Digital printing can be applied to a wide range of different processes and purposes, from the batch coding of soft drink cans to 3D printing for rapid prototyping in product design" [5].

Ink jet technology was first developed by Lord Kelvin in 1867 using an electric field & capillary tube. Milliken and Company developed the air-valve deflection continuous ink jet system (Milliken) for carpet printing in 1975 [28]. In the 1990s, textile digital printing emerged as a prototyping tool and a vehicle for printing small batches of fabric for niche market products and for producing advertising materials such as flags and banners [29]. Much of printing with disperse inks to meet performance on synthetic banners is through indirect printing on paper for heat transfer printing.

Ink jet printers are supplied with up to eight different inks from individual ink reservoirs [22]. The eight colors are based on cyan, magenta, yellow, and black (CMYK) complemented by other colors. The merging of the colored ink droplets occurs on the pretreated textile surface forming the process colors in the design image. Some limitations on the color gamut obtainable are imposed by the use of process colors in ink jet printing compared with the spot colors used in conventional screen printing of textiles. The spot colors are prepared by premixing the colors in advance of screen printing [11].

The ink properties are optimized in order to generate high operating performance in specific print heads. The water-soluble organic solvents and surfactants are present to control the ink viscosity and surface tension as well as the absorption speed of the ink on the pretreated textile substrate [27].

Pigment printing accounts for almost half of all printed textiles produced worldwide and are, therefore, an important coloration system [31].
Pigmented ink formulations depend on the print head type and the ink viscosity required [26]. Pigment inks have thus been prepared either without a textile binder or with a conventional or an unconventional textile binder. A typical pigment ink formulation contains finely dispersed pigment particles, a polymeric binder, water, cosolvent, surfactants, humectants, an antifoam agent, a viscosity control agent, a biocide to prevent spoilage, and a penetrant to speed drying on textile materials. The particle size and size distribution of the pigment affects the image quality, particularly color density, and influences the settling of the pigment in the ink, the colloidal stability, and clogging of the jet nozzles and thus can impact jetting reliability [11, 27].

2.2.1 Comparison between Digital Inkjet Printing and Conventional Printing

Although screen printing is still the most dominant process for over 80% of printed textile production, due to the rapidly proceeding application of digital inkjet printing on textiles, it is foreseen that the traditional flat and rotary screen printing and roller printing techniques may be superseded by digital printing technologies [30]. According to the Global Printed Textile Industry Report (2004), textile printing production was forecasted to change from a few major textile mills to many small digital textile printing [28].

The digital ink-jet printing technique stands out for benefits like speed, flexibility, creativity, cleanliness, competitiveness and also eco-friendliness. Conventional and digital inkjet printing are compared in Table 2.2 showing a comparison of different printing methods with digital inkjet printing in technical terms [31].

Table 2.2 Comparison of technical details of conventional printing methods with digital inkjet printing [31]

Printing Operation	Flat screen printing	Roller printing	Rotary screen printing	Heat transfer printing	Digital ink-jet printing
Squeegee	Moving to and fro	No squeegee system	Continuous rotating	No squeegee system	No squeegee system
Fabric motion	Intermittent motion	Continuous	Continuous	Intermittent or continuous	Intermittent or continuous
Screen movement	Lifting and lowering	No screen system	Rotary	No Screen system	No screen system
Colour supply	By hand	By hand	Automatic	No colour supply	Automatic
Design and effect	Fine design, no half tone effect and continuous strip	Very fine design, half tone effect, no horizontal line and no large design repeat	No fine design, has half tone effect and continuous strip possible	Varied	Varied
Types of fabric suitable	Not for knitted fabric	Not for knitted fabric	Knitted and woven fabric	Mainly for polyester	Mainly for woven fabric, cotton and polyester
Sampling	Easy	Difficult	Difficult	Easy	Easy
Engraving cost	Relative lower	Expensive	Expensive	Varied	Low

For long runs, analog printing technology like rotary printing is fast (30 – 70 m/minute), continuous and economical. The color gamut is wide and no special pretreatment of fabric is required before printing [33].

For short runs, however, conventional printing types are not economical due to high downtimes, high wastage of fabric and inks, high engraving cost, high labor costs and cost of time spent on color-matching, paste making, sampling, design, registration, etc. Operations like screen engraving, print washing, and screen washing add significantly to the pollution load as well as maintaining an inventory of screens, and replacement or repair of screens [33]. Design sampling or printing strike offs is particularly a very lengthy and expensive process as shown in Figure 2.7.

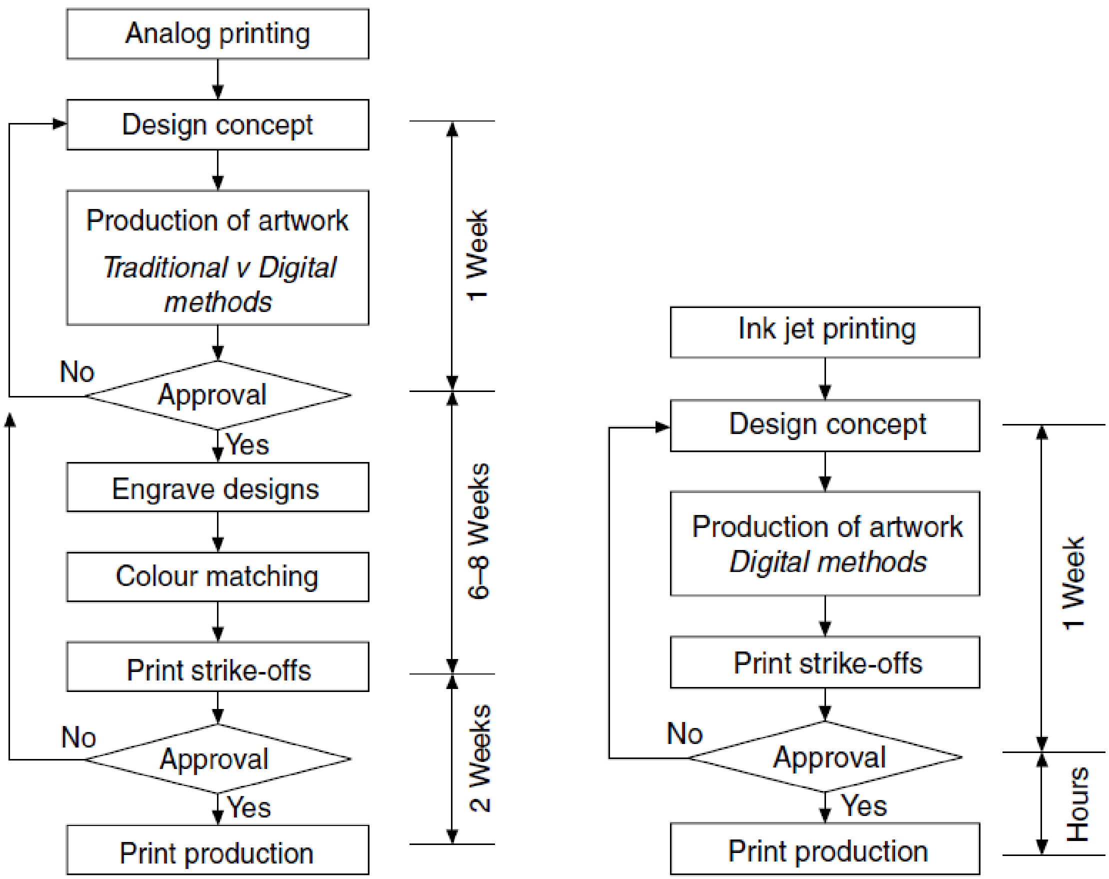


Figure 2.7 Production Process of Conventional Printing (Left) vs. Digital Ink-jet Printing (right) [32]

Digital inkjet printing, therefore, offers distinct advantages for short runs, sampling and proofing. There are no screens so that all costs pertaining to screen engraving, paste making, strike-offs, downtime and wastage are eliminated [33]. Inventory and pollution control costs are minimal as all the dye goes onto the fabric, no thickener or paste is used and, water and energy consumptions are low. The technology is amply suitable for just-in-time deliveries and mass customization [33].

Table 2.3 Comparison of Rotary Screen with Digital Inkjet Printing [32]

Rotary screen printing	Digital ink-jet printing
Aqueous pastes made up on site in large batches	Special inks in small containers from the machine maker
30-70m/min	1m/min
No fabric pre-treatment	Fabric pre-treatment required
Usually up to 100 dpi, but 255 max.	1440 dpi
Digitised design information to laser engraver	Fully integrated with CAD
Restrictions on repeat distance	No restrictions on repeat
Screen cost, engraving, washing, storage	No screens
Contact with fabric	Non-contact
Half-tones not straightforward	Half-tones no problem
Usually designs mis-registration at set-up	Instant registration
Strike-offs on proofer may be different from bulk	Strike-offs on bulk machine

Traditionally, inks used for the printing of textiles are most often applied by a screen printing process. One of the disadvantages of screen printing is machine efficiency and the long wash time that is usually required. Machine downtime also reduces the efficiency of screen printing[13] . To overcome these disadvantages, digital inkjet printing on textiles has been predicted to continue growing in popularity because of the simple process, high efficiency and obvious benefits.

The print qualities of cotton fabric prints achieved through inkjet printing in comparison with screen printing using the same pigment dispersion systems were investigated in the research by Kiatkamjornwong, Putthimai, and Noguchi [13] . Stiffness and crock fastness of digital printed and screen printed fabrics were compared in their research.

Stiffness

Stiffness is defined as the ability of a material, such as the cotton fabric, to resist deformation. A high bending length value implies a higher stiffness of fabric [13].

In Kiatkamjornwong, et al.'s research, scoured, unfinished and plain weave cotton fabric, with a construction of 140 epi x 75ppi, and a basic weight of 127.3g/m^2, was used as a printing substrate. The stiffness, reported as the flexural rigidity, see Figure 2.8.

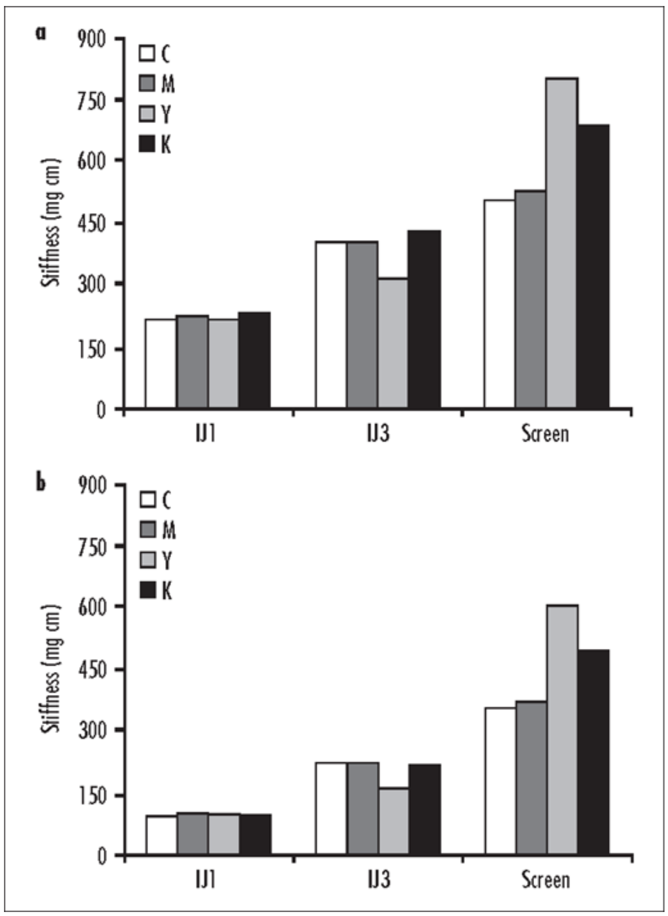


Figure 2.8 The stiffness of cotton fabrics printed by the inkjet ink deposition method and by the screen printing ink deposition method: a) on non-treated and b) treated fabrics in two

directions, with inks for four colors (IJ1 = one-pass inkjet printing, IJ3 = three-pass inkjet printing) [13]

The warp direction printing (see Figure 2.8a) gave a much higher value of stiffness on both the non-treated and the treated fabrics than the weft direction printing, as shown in Figure 2.8b, because the ends per inch (epi) is higher than picks per inch (ppi).

Each ink color of the four-color process inkjet inks produced almost equal bending stiffness regardless of one-pass or three-pass printing. On the other hand, each ink of the four-color process inks for screen printing gave different bending stiffness values. The trend of bending stiffness was found similarly in both directions (warp and weft). In other words, the stiffness not only depended on the ink chemistry, but also on the fabric mass per unit area. Stiffness values of the cotton fabrics that were printed with inkjet inks were significantly lower than those which were printed with screen inks.

Because of the high ink viscosity of screen printing ink, more ink was deposited on the surfaces to give a harder hand or touch. Even when the inkjet ink was deposited three times, the stiffness values of all the prints were still lower. This is an additional advantage of inkjet prints in that they give a smoother and softer touch and wearer comfort[13] .

Crock Fastness

Dry and wet crock fastness is measured by a crock meter to determine the amount of color transferred from the surface of colored textiles material to other surfaces by rubbing.

Table 2.4 shows the dry and wet crock fastness of inkjet prints and screen prints in Kiatkamjornwong, et al ‘s research, achieved by printing on the PEO-treated and non-treated cotton fabrics, respectively. The rating scale is 1-5, with 5 representing excellent and 1 being poor performance.

Table 2.4 Dry and wet crock fastness of the inkjet ink and screen ink printed cotton fabrics[13]

Type of ink	Crock fastness on cotton fabric							
	Dry				Wet			
	C	M	Y	K	C	M	Y	K
Inkjet Ink	4	4	4	4-5	2	3-4	3-4	2-3
Screen Ink	1-2	1-2	1-2	1	1	1	1	1

Dry and wet crock fastness are controlled by the amount of ink deposited on the cotton fabrics. The extent of crock fastness depends on the degree of cohesion in comparison with adhesion between interfaces. The thicker ink film usually has a poor interfacial adhesion so that it tends to be more easily removed. The dry crock fastness of the inkjet printed fabric was better than the wet crock fastness while the wet crock fastness of the screen ink printed fabric was somewhat better than the dry crock fastness [13].

Digital inkjet printing offers distinct advantages such as speed, flexibility, creativity, cleanliness, competitiveness compared to other conventional printing, it is foreseen that the traditional flat and rotary screen printing and roller printing techniques may be superseded by digital printing technologies according to Dehghani, et al. [30].

2.3 Fabric preparation and processing for digital inkjet printing

Substrates for digital inkjet printing may need to be prepared and handled differently from traditional printing to meet requirements.

Substrates currently being printed are specially prepared for at least one of two properties: (i) for ease of fabric handling, or (ii) for improved absorbency and dye / pigment retention [31]. Digital inkjet process factors and woven properties were studied in this part of the literature review.

Similar to conventional printing processes, the success of digital inkjet printing depends mainly on fabric preparation processes according to Byrne and Perkins's research [35, 36]. Fabrics for digital inkjet printing have to be properly desized, scoured and pretreated.

2.3.1 Pretreatment

Depending on the type of dye applied and the substrate content, the textile material needs a certain type of pre-treatment before being digital inkjet printed [37].

The initial fabric pretreatment steps and subsequent pretreatment for digital textile printing (PFDP) are critically important to ensure that the print definition, color, and brightness as well as the color fastness performance are at a high level [11]. Fabric pretreatment with thickeners and other chemicals matched to the dye being ink jet printed is vital to ensure good print definition and high dye fixation. "Such thickeners and chemicals cannot be incorporated into the ink formulation because of problems affecting dye solubility, ink stability, corrosion of the jet nozzles, and undesirable rheological properties that would adversely affect the jetting performance and print runnability" [11].

The fabric is normally pretreated and placed in the printing machine in roll form, printed, and then the dyes are fixed, usually by steaming in a separate machine, washed off, and dried. SEM micrographs in Figure 2.9 show fiber appearance of cotton fabrics, with and without PEO treatment.

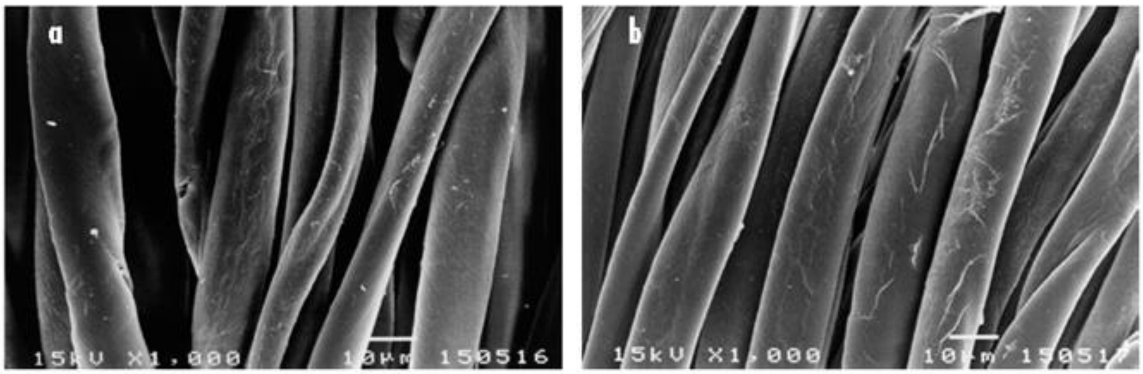


Figure 2.9 The SEM photographs of the non-treated and pretreated cotton fabrics (x 1000): (a) non-treated cotton fabric, (b) pretreated cotton fabrics (at 15 V) [13]

In previous work, the PEO polymer was found to cover the fiber surfaces and increase the thickness of the fibers [34]. However, Kiatkamjornwong et al. reported that, PEO, the pretreatment polymer, did not significantly affect the air permeability of the printed fabric. "Fabric air permeability depends on the passage of air in between the yarns/inter-yarn spaces, which is the major factor, and between fibers in the yarns or inter-fiber spaces". The PEO treatment covers the inter-fiber spaces instead of the inter-yarn spaces. Inkjet printing will cover mainly inter-fiber and has minor effects on inter-yarn air permeability because of the lower add-on [13]. Thus, the ink penetrates and fills the inter-fiber spaces, as shown in Figure 2.9. The fabric that was treated with the aqueous PEO polymer gave better air permeability.

Pretreatment also has influence on print clarity. Figure 2.10 contrasts drop-wicking on an untreated substrate with the greater control obtained by pre-treatment [25].

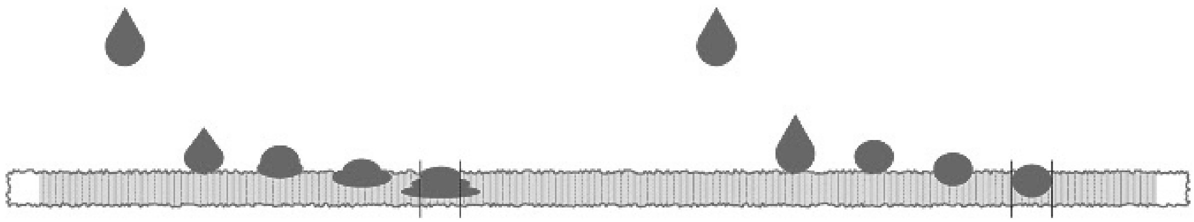


Figure 2.10 Operating principle of pre-treatments. Left – no pre-treatment. Right – with pre-treatment. (Image courtesy of BASF) [25]

To achieve better print quality on fabric by inkjet printing, it is necessary to pretreat the surface of the fabric in order to prevent excess penetration of fluid ink.

2.3.2 Shrinkage

Digital inkjet printing is a non-contact printing method which means that the fabric is printed without being touched. Not much strain is put on the material being printed. Therefore, digital inkjet printing does not require an aggressive fabric hold down method as in conventional screen printing. According to Choi et al., when the pre-treated fabric is being printed, it comes down to a local wetting of the fabric. Most fibers tend to swell upon wetting, which causes a local shrinkage. The deeper the shade of the color being printed is, the wetter the fibers get and the more visible the shrinkage phenomenon becomes [38].

Fabric structure and fabric finish can also cause large variations in shrinkage. Fabric for digital inkjet printing has to be desized, scoured, pretreated before printing, cured and some need to be post-washed after printing. Shrinkage could occur in any of these processes due to the wetting and high temperature fixation of the fabric. Shrinkage of fabric for digital printing is a critical factor which need to be considered.

2.3.3 Fabric Tension

It is commonly known that the fabric needs to be laid flat during printing. In digital inkjet printing, this is mainly done by gently stretching the fabric when guiding it through the machine. Many elastic fabric constructions do tend to stretching during printing, which cause problems like wrinkling. Hence, careful attention needs to be paid to minimize the tension and to keep the fabric as flat as possible. Since digital inkjet printing is a printing method in which each print head movement is followed by a pause, there is a risk of printing stripes being formed, because of the stretching being followed by relaxation [38].

An adhesive belt would secure the fabric flat on the beglt, in this case, adhesive needs to be reapplied to the belt as a regular maintenance procedure to ensure the continued effectiveness of the adhesive belt in holding the fabric in place.

2.3.4 Warp and Weft Alignment (bow and bias)

It is important not only to keep the fabric flat when feeding it into the printer but substrate also needs to remain straight during the printing process so that a printed line remains unchanged and does not become a curve after fixation and washing. Bow and bias or skew would happen if the fabric is not well aligned.

So if warp and weft yarns are not at right angles in the interlacing during printing, even the best tenter frame, which would carry woven fabric through an oven to heat set the (suspended on pins)fabric or keep it from shrinking during drying, cannot get it straight again during the drying operation in the after treatment. Hence, it is very important to print on straight grain fabric and to keep the fabric straight(pick line perpendicular to selvedge edge/warp yarn? And edge of printer belt?) on the printer. As the speed of the digital inkjet printer increases, the need to align and maintain the alignment of the fabric well on the printer also becomes more acute [38].

2.3.5 Selvedge

Depending on the type of loom upon which the fabric has been woven, the sides (selvedges) of the textile material do not always behave in a desired way. As some digital inkjet printers have no selvedge pins or holders, once the print head catches any protruding fibers or wrinkling in the fabric, friction of the fabric against the print head can block some ink channels, or in some cases it can cause serious damage to the printer if the fabric gets stuck against the print head, thereby preventing it from moving along [38]. The faster the printers move, the more serious this problem is.

2.3.6 Post-treatment Process

Pigment printed fabrics do not require post treatment steaming or washing but do require curing. After digital dye or ink printing, the printed fabric needs a post-treatment to complete the process. It's normally steamed to fix the dye to the cotton and washed to remove any unreacted dye, chemicals and thickener [53]. Steaming allows cotton fibers within the fabric to open up and allow the dyes to be fixed. Steam serves as a convenient source of both water and heat which can be transferred rapidly and uniformly over the surface of the fabric. Superheated steam is used because it offers advantages of faster heating, shorter fixation time and lower spread of colors [40].

2.4 Woven properties impact on digital printing image

One of the largest problems with digital ink-jet printing on textiles is obtaining the desired color, as there exists a strong interaction between texture of the substrate and the ink. The relationship between fabric, inks and the resulting color is complex since the number of different textile substrates being used in the industry is very large [31].

Printing of woven substrates dominates print activities worldwide. Knits and non-wovens are quickly advancing as effective substrates, although at the expense of wovens [28].

Cotton and polyester woven fabrics are the most widely used substrates in digital inkjet printing. It's critical to find the woven properties' impact on digital inkjet printing.

In digital inkjet printing on textiles, the print quality, color and appearance, is dependent upon many variables shows in Figure 2.11.

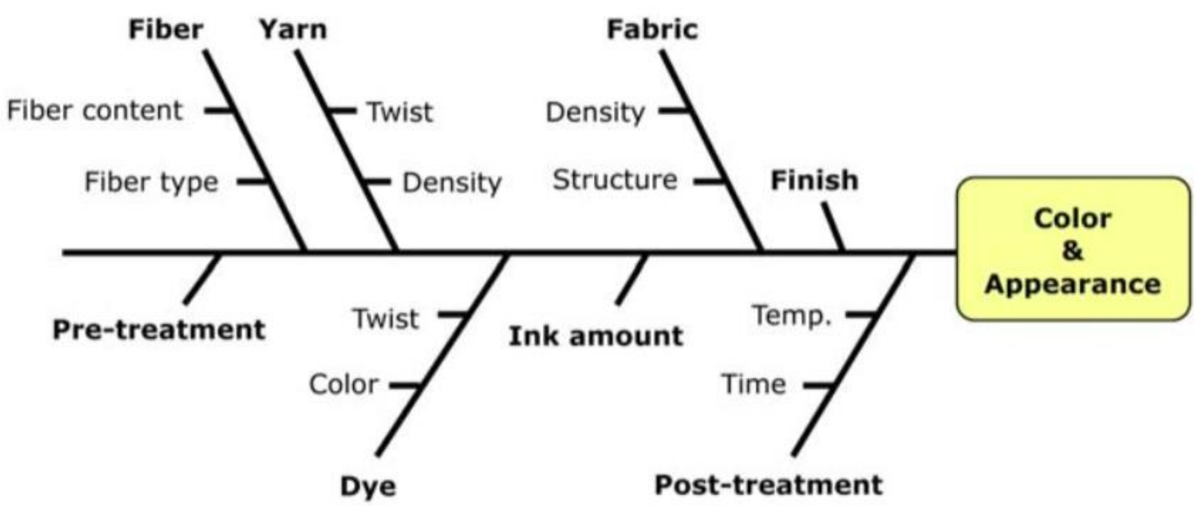


Figure 2.11 Variables in digital inkjet printing on textiles [39]

The quality of the digital print image on woven fabric is greatly influenced by the spreading behavior of an ink droplet on a woven fabric's surface rather than wicking behavior. This spreading behavior is dependent on a liquid's capillary property and the woven fabric properties: fiber type, yarn structure, and weave structure.

Woven fabrics are constructed from yarns that can have different diameters and twists. The yarns are made from fibers with various structural properties such as cross-sectional shape, diameter, and longitudinal shape.

In a woven fabric, reflection occurs between two media, between air and a fiber or air and a pigment particle [39]. Figure 2.12Figure 2.12(a) shows light striking a simplified circular cross-section fiber. When a light beam strikes normal to the surface and is passed back from the media, reflection occurs. The amount of the surface-reflected light from textiles normally falls somewhere between 0 and 4% [41, 42]. When many fibers are grouped in a yarn, as in Figure 2.12(b), which shows several fibers in cross-section, some of the reflected light from the surface becomes trapped and lost by absorption [41, 43]. Figure 2.12(c) represents pile fabric, such as velvets, corduroys, and carpets, which have more opportunity for the incident light to be trapped between the fibers or yarns [39].

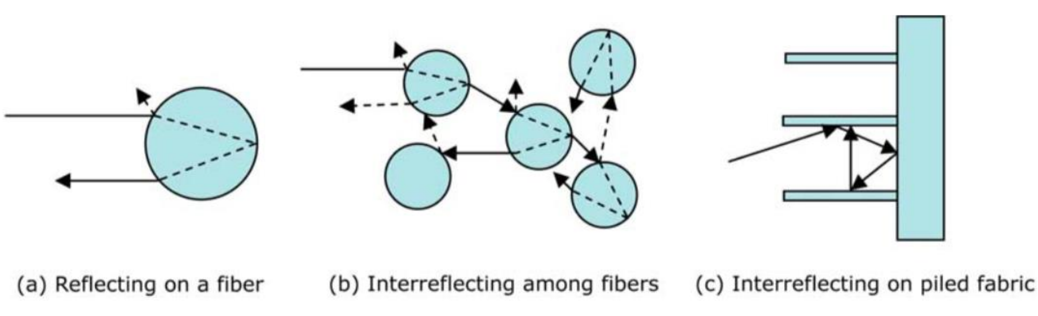


Figure 2.12 Diagram of light reflection on a fiber, yarn, and pile fabric [39]

Due to these light reactions, when woven fabrics of different structures are dyed or printed with the same colorants and under the same conditions, the color appearance can vary according to the configuration of the fabric, fibers, or yarns. The microscale structure of the fiber, the yarn, the textile, and the finishing may affect color appearance [44].

2.4.1 Fiber

When comparing the spreading area for different fibers: cotton and polyester, cotton fiber fabric tends to obtain less spreading area than polyester due to the high absorbency of the cotton fiber[6, 15]. As a result, digital inkjet prints on cotton fabrics have had better image qualities than those on polyester fabrics according to Daplyn and Lin's research on pigment ink for digital inkjet printing onto fabrics as shown in Figure 2.13.

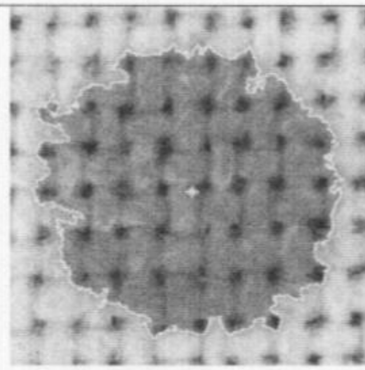
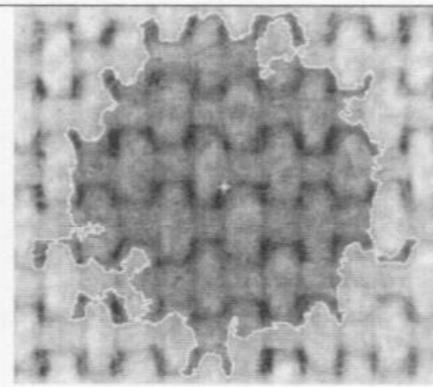
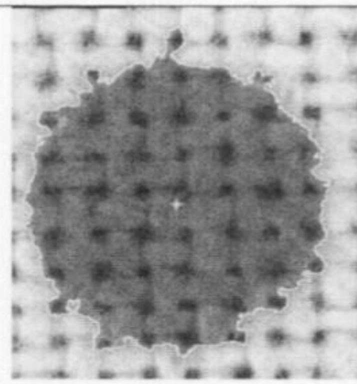
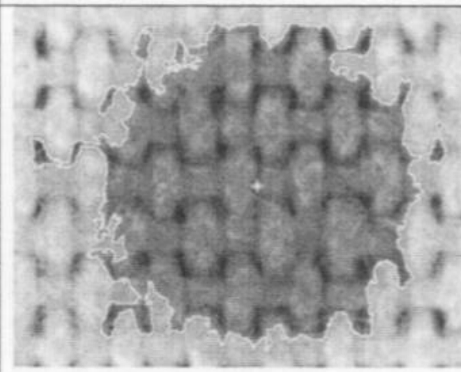
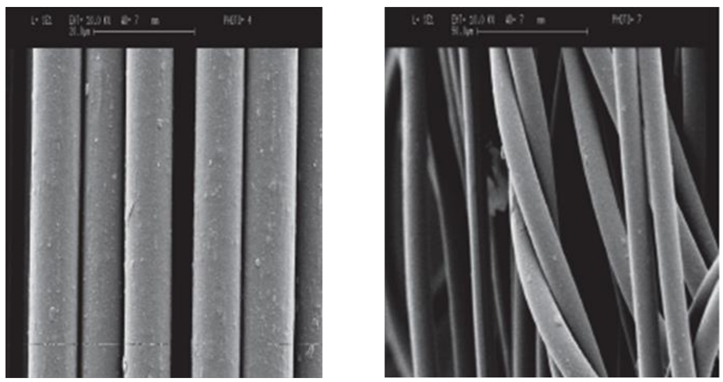
Ink formulations	On cotton	On polyester
Ciba Microlith Magenta B-WA		
Cabot Magenta IJX 266		

Figure 2.13 Micrographs of digital inkjet printed dots on cotton and polyester woven fabrics [45]

Even though there is high capillarity in polyester, polyester is widely used as an ink-jet printing substrate for textiles of soft furnishings products such as chair or sofa upholstery. This is because the hydrophobic group in polyester interacts and forms the bonds with the hydrophobic group in the disperse dyes occurring while inkjet printing on the polyester substrate. However, for this polyester substrate in Figure 2.13, pretreatment is required to control the dye wicking [25].

2.4.2 Yarn

The wicking behavior is also affected by the yarn structure. When a yarn is texturized, the wicking occurs less than in a continuous filament yarn. In the texturized yarn, the irregular capillary void space created plays a role in holding a liquid droplet in the space while increasing the inter-filament wicking rate. Also the capillary for wicking increases in the closely packed multifilament yarn structure and in the high density of warp yarns in a woven fabric[18] .



(a) (b)

Figure 2.14 SEM images of (a) Continuous filament yarn and (b) air texturized yarn (nylon 6,6)[18]

2.4.3 Fabric construction

According to the study by Mhetre et al., inkjet printing quality increased as the ink droplet's spreading became less on a woven fabric surface. This is because the decreased spreading prevents the creation of the excess line on the transverse threads, which is critical in improving the ink-jet printing quality. The fabric's absorbency of the liquid is important in determining the ink's spreading area on the fabric surface. The poorly absorbent fabric has less spreading area than the highly absorbent fabric. Also, the high capillarity in the woven fabric allows an ink droplet to spread out further, resulting in the larger spreading area on its surface. This means that the high wicking behavior can lead to the poor printing quality by increasing the ink's spreading in woven fabric[15].

The quality of digital print images on woven fabric is influenced by different weave structures in the basecloth.

Figure 2.15(a) shows a schematic of printing in the warp direction along a warp yarn. For a 5-harness filling-faced satin polyester, notice that four out of five filling yarns interlaced with the warp yarns run over the warp yarns [19].

When the ink drops fall on these filling yarns, the ink wicks in the filling yarn direction, which is transverse to the printing direction. The wicking distance is large since these filling yarns float over up to four warp yarns, causing the line image quality to be poor. The wicking of the ink in the filling direction can be seen in Figure 2.15(c), which is a scanned image of fabric printed in the warp direction. When ink falls on the warp yarn, notice that wicking in the filling direction is much smaller [19].

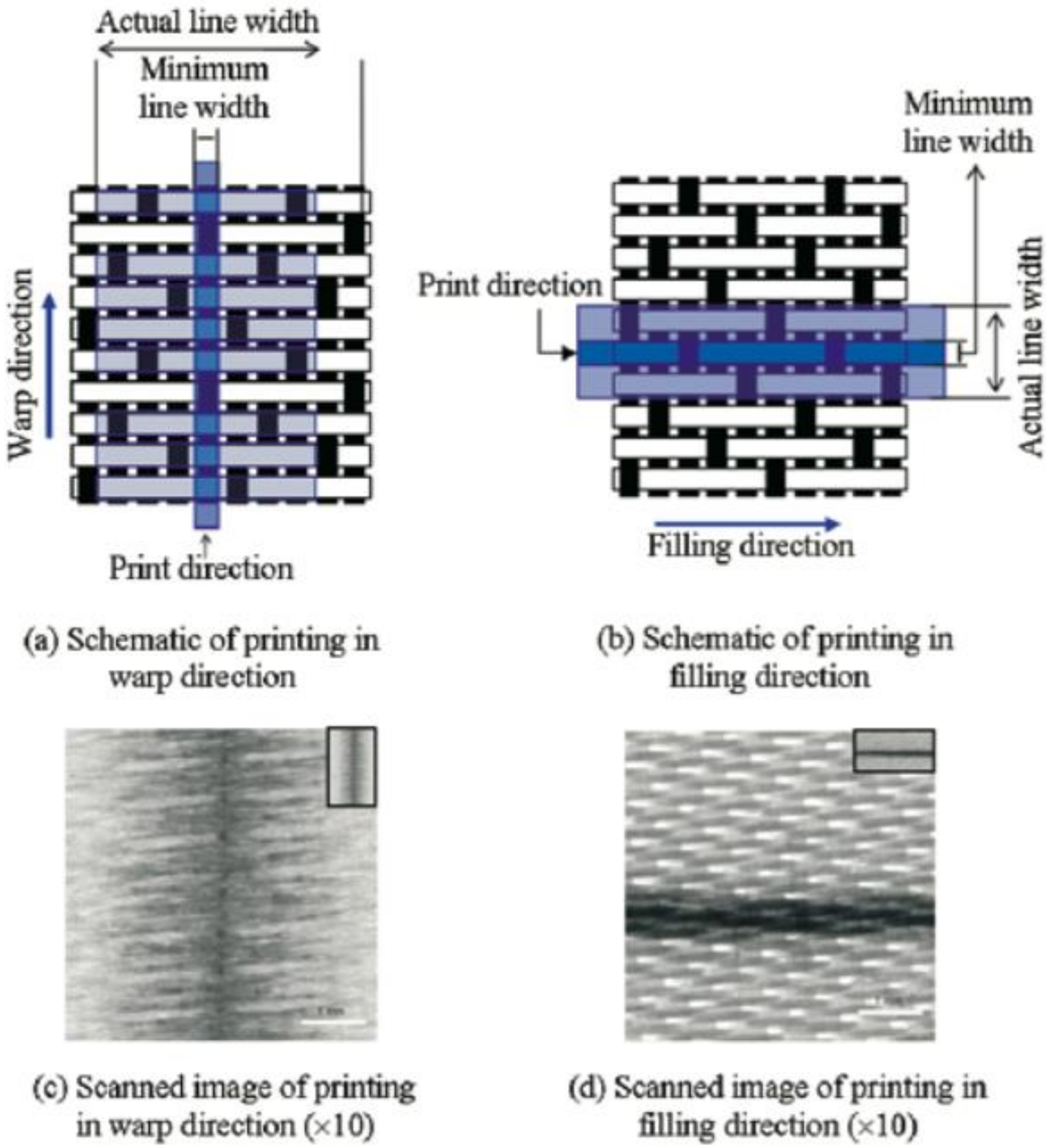


Figure 2.15 Schematic of structure printed in warp and weft direction [19]

As each filling yarn floats over four warp yarns before interlacing with a warp yarn, most of the ink falls on the filling yarn. Ink falling on the filling yarn, tends to wick in the filling direction which is the line direction. This tends to reduce wicking in the warp direction. Due to these two factors, wicking perpendicular to the print direction is much less for printing in the filling direction than in the warp direction. Consequently, line image quality is much better when printing in the filling direction on a filling-faced satin fabric. This shows the printing direction plays an important role in line image quality for non-pretreated fabrics. The printing direction also has an effect on plain and twill weaves, but the effect is much less than for the satin fabric [19].

When ink droplets fall onto warp and weft yarns during digital printing, wicking behavior needs to be considered in improving the image quality. If the image is printed in the weft direction, the wicking on a weft yarn will occur proportionally to the float length of weft yarns passing over warp yarns. This means that a satin weave structure with the longest float length amongst the three basic weave structures will produce the poorest quality of image in digital printing. On the other hand, plain and twill structures possess more intersections of warp and weft yarns, leading to a shorter float length relative to the satin weave structure[19]. The short float length of a weft yarn can decrease the wicking on a weft yarn. Thus, the image quality will be increased as the float length becomes short [19]. This indicates that it is necessary to define the appropriate weave structure and fabric density for highly improved image quality of digital printing on woven fabric.

2.5 Print Clarity (Image Sharpness)

Print clarity of a digitally printed product has great impact on the final aesthetic appearance and performance of the printed products. In this research, print clarity of digitally printed images on various substrates is considered as image sharpness.

Sharpness is defined as the clarity of detail in an image, which is a combination of resolution and acutance [62]. Sharpness determines the amount of detail an imaging system can reproduce. It can be characterized by the boundary zones of different tones or colors [63]. A quantitative test method to evaluate print clarity need to be explored and developed.

2.5.1 Modulation Transfer Function (MTF)

The Modulation Transfer Function, MTF, which is generally identical to Spatial Frequency Response (SFR) [63], is used to illustrate radiographic sharpness, and is a measurement of the contrast reduction, or blurring, imposed by the system as a function of spatial frequency [58]. MTF analysis was discussed by Imatest® for "resolution" measurement. Imatest LLC is a company that produces image quality testing software, charts and equipment to test digital camera image quality [64]. The illustration of MTF shown in Figure 2.16.

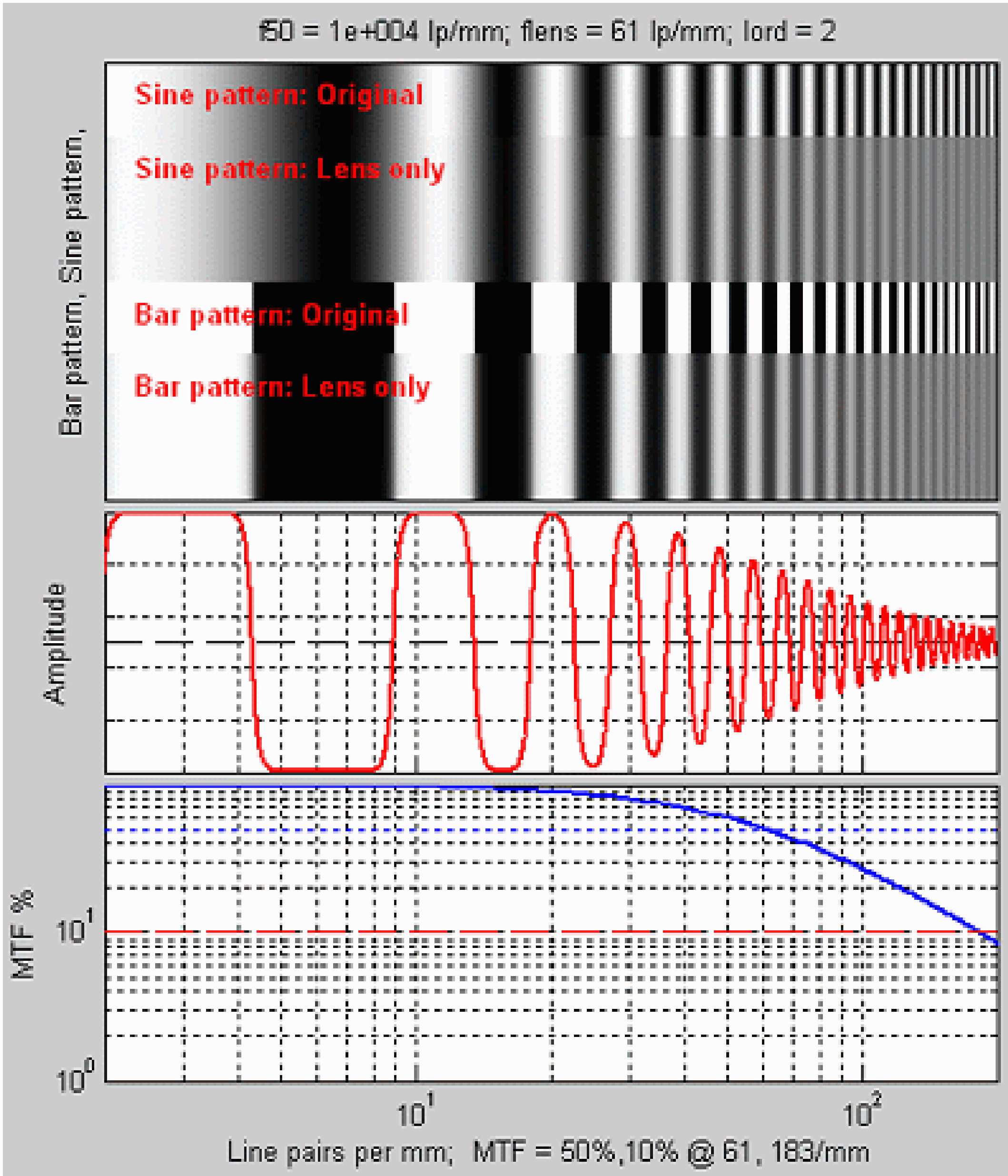


Figure 2.16 Sine and bar patterns, amplitude plot, and Contrast (MTF) plot [63]

The original sine pattern, the sine pattern with lens blur, the original bar pattern and the bar pattern with lens blur were displayed in the upper plot. Lens blur could cause contrast drop at high spatial frequencies [63]. The red curve in the middle plot showed the luminance (“modulation”, V). Contrast decreases at high spatial frequencies. The modulation of the sine pattern was used to calculate MTF by Imatest®[63].

2.5.2 MTF Analysis

The blue curve in the lower plot demonstrated the corresponding sine pattern contrast. The equation for MTF is developed from the sine pattern contrast $C_{(f)}$ at spatial frequency f, where $C_{(f)} = \frac{V_{max}-V_{min}}{V_{max}+V_{min}}$ for luminance (“modulation”) V [63].

$MTF_{(f)} = \frac{100\%\hat{}C_{(f)}}{C_{(0)}}$ was used to normalize MTF to 100% at low spatial frequencies.

The primary Imatest® MTF calculation is the slanted-edge, which applied a mathematical operation known as Fourier transform. MTF is the Fourier transform of the impulse response, the response to a narrow line, which is the derivative (d/dx or d/dy) of the edge response [63].

CHAPTER 3 METHODOLOGY

3.1 Objectives

This research seeks to determine the key factors in the material and process aspects that affect digital printing on textiles' quality and to improve substrate fabrics for digital printing enhancement. Improved print substrates or prepared for digital printing base materials will contribute to the final product's qualities in meeting performance, styling and cost requirements. Each step in the general process from fiber to finished product for a woven substrate and digitally printed product impacts the final performance and aesthetic appearance of the printed products. Figure 3.1 shows the process from fiber to a digital inkjet printed product. The blue highlighted areas in the Figure are the focus of this research.

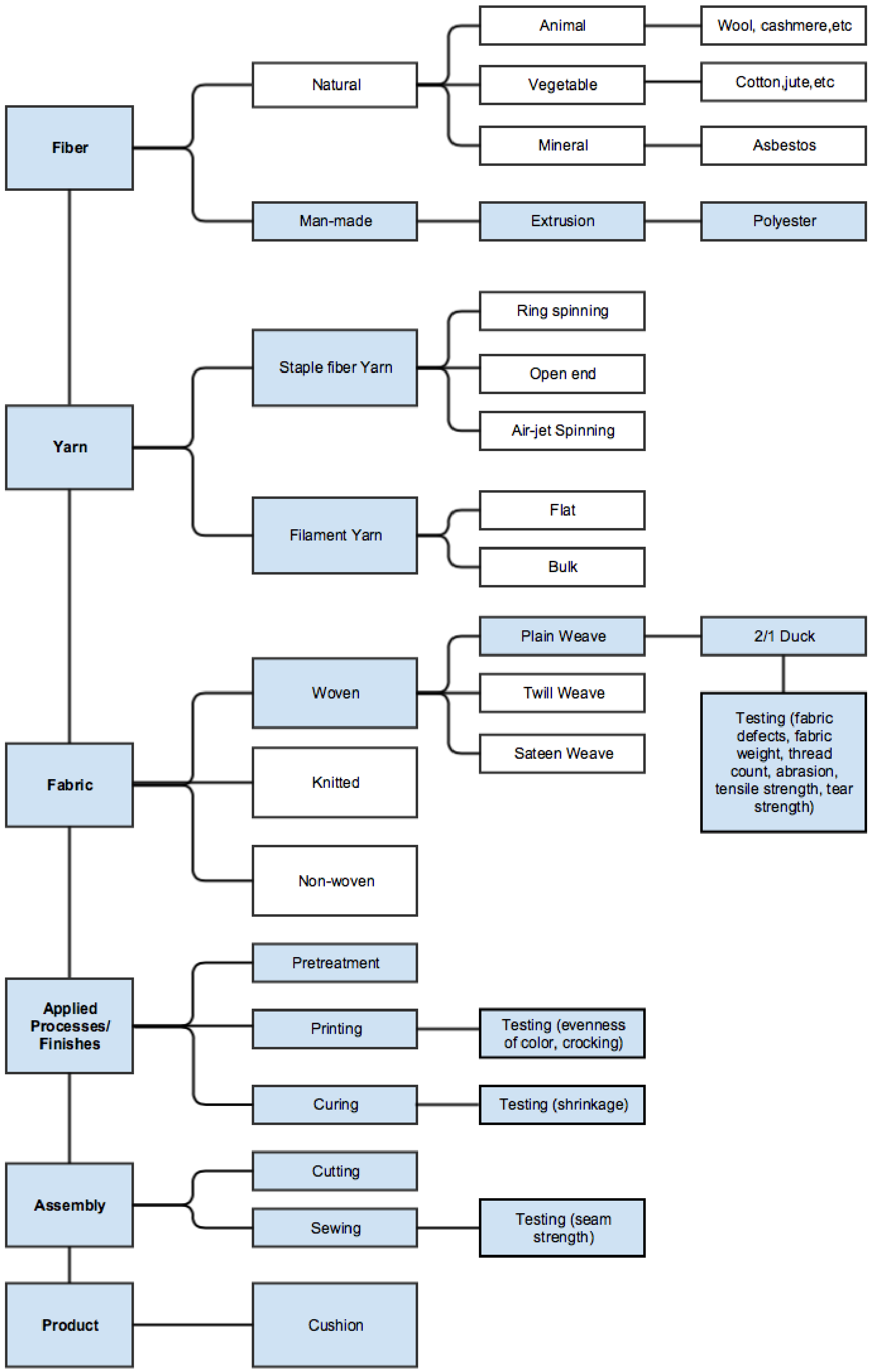

Fiber
Natural
Animal
Wool, cashmere,etc
Vegetable
Cotton,jute,etc
Mineral
Asbestos
Man-made
Extrusion
Polyester
Yarn
Staple fiber Yarn
Ring spinning
Open end
Air-jet Spinning
Filament Yarn
Flat
Bulk
Fabric
Woven
Plain Weave
2/1 Duck
Testing (fabric defects, fabric weight, thread count, abrasion, tensile strength, tear strength)
Twill Weave
Sateen Weave
Knitted
Non-woven
Applied Processes/ Finishes
Pretreatment
Printing
Testing (evenness of color, crocking)
Curing
Testing (shrinkage)
Assembly
Cutting
Sewing
Testing (seam strength)
Product
Cushion

Figure 3.1 Continued Process from Polymer to a Digitally Printed Product

The impact of fiber, yarn, woven structure, selvedge construction, fabric density and weight on printing performance, durability, color appearance and design clarity will be analyzed according to the major retailer's current standards for Outdoor Cushions and Pillows and to industry upholstery standards. See Table 3.1 for standards.

Understanding the substrate factors impacting digital printing will contribute to the quality and efficiency of digital printing. Here are some key factors considered in this research:

Key Factors

Yarn

As discussed in the literature review before, fiber, yarn and fabric properties all have impacts on printing effectiveness. This research proposes to consider the impact of these properties on specifically inkjet printing. Both spun yarn and filament polyester yarn as warp and weft are studied in this research.

Fabric construction

Based on the literature review, and understanding of printing on fibrous materials, two optimum fabric constructions were selected in commercial fabric for digital inkjet printing: plain and 2/1 duck.

Yarn density

As spun and filament polyester yarn warp were made, the warp density of each type of warp yarn was controlled. Pick density may change the wicking properties of ink on woven fabric.

Two levels of pick density were designed in each type of warp. Both spun and filament polyester yarn were inserted as filling yarns into each warp to form a balanced construction.

Selvedge

Selvedge may impact fabric handling and lay of the basecloth on the print belt during digital printing. Plain, twill, basket and 2/1 duck structures for selvedges were designed will be conducted to compare the impact of selvedge on the substrate for digital printing.

3.2 Testing Standards

Printing within the multinational retail corporation’s color gamut meeting fade/lightfastness standards will beset as a critical objective, and the print basecloth’s impact on this performance is essential to understand.

The researchers will refer to the ASTM standards for upholstery fabric woven and printed. Also the multinational retail corporation has provided their current standards for Outdoor Cushions and Pillows. The retail corporation’s priorities for outdoor cushions/pillows include: durability, tear strength, crocking, tensile strength, tear strength, yarn slippage, fabric defects, evenness of color, and weight. Abrasion tests were included according to ASTM standards to predict the durability of the fabric. See Table 3.1.

Testing Standards with procedures were gathered and reviewed with COT physical testing lab manager to determine which tests can be administered in the college labs.

Table 3.1 Testing standards for woven basecloth [46]

Test Description	Test Method	Performance Requirement
Fabric Defects	ASTM D3990	No major defects, such as stains, holes, slub yarns, mis-stitches, etc.
Fabric Weight (oz/sq yd) (g/sq m)	ASTM D3776	As specified in Product Specification or Previous Testing (±5%)
Thread Count (Woven)	ASTM D3775	As specified in Product Specification or Previous Testing (±5%)
Evenness of Color	Visual	Uniform and even color within a sample and between samples
Tensile Strength (lb)	ASTM D5034	Warp 200.0 lbs Fill 100.0 lbs
Tear Strength (lb)	ASTM D2261	Warp 10.0lbs Fill 8.0 lbs
Seam Strength (lb) Woven	ASTM D1683 (Across seam)	20.0 lbs
Abrasion Resistance	ASTM D4157	Wyzenbeek Light Duty 15,000 cycles Heavy Duty 30,000 cycles
Dry Crocking	AATCC 8	Minimum of: Grade 4.0
Wet Crocking	AATCC 8	Minimum of: Grade 3.0

Evenness of color is the uniform and even color within a sample and between samples. Visual assessment is used to evaluate evenness of color.

Print clarity is also an important factor which can be used to evaluate the quality of digital printing on textiles. The retailer did not provide a testing standard for print quality. ASTM F1944 could be an alternate way to evaluate print quality, however, it's still based on subjective visual assessment, which cannot quantify the value of print clarity. A quantitative test method for evaluating print clarity is needed.

This substrate analysis continues as the experimental work proceeded further testing and review of results would be part of the objectives after completing samples for testing. Printed lab samples were tested for seam strength, crocking, lightfastness, and any other pertinent performance standard for digital printed upholstery woven fabrics. These results were compared to the commercial fabrics previously digitally printed. Based on this evaluation, sample development can move forward with improvements in the basecloths.

3.3 Design of Experiment

Sixteen fabrics weighing in the range of 4-7 oz/yd^2 relating to the retailer's current production bases were selected from the commercially available substrates to be analyzed and act as a basis of comparison to any newly developed fabrics samples. These fabrics were discussed with the supplier to understand any additional material processing in preparation for print.

Table 3.2 shows the selected sample constructions from commercial suppliers that were considered as a guide for new sample development and comparative analysis.

Table 3.2 Commercial fabrics final selections related to weight and structure for print basecloth

Sample Number	Vendor	Warp Yarn	Weft Yarn	Weight	Scoured Weight (osy)	Weave	Count	Wet Pick up	Cover Factor
NC_WM 15_007	A	15.5 PET o.e. spun	8/1 PET o.e. spun	7	7.352	2/1 Duck	84×28	77%	12.068
NC_WM 15_011	B	2/150/48 denier PET dull stretch textured	2/150/48 denier PET	5.3	5.885	plain	61×52	39.3 %	9.66
NC_WM 15_012	B	2/150/48 denier PET dull stretch textured	30/2 ring spun PET	5.3	5.387	plain	61×50	65%	10
NC_WM 15_013	C	2/150/68 PET FR	2/165/48 PET FR	4.9	5.097	poplin	62×43	52%	9.22
NC_WM 15_015	B	2/150/48 denier PET dull stretch textured	2/150/48 denier PET	5.3	5.335	plain	62×56	56.6 %	10.03

A labeling or identification protocol was recommended for the research project and sample development: NC_WM14_001 (North Carolina/Woven Material/Year/Sample Number). Selected polyester woven fabrics for print trials were prepared through scouring on the College of Textiles' range which required all fabrics to be cut to a similar width (about 54 inches or wider) for scouring, washing and heat setting on the tenter frame. Also information on the sizing (PVA) or other preparation of yarns for weaving need to be understood and removed in scouring. Chemical pretreatment of all fabrics will further prepare the substrate for printing with pigments or disperse inks.

Wet pick up of commercial fabrics were measured after scouring.

Wet pick up = $\frac{Wet\ weight\ after\ pad - Air\ dry\ weight}{Air\ dry\ weight} \times 100\%$

The wet pick up value determined the percentage of pretreatment chemicals.

Fabric cover factors were calculated based on yarn information provided by the suppliers. Yarn sizes were also tested to confirm the information provided by the suppliers. The cover factor equation was shown in the Literature Review on Page 18. Based on the commercial fabric selections, which were aligned with the screen printed basecloth already meeting requirement by the cushion supplier and retailer, fabrics with a cover factor higher than 9 would be considered as appropriate substrate fabric for digital printing.

3.3.1 DOE theoretical sample plan

The Design of Experiments (DOE) was developed to weave samples on the CCI narrow loom for various polyester yarns, structures and densities. As discussed before, yarn type, fabric construction, pick density and selvedge were considered in Design of Experiment.

Table 3.3 DOE theoretical sample plan of woven polyester

Warp Yarn (PET)	Filling Yarn (PET)	epi	ppi	Calculated Weight (osy)	Calculated Weight (osy) 3% crimp	Cover Factor	Structure
2/145	2/145/36 denier	64	52	4.34	4.47	9.74	Plain
			48	4.19	4.32	9.45	
	19/1 cc		52	4.27	4.40	10	
			48	4.13	4.25	9.69	
16/1	8/1 cc	84	28	6	6.18	11.96	2/1 Duck
			25	5.74	5.91	11.65	
	4/150/34 denier		28	5.91	6.09	11.67	
			25	5.66	5.83	11.4	

Two different polyester warps were created for the CCI loom: one filament yarn and the other was a spun yarn (See Table 3.3), yarn counts were chosen to be similar to appropriate commercial fabrics to achieve good performance in printed fabrics for this upholstery application. Each of the warps were crossed with filling picks of polyester both filament and spun at similar yarn counts. Each filling had two pick levels to be compared for performance and appearance as a print substrate. Basis weights (with and without crimp) were calculated before weaving to ensure the designs meet the requirements, weighing in the range of 4-6 oz/yd^2. Two types of weave structures were determined to be the most reliable: plain and 2/1 duck were compared in the research.

In considering a more aesthetically pleasing fabric utilizing a more complex structure, a herringbone structure was also woven as a good basis for comparison as a twill variation.

The minimum length of warps was calculated as shown in the Appendix to meet the requirements for basic testing. The maximum length of warp for the CCI loom prepared on the BENNINGER S.A. warper in the College of Textiles is 40 yards and 20 inches width.

The Design of Experiments has been amended to include trials on several different selvedge structures, and samples will be tested with selvedges and with selvedges removed to confirm impact of selvedges on wrinkling and effective introduction of the fabric to the adhesive belt as it progresses to the printing zone.

In fabric A and fabric B as shown in the Appendix, three types of selvedges will be woven as the selvedge structure is a critical factor for determining whether fabric will stick and lie flat on the adhesive belt during digital printing or cause any print head interference. 80/20 poly/cotton yarn was also woven as filling yarn in fabric A and fabric B to compare the difference between polyester and poly/cotton as a print base.

One yard of spun filling and one yard of filament filling at the higher pick level in fabric A and fabric B will be maintained as control fabrics before scouring.

3.3.2 Fabric structure simulation (EAT)

Fabric structure was simulated by EAT DesignScopeVictor® before weaving. Figure 3.2 shows fabric structure simulation on Fabric B with a 2/1 duck construction.

Although the epi is more than twice that of ppi in Fabric B, the fabric structure is still a balanced construction due to the yarn size, as the weft yarns are twice the size of the warp yarns.

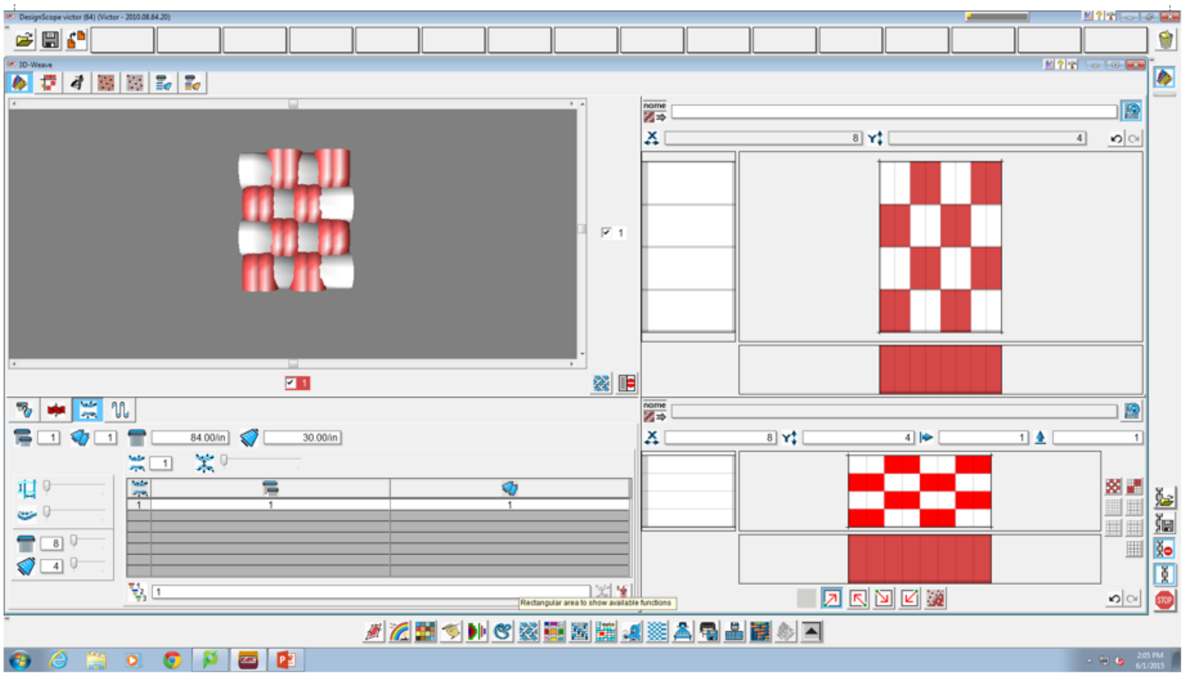


Figure 3.2 Fabric structure simulation on Fabric B for a 2/1 duck fabric (EAT DesignScopeVictor®)

The balanced structure ensures it is an appropriate substrate design for digital printing.

3.3.3 Digital Printer

Commercially available fabrics were analyzed as a basis for the polyester samples to be developed in the laboratories of the College of Textile, and printed with the MS JP5 Evo digital printer equipped with Kyocera piezo drop-on-demand print head [56]. The printer was installed with a six-color nano-pigment set, comprised of cyan, magenta, yellow, black, red and blue [57]. Technical specifications of MS JP5 Evo digital printer are shown in Table 3.4 below.

Table 3.4 MS JP5 Evo digital printer technical specifications [50]

Technical Specifications	
Production Speed up to 8 colors	55 lin. met./h
Production Speed CMYK	100 lin. met./h
Printing heads	Up to 4
Dpi resolution	600 × 600 dpi (dots per inch)
Gray levels	16
Drop Size	From 4 to 72 pl
Printing width	180 cm (70.86 inch)
Features	Open ink system Embedded romote diagnostic Embedded web server for cost report **Sticky Belt**™ fabric handling system with washer

The MS JP5 Evo digital printer has a sophisticated printing blanket with an adhesive coating called a Sticky Belt which holds the fabric in place while printing, which allow for printing on a 4-way stretch material that is not possible for an entry level digital inkjet printer. Print resolution is 600 × 600 dpi (dots per inch) [50].

With a specific focus on substrate fabric development for digital inkjet printing, two other impacting factors, ink and print mode, are controlled in this study.

Pigment ink is chosen for digital printing in this research since almost half of all printed textiles produced worldwide are pigment printed [31]. Vendor supplied pigment will be used.

Droplet size (ink volume) of pigment ink is from 4 to 72 pl, which varies by the Print Mode in MS JP5 Evo digital printer. There are eight modes A to H and three carriage speeds: HQ, High, Max (the mode and speed are intrinsically synced).

C2 Mode, which is the optimum print mode to achieve a balance between print clarity and production speed on upholstery weight polyester woven fabrics, was selected for the research based on discussions with multinational retail corporation personnel, and industry experts. It has seven variable drop sizes (4, 7, 11, 14, 16, 19, 24); 4 pass, Bidirection and the carriage speed is High. The RIP can be set to either Unidirection or Bidirection [57].

CHAPTER 4 EXPERIMENTAL WORK

From yarn to woven fabric to the final digitally printed fabric, many processes are required to achieve high quality and printing efficiency for digital printed products.

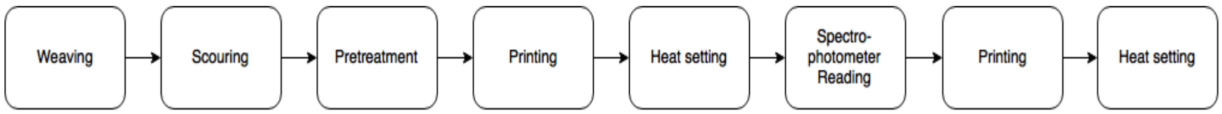


Figure 4.1 Digital printing processes

This chapter introduces experimental work of digital printing processes step by step to explore the best practices in preparing polyester woven fabric for direct digital printing.

4.1 Fabric Preparation

As discussed in 3.3.1 DOE theoretical sample plan, Fabric A and Fabric B were developed in the laboratories of the College of Textiles.

4.1.1 Yarn Physical Properties

Yarn procurement: warp yarns (2/145/36 denier and 16/1 cotton count) were provided by the National Spinning Company.

Before making warps for Fabric A and Fabric B, physical properties of the warp yarns were tested to ensure the single ply yarns are strong enough to make warps without sizing. Also this would provide a comparison between the spun and the filament polyester’s characteristics. Testing results show in Table 4.1.

Table 4.1 Physical properties of Warp A and Warp B

Warp	Physical Properties	Time to Break (s)	B-Force (gF)	Elong. (%)	Tenacity (gF/den)	B-Work (gF.cm)	Modul 2% (N/tex)
Warp A (PET) (2/145/36) den	Mean	1.34	1470	22.12	5.07	9800	4.171
	s†	0.08	29.92	1.33	0.10	996.0	0.583
Warp B (PET) (16/1 cc)	Mean	0.52	850.9	8.62	2.56	1910	2.730
	s	0.05	87.93	0.84	0.26	325.3	0.856

†s is the standard deviation

The tensile strength of Warp A, filament polyester, is much higher than Warp B, spun. Warp A is 2/145/36 textured filament, while Warp B is 16/1 waxed spun yarn. Although the spun Warp B is weaker than Warp A and broke several times during warping and weaving, it still worked as a warp. Any wax, sizing or processing oils will be removed during the scouring process.

4.1.2 Warp Preparation

With a consideration of yarn types and the width and yardage requirements for testing as seen in Table 1 in the Appendices, a warping plan was determined.

The CCI Tech Mini Warper, SL8900 Evergreen, and Single-end Sizing Unit, is available for research in the College of Textiles lab and is suitable for creating small sample woven fabrics using just one yarn package. The warp beam produced can be up to 20 inches wide and 3.6 meters long. However, this was not sufficient nor efficient to make the required longer warps. Based on the 18-inch-wide continuous oven in the Pilot Lab which will be used to prepare the narrow sample goods for printing, with a consideration for about one-inch shrinkage in the width on the woven polyester samples, the width of the two warps was 19 inches. To meet the design of experiment requirements, the BENNINGER S.A. warper in College of Textiles was used to make warps for the CCI loom as the beam for this loom can accommodate 40 yards maximum.

Winding yarn onto the appropriate number of packages for creeling is the first step for making the warps. Based on the DOE in Table 3.3 and calculations, in making Warp A it was necessary to divide the yarns into 61 packages to make 20 bands, each package needed to be at least 0.052 pounds; Warp B needed to split the yarn packages into 83 packages to make 20 bands, each package was required to contain at least 0.15 pounds.

Figure 4.2 Yarn package set up on the creel for warping

The packages were arranged in order on the creel as Figure 4.2 shows. The yarns were drawn by hand through the guides and the two reeds, making sure the band width of the yarns in the second or v-reed is one inch.

Twenty-one-inch-wide bands were taped on the roller, each of the bands is 40 yards long. The CCI warp beam was placed beside the roller. The 20 bands were taped tightly onto the beam, Figure 4.3 shows the start of the warping.

Figure 4.3 Warp yarns being wound from the Benninger warper to the small CCI beam

4.1.3 Drawing-in of warp yarns

Drawing-in is the next step, processed by hand, by threading the individual yarns from the warp sheet's leasing threads in sequence into the heddles on the harnesses and subsequently the yarns are pulled through the reed dents.

Fabric A and Fabric B are both designed using 4 harnesses for the body of fabrics and 4 separate harnesses for the selvedges. Half-inch-wide selvedges on the left and the right sides of the warp sheet were designed, so the first and last 32 ends in Fabric A and the first and last 42 yarn ends in Fabric B were drawn through the heddle eyes on harnesses 5 to 8.

As discussed in 3.3.1 DOE theoretical sample plan, the constructions of Fabric A were plain weave, one yarn drawn through each heddle eye designed for the plain weave. As for Fabric B, to achieve 2/1 Duck balanced structure in the fabric body, two yarns per heddle from harnesses 1 to 4 was required. In order to weave different selvedges in Fabric A and Fabric B, one end per heddle from harness 5 to 8 was required.

Both Fabric A and Fabric B warps were drawn in at two ends per dent. Based on the end density in Table 3.3, the reed used for Fabric A was 32 dents per inch and the reed used for Fabric B was 42 dents per inch.

4.1.4 Weaving

Next, the warp beam and the threaded frames/harnesses are transported to the loom, and set into place. The drawn warp is attached to the front cloth beam and placed under tension in preparation for weaving. CCI SL8900 Evergreen Sample Weaving Loom was used in the weaving process. As seen in Figure 4.4, the computer controller is on the right, and cut selvedges are at the front of the fabric take up roll.

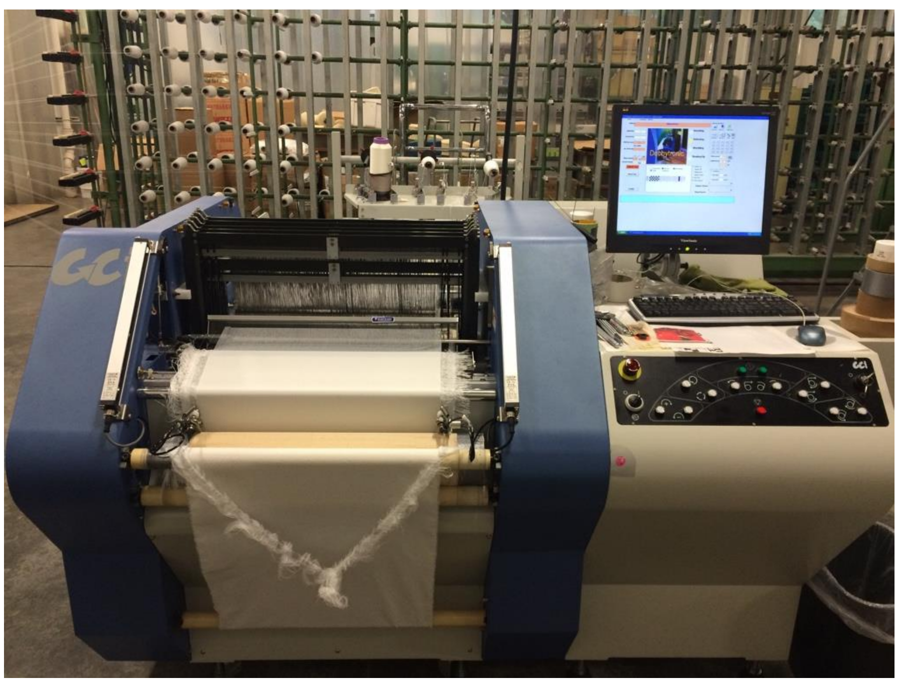


Figure 4.4 Weaving on CCI Loom in the laboratories of the College of Textiles

The CCI loom has computer-controlled shedding and an automatic weft selection device. This loom is capable of producing all types of complicated weaving designs and weft arrangements. Warp tension is maintained at a constant level by the electronic let-off device, ensuring high quality samples [54].

The weave design including weave structure and pick density were inserted into the computer controller to set up the loom for weaving. The shedding speed was controlled electronically to maximize the speed of weaving without breaking warp ends. The loom needed to be monitored after beginning to weave since it would not automatically stop if a warp or filling yarn breaks (as it would be on a full width production loom).

The specified woven length was labeled at each one-yard point. The weave structure of body and selvedge and fabric style numbers were also labeled with permanent ink on the fabric near the selvedge. Information on Fabric A and Fabric B in detail is shown in Tables 2 and 3 in the Appendices.

4.1.5 Scouring and Drying

Polyester samples developed in the laboratories of the College of Textiles and commercially available fabrics needed to be scoured and dried before digital printing.

It is very important to scour fabrics to remove any machine oil or other contamination on the fabrics, which would affect the appearance and quality of digital printing. The Mini-soft Fabric Dyeing machine shown in Figure 4.5 was used for scouring in the College of Textiles Pilot Lab.

Figure 4.5 Thies mini-soft fabric dyeing machine in the College of Textiles Pilot Laboratory

The two rolls of sample fabrics were sewn together to form a continuous length of fabric that was loaded into the machine. 2g/L Soda Ash and 2g/L CLARITE JBS were weighed and added to the machine. After closing the hatch door, the fabrics were washed and spun in the Thies until all the wax and machine oil were removed.

After scouring, the fabrics were dried in the continuous oven shown in Figure 4.6.

Figure 4.6 Sample fabrics moving through the narrow continuous oven in the College of Textiles Pilot Lab

The continuous oven squeezes excess moisture between two rollers from the fabrics and dries them. Fabrics may become wrinkled during this process since there is no tenter framing in this continuous oven to hold the fabrics under tension on pins at the selvedges.

4.1.6 Pretreatment

Pretreatment can optimize print quality, durability, fabric integrity, and ink efficiency. After pretreatment, the fabric is prepared to print.

PrintRite DP textile pretreatment technologies were used; they deliver high optical density blacks, expand color gamut with high color vibrancy, improve crock, maintain fabric hand, and produce an overall desired textile experience [55].

PrintRite™ DP307, an innovative, ready-to-use, waterborne pre-treatment formulation for the preparation of light-colored polyester, was applied to the fabric through padding. According to the manufacturer, it provides a high quality digital print image with vivid colors, sharp definition and excellent wash durability, while maintaining the soft textile feel and flexibility of the original fabric [55].

To achieve the best results, PrintRite™ DP307 needs to be uniformly applied to the fabric at an add-on weight of about 0.06 g/in^2 (90 g/m^2) for polyester fabric.

Add-on is the amount of chemicals applied to the fabric, it depends on the concentration of chemicals in the formulation and the wet pickup of the substrate.

% Add-on=Concentration of formulation× Wet pickup

In this case, add-on should be constant in different fabrics. To meet the requirement of add-on weight, wet pickup needs to be measured to determine the exact concentration of the chemicals.

Wet pickup is the amount of chemical formulation absorbed by the fabric and is usually expressed as a percentage of the weight of the dry fabric.

%Wet pick up $=\frac{final\ wet\ wt. - original\ dry\ wt.}{original\ dry\ fabric\ weight} \times 100$

Wet pickup results of designed fabrics are shown in Table 4.2.

Table 4.2 Wet pickup

Fabric Content		Dry (g)	Wet (g)	Wet pickup (%)
Warp	Weft			
Filament	Filament	4.63	7.71	66.52
Filament	Spun	4.31	8.03	86.31
Spun	Filament	5.38	10.58	96.65
Spun	Spun	5.42	10.36	91.14

Filament-filament fabric has the lowest wet pickup. As long as there is spun yarn in the fabric, wet pickup is relatively high, which up to 97%.

To make the add-on in different fabrics similar, it is essential to treat the 100% spun content fabrics and the spun combination fabrics with a 2% DP 307 solution, and the filaments with the 4% DP 307 solution.

Figure 4.7 Pretreatment though padding

PrintRite™ DP307 was applied to the fabric through padding. The fabric was padded at a speed of 1.1 m/min with 1 bar of pressure. And then, fabrics were dried in the continuous oven. Recommended drying/curing temperature is 135°C (275°F) until dry to the touch. Recommended dye-fixation temperature is 185-190°C (365°-374°F) for 1-3 minutes for the sublimation process. Fabrics need to be well-aligned during this process to prevent wrinkling.

4.2 Digital Printing

Commercially available fabrics and the designed fabrics developed in the laboratories of the College of Textiles were printed with the MS-JP5 Evo digital printer equipped with Kyocera print heads.

With specific focus on substrate fabric development in digital inkjet printing, two impacting factors, ink and print mode, are controlled in this study.

Vendor supplied pigment ink was chosen for digital printing in this research.

Dry and wet crocking test specimens are at least 2.0×5.1in and position for testing preferably with the long dimension oblique to warp and weft.

The Test pattern prints different sizes of lines in warp and weft direction to evaluate the clarity of printing. B, C, D Mode were selected for test pattern to compare the impact of droplet size on print clarity.

4.2.1 Calibration and Characterization

RIPMaster v11 and Xrite ilProfiler version 1.6.3 software were used for calibration and characterization, and creating profiles for the ink and substrate combinations.

A Color Table (CTB) profile was developed by RIPMaster software. A CTB profile is proprietary to RIPMaster and was used in the printer calibration and color gamut plotting. The procedure for color calibration and creation of CTB profile is shown in Appendix B.

A color channels page was created in RIPMaster software. Six colors (cyan, magenta, yellow, black, blue and red) were digital printed and heat set at 200 °C for two minutes, which is necessary since the unset color could crock or migrate, and possibly contaminate adjoining colors.

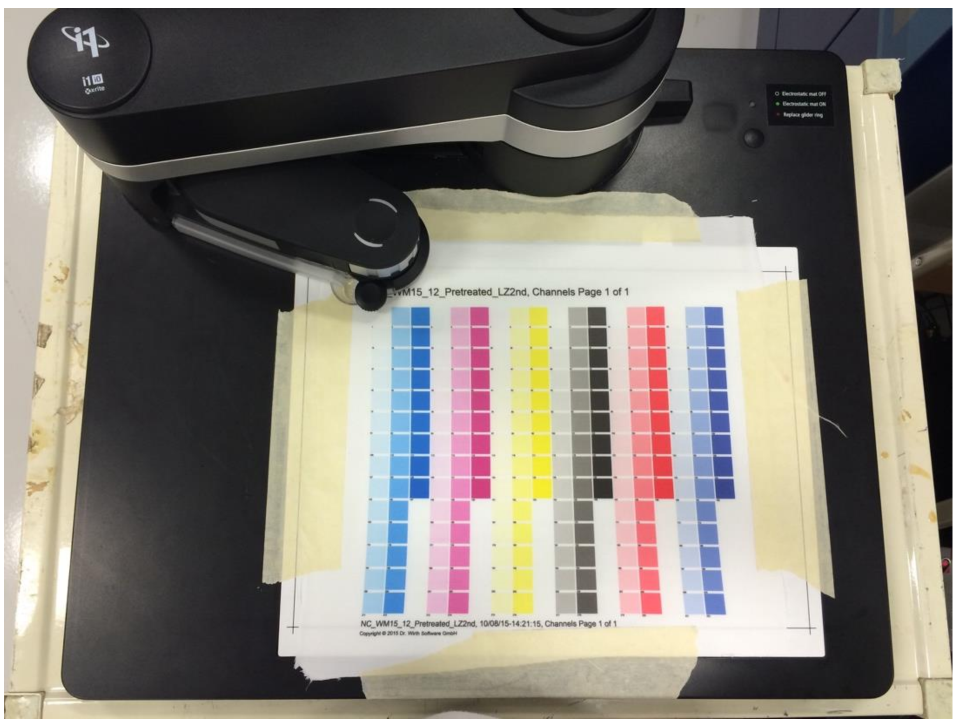


Figure 4.8 Spectrophotometer reading

After heat setting of the printed color channels, they were measured by an X-rite 2nd generation iliO spectrophotometer to form the color gamut, data was inputted using L* a* and b* values to describe the individual and mixed color. Calibration of commercial fabrics and designed fabrics were performed. A color blanket was generated after characterization, which provided physical samples of printed color chips, used as a resource for color-matching.

Color gamut was created to show the range of colors available to the designer for this basecloth. The color gamut was digital printed as showed below.

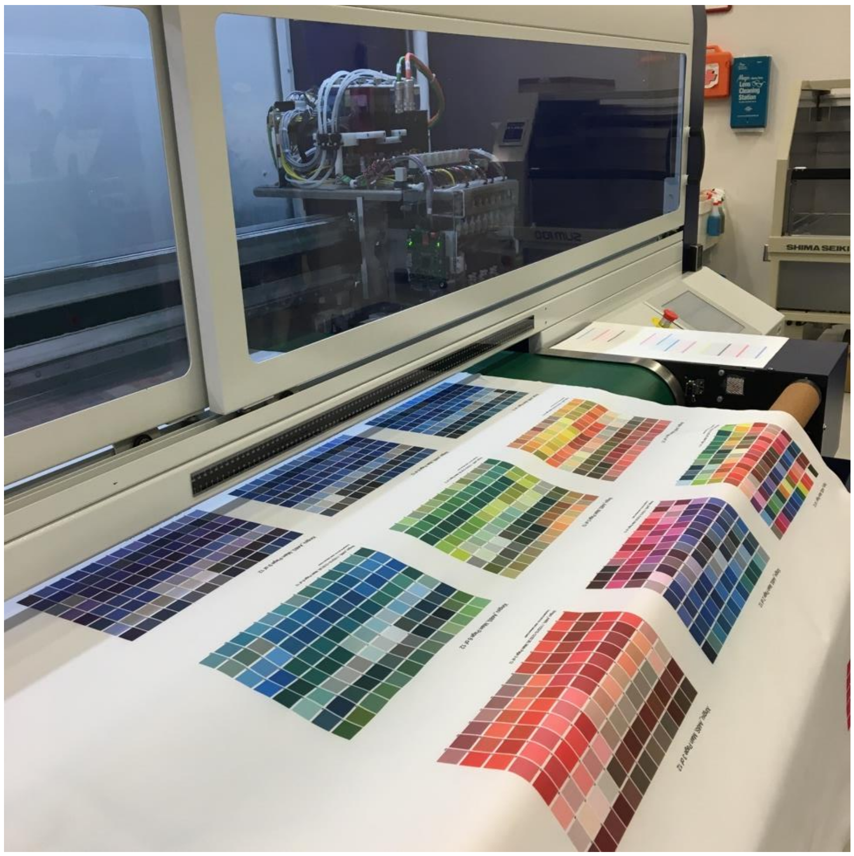


Figure 4.9 Digital printing of the color gamut on the polyester substrate

4.3 Heat Setting (Curing)

After printing, the sample fabric requires heat setting to activate the pigments and to set the ink on the material. Two types of equipment were available and used for heat setting.

For the long continuous fabric roll, a continuous oven at a speed of 0.91 m/min at 180°C as shown in Figure 4.10 were applied.

Figure 4.10 The sample fabric roll heat set through a continuous oven

For the small pieces of fabric, the Werner Mathis AG oven was used for heat setting.

Commercial fabrics and designed fabrics are required to be heat set in the Werner Mathis AG for 2 minutes at 180°C.

Figure 4.11 Small piece of fabric heat set in Werner Mathis AG

CHAPTER 5 TESTING RESULTS AND DISCUSSION

5.1 Physical properties testing results of fabrics

After scouring, preshrinking (optional), pretreatment, printing (optional), physical properties testing including basis weight, tear strength, tensile strength, seam strength and abrasion and shrinkage were measured.

5.1.1 Weight

Basis weight is a critical factor which impacts the durability of polyester woven fabric.

A Universal Sample Cutter (King Scales) was used to cut samples. Samples were weighed with a King Yield Scale.

5.1.2 Tear Strength

Tear strength relates to the durability of fabrics which impacts the final quality of digital printed products.

According to ASTM D2261, polyester woven fabrics were cut into 3 inches by 8 inches rectangular specimens. A 3-inch-long preliminary cut was made at the center of the width in each specimen. Five repeat specimens were prepared in both warp and weft direction for each type of polyester woven fabric.

Conditioned specimens were tested in the standard atmosphere, which is 21 ± 1 ˚C (70 ± 2 ˚F) and 65 ± 2 % relative humidity.

QTest™/5 was used to test tear strength.

Figure 5.1 Tear strength test

5.1.3 Tensile Strength and Seam Strength

Tensile and seam strength are crucial for final digital printed products, especially for cushion or pillow covers. ASTM D1683 was chosen as the testing standard.

Polyester woven samples were cut into 4 inches by 14 inches specimens in both warp and weft direction. Samples were repeated five times to ensure the final test results were accurate.

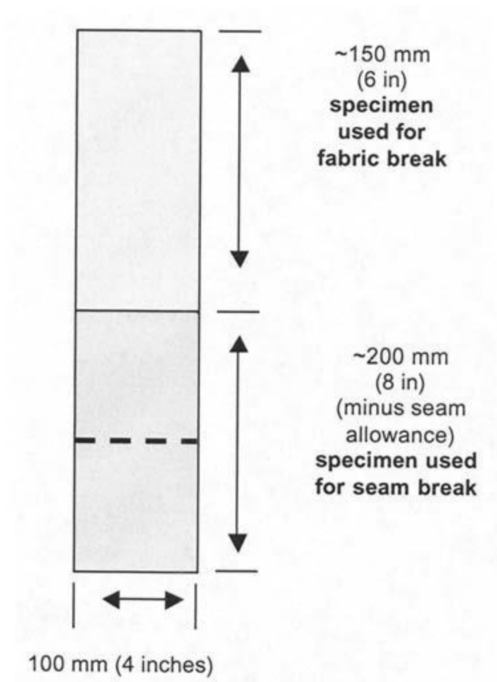


Figure 5.2 Seamed specimen removed from manufactured item

As Figure 5.2 shows, the first 6 inches of the specimen was used for testing fabric break, which is tensile strength of the fabric sample in the same direction. The other 8 inches was used for testing seam break. The standard advises to fold the specimen 4 inches from the other end with the fold parallel to the short direction of the fabric. Next, the standard procedure requires sewing of a seam and cutting the fold open. Each test specimen will contain sufficient material for one seamed and one fabric test (ASTM D1683).

Samples were sewn by a manufacturing vendor participating in the funded project.

According to ASTM D1683, seam type was SSn-2, stitch type was 301.

The size of needle for sewing was metric 140. Size of sewing thread was tex 45 polyester thread.

According to the manufacturing vendor's standards, samples were sewn at 6 spi (stitches per inch) stitch density, which is lower than ASTM standards for the requirement of spi.

QTest™/5 was applied to test tensile and seam strength.

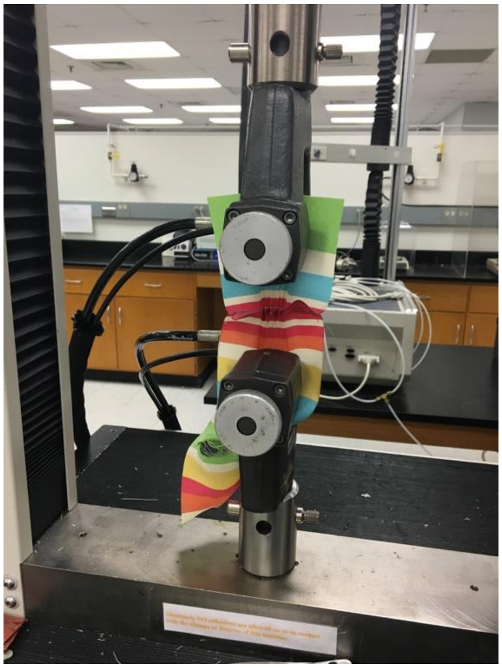


Figure 5.3 Seam strength test

5.1.4 Abrasion

The Wyzenbeek test method was used for abrasion testing since it's typical for the end use of the woven polyester samples.

Test specimens were 73mm by 245mm in both warp and weft directions according ASTM D 4157. At least two repeat specimens in each case were tested.

Cotton Duck #10 was used as the abradant.

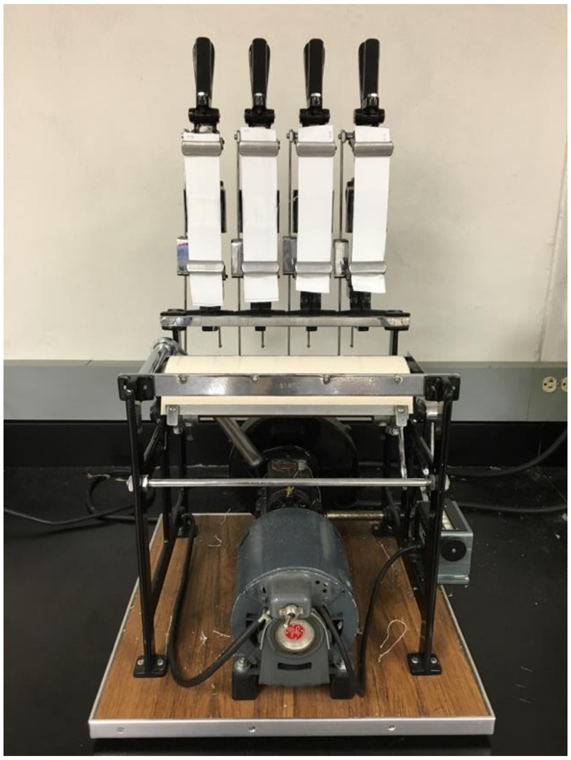


Figure 5.4 Abrasion test (Wyzenbeek)

According to industrial upholstery fabric testing standards, light duty is 15,000 cycles; heavy duty is 30,000 cycles. Samples were rated from 1 to 5.

1= Very obvious wear - 10 or more yarn breaks

2= Obvious wear - 5 to 9 yarn breaks, severe appearance change

3= Noticeable wear - 1 to 4 yarn breaks, medium appearance change

4= Very slight wear - no yarn breaks, slight appearance change

5= No apparent wear

Physical properties testing results of polyester woven samples show in Figure 5.1 below.

Table 5.1 Physical properties results of polyester woven samples

Sample Name	Supplier	Warp Yarn (PET)	Weft Yarn (PET)	Count epi x ppi	Weight (osy)	Tear Strength (Peak Load lbf)		Peak Load lbf				Light Duty (15,000 cycles)		Heavy Duty (30,000 cycles)	
								Test direction Warp		Test direction Weft					
						Across Warp	Across Fill	Fabric	Seam	Fabric	Seam	Warp	Weft	Warp	Weft
NC_WM15_011	B	2/150/48 dull stretch textured	2/150/48 denier	66×62	5.92	10.75	10.06	356.04	69.66	322.06	57.46	5	5	5	5
NC_WM15_012	B	2/150/48 dull stretch textured	30/2 ring spun	67×56	6.16	13.63	13.38	351.69	67.93	250.46	50.66	5	5	5	5
NC_WM15_014	A	12.4/1 OE	12.4/1 OE	67×44	7.44	13.89	11.42	288.40	59.95	190.28	58.25	5	5	5	5
NC_WM16_016	D	280 denier filament	10/1 spun	83×33	5.52	17.64	13.49	318.21	58.56	152.20	47.33	5	4	5	3
A48F	Designed	2/145	2/145/36	73×54	6.88	16.62	13.67	350.24	55.73	263.17	50.99	5	5	5	5
A48S		2/145	19/1	76×54	6.72	17.08	7.84	347.81	59.25	142.46	69.11	5	5	5	5
B25F		16/1	4/150/34	103×28	8.4	34.11	30.46	352.22	49.87	247.79	49.78	5	4	5	4
B25S		16/1	8/1	93×28	7.52	34.85	33.77	334.21	52.36	247.35	49.23	4	5	4	4
AD39	D	280	10/1	88×33	5.92			284.75	57.09	147.53	53.88	5	5	5	5
DF05	D	150	150	75×54	2.96			168.03	59.49	130.52	57.83	5	5	5	5
GE14	D	280	280	56×48	4.32			237.49	54.70	217.03	53.75	5	5	5	5

Screen printed polyester woven samples AD39, DF05 and GE14 provided by a manufacturer participating in the funded project were also compared with commercial available and designed polyester samples. Tear strength of samples AD39, DF05 and GE14 wasn't tested due to limited material.

Sample NC_WM15_011, NC_WM15_012 and NC_WM15_014 have similar tear strength, NC_WM15_016's tear strength is the highest among the four commercial samples. Tear strength across the warp is slightly higher than tear strength across the weft. When the warp is spun yarn, tear strength is twice as high as any other fabric.

Tensile strength in the warp direction is higher than tensile strength in the weft direction. Tensile strength is relating to fabric basis weight; the higher fabric weight, the higher the tensile strength.

Four commercial samples have similar seam strengths. However, for the designed polyester woven samples, spun warp fabric has the lowest seam strength.

Yarn type has an impact on abrasion. The filament yarn fabrics have better abrasion performance than spun yarn fabrics. Spun combinations like sample B25F and B25S have lower rate (4) of abrasion test. However, with spun yarns in warp and filling, NC_WM15_014 passed the abrasion test.

Except for the abrasion test results in the weft direction of NC_WM15_016, the commercial samples passed Testing Standards for upholstery fabrics, even though stitch density in the seam strength test is lower than ASTM standards.

5.1.5 Shrinkage

Shrinkage is a very critical problem in the preparation process, it determines the size and weight of final digital printed products. Shrinkage increases the density and weight of fabric, which affects the final print quality.

The width and length, weight and thread density of designed polyester woven samples were measured before and after scouring and curing. Shrinkage of polyester samples show in Table 5.2 below.

Table 5.2 Shrinkage of designed polyester woven samples after scoring and curing

<table>
<tr><th colspan="2">Warp (PET)</th><th colspan="2">Weft (PET)</th><th rowspan="2">Structure</th><th rowspan="2">Shrinkage decrease in width after scouring and drying</th><th rowspan="2">Shrinkage decrease in width after curing</th><th rowspan="2">Shrinkage decrease in length after curing</th><th rowspan="2">Increase in weight after scouring and curing</th><th rowspan="2">Increase in density after scouring and curing</th></tr>
<tr><th>Size</th><th>Epi</th><th>Size</th><th>Ppi</th></tr>
<tr><td rowspan="2">2/145 denier</td><td rowspan="2">64</td><td>2/145/36 denier</td><td rowspan="2">52</td><td rowspan="2">Plain</td><td>11.8%</td><td>1.2%</td><td>1.8%</td><td>32.1%</td><td>14.1% weft 11.5% warp</td></tr>
<tr><td>19/1 cc</td><td>13.1%</td><td>0.8%</td><td>2.5%</td><td>28.8%</td><td>18.8% weft 13.5% warp</td></tr>
<tr><td rowspan="2">16/1 cc</td><td rowspan="2">84</td><td>4/150/34 denier</td><td rowspan="2">28</td><td rowspan="2">2/1 Oxford</td><td>12.4%</td><td>3.3%</td><td>3.8%</td><td>30.1%</td><td>21.4% weft 14.3% warp</td></tr>
<tr><td>8/1 cc</td><td>5.2%</td><td>2.7%</td><td>2.4%</td><td>15.7%</td><td>10.7% weft 10.7% warp</td></tr>
</table>

Shrinkage mainly occurred during scouring. Polyester woven fabric with filament yarns shrinks up to 13% during scouring while it's only 5% shrinkage when the warp and weft are both spun yarn. The spun-spun fabric has the smallest shrinkage. As long as there is filament yarn in the fabric, the fabric shrinks twice as much as the 100% spun or spun-spun fabrics.

Shrinkage also occurs during heat setting due to the high temperature, and is noted at approximately 2% shrinkage in both directions.

Increase in density after scouring and curing of polyester samples were also measured, along with the size and weight of fabrics. These shrinkage results are vital for fabric preparation, especially for predicting the size, weight and thread density of certain polyester woven fabric after scouring and heat setting.

5.2 Crock Fastness

Crocking is the transfer of colorant from the surface of a colored fabric to another surface.

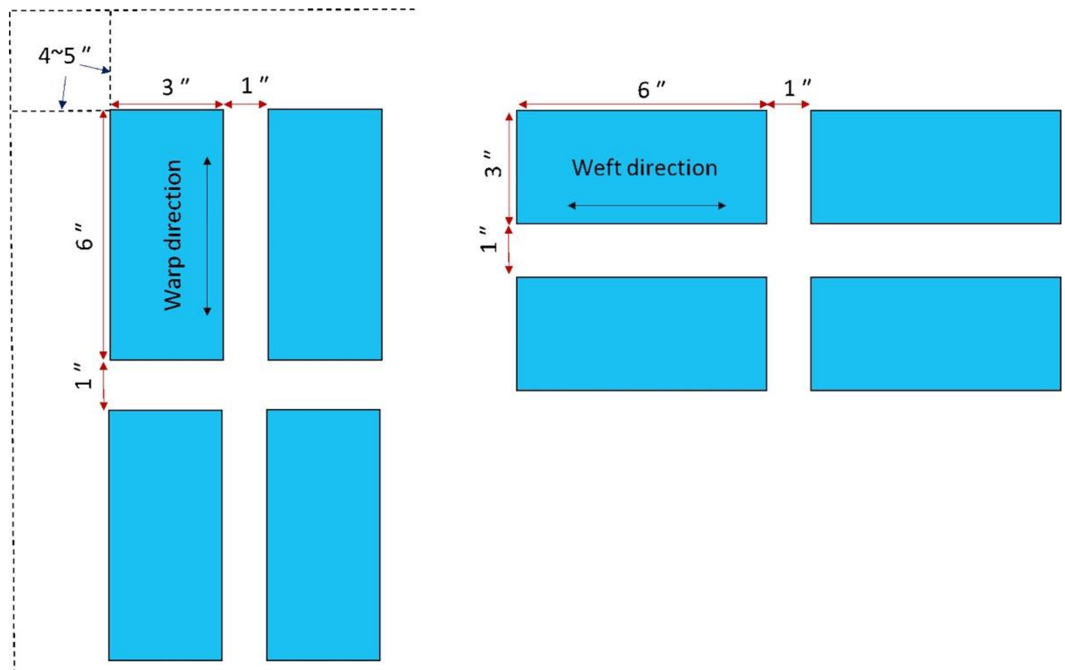


Figure 5.5 Schematic of sample pattern arrangement in crocking colorfastness test: warp and weft directions

The crocking test patterns were prepared by digital printing at least 5.1″ by 2″ blocks of color on four commercial fabrics. Six colors: cyan, magenta, yellow, black, blue and red in both warp and weft directions were printed. Schematic of sample pattern arrangement in crocking colorfastness test in warp and weft directions is shown in Figure 5.5. The dotted lines represent the edge or selvedge of fabric.

The colorfastness to dry and wet crocking was tested using the A.A.T.C.C. Crockmeter (Atlas Electric Device Co.) to observe the amount of color transfer from the surface of woven fabric digital printed with pigment ink to the white test square of bleached cotton.

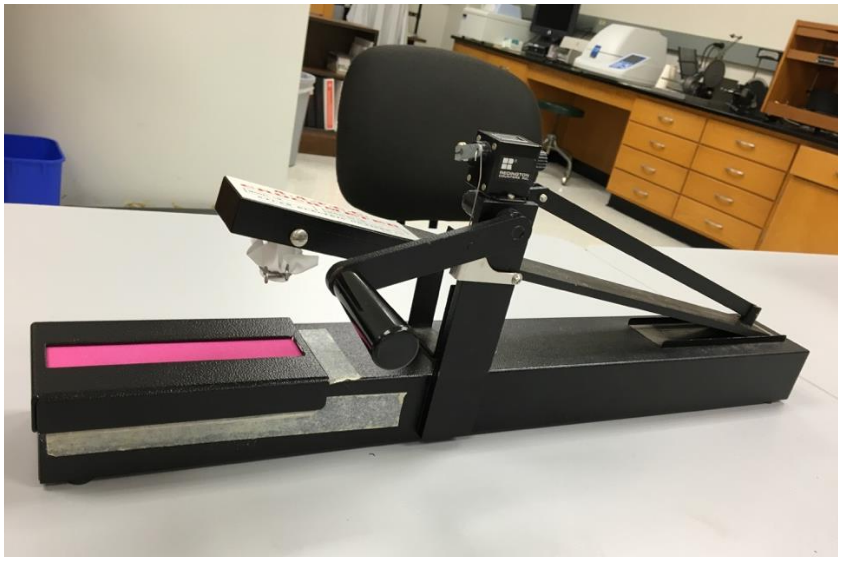


Figure 5.6 Crockmeter for testing crock fastness

Before conducting the crocking test, the test fabric samples and the white test squares were conditioned overnight in 21 ± 1 ˚C (70 ± 2 ˚F) and 65 ± 2 % RH. For the wet crocking test, the white test square was pre-wetted by 65 ± 2 % wet pick-up. The dry or wet white test square rubbed the surface of the test fabric sample placed on the crockmeter by cranking the meter handle back and forth 20 times, and the same procedure was repeated three times for each test fabric samples. After that, the dry and wet crocking fastness of the test fabric samples was evaluated in rating the staining of white test square by means of grayscale in the X-Rite Colormetric. (AATCC 8)

The crock fastness results of commercial available fabrics show in Figure 5.3. Pretreated and non-pretreated NC_WM15_012 samples were compared.

Grey scale stain value is from 1 to 5, 1 is poor 5 is excellent.

Table 5.3 Crock fastness of selected commercial fabrics [51]

Direction	D/W	Color	Pigment ink G1-CMYK			
			Pretreated			Non-pretreated
			NC_WM 15_015	NC_WM 15_014	NC_WM 15_012	NC_WM 15_012
Weft	Dry	Cyan	2.5	2	1.5	2.5
		Magenta	2.5	2	1.5	2.5
		Yellow	3	2	2	2.5
		Black	2	2	1.5	3
		Blue	3	1.5	2	3
		Red	2.5	2	2	2.5
	Wet	Cyan	2.5	2	1.5	2.5
		Magenta	2.5	1.5	1.5	2.5
		Yellow	3	1.5	2	2.5
		Black	2	1	1	2
		Blue	3	2	2	3
		Red	2.5	1.5	1.5	2.5
Warp	Dry	Cyan	2.5	2	2	2.5
		Magenta	2.5	2	2	2.5
		Yellow	3	2	2	2.5
		Black	2.5	2	1.5	3
		Blue	3.5	2	2	3.5
		Red	3	2	2	2.5
	Wet	Cyan	3.5	2	1.5	2.5
		Magenta	3.5	1.5	1.5	2.5
		Yellow	3.5	1.5	1.5	2.5
		Black	2.5	1	1	2
		Blue	3.5	2	2.5	3
		Red	3.5	1.5	1.5	2.5

According to Testing Standards, grey scale stain value of dry crock fastness should reach 4, and wet crock fastness should not be less than 3. Only the color blue in the warp and weft direction meets the Testing Standards in dry and wet crock fastness. As the other pigment colors failed this type of pigment ink is not preferred, and an alternative pigment must be found for further printing.

GS stain value of dry crock fastness is slightly better than wet crock fastness.

Pretreated NC_WM15_015 samples and non-pretreated NC_WM15_012 samples have better performance in crock fastness.

GS stain value of non-pretreated NC_WM15_012 is better than GS stain value of pretreated NC_WM15_012 samples, which is in conflict with the research results found in the Literature Review.

To understand the impact of fabric properties on crock fastness better, designed polyester woven fabrics were also tested.

Table 5.4 shows the gray scale of crock fastness of Fabric A (filament warp) and Fabric B (spun warp).

Table 5.4 Dry and wet crocking test of designed polyester woven samples

Color	Sample	Warp direction		Weft direction	
		Dry	Wet	Dry	Wet
Cyan	A52S	3	3.5	2.5	2.5
	A52F	3.5	3.5	2.5	3
	B25F	2	1.5	2	1.5
	B28F	2	1.5	2	1.5
Magenta	A52S	3	3	3	2.5
	A52F	3.5	3	3	2.5
	B25F	2	1.5	2	1.5
	B28F	2	1.5	2	1.5
Yellow	A52S	3	3	3.5	2.5
	A52F	3.5	3.5	2.5	2.5
	B25F	2	1.5	2	1.5
	B28F	2	1.5	2	1.5
Black	A52S	3.5	3	3.5	2.5
	A52F	3.5	3.5	2.5	3
	B25F	2	1.5	2.5	1.5
	B28F	2.5	1.5	2.5	1.5
Blue	A52S	3.5	3	3.5	2.5
	A52F	4	4	3.5	3
	B25F	2	1.5	2.5	1.5
	B28F	2.5	1.5	2	1.5
Red	A52S	3.5	3.5	3.5	2.5
	A52F	3.5	3.5	3	3
	B25F	2	2	2	1.5
	B28F	2	1.5	2	1.5

Designed polyester woven fabrics had better performance in dry and wet crocking than commercial fabrics. More fabrics passed the Testing Standards.

The best crock fastness is achieved when the warp and weft are both filament yarn. Filament polyester warp fabric has better crock fastness.

5.3 Print Clarity

Print clarity of a digitally printed product has great impact on the final aesthetic appearance and performance of the printed products. It's critical to improve print clarity in order to develop the final product's qualities in meeting performance, styling and cost requirements. In this research, print clarity of digitally printed images on various substrates is considered as image sharpness. Sharpness is defined as the clarity of detail in an image, which is a combination of resolution and acutance [62]. Sharpness determines the amount of detail an imaging system can reproduce. It can be characterized by the boundary zones of different tones or colors [63]. A quantitative test method to evaluate print clarity was created based on the estimation of image sharpness.

5.3.1 Test Pattern

The Modulation Transfer Function, MTF, is used to illustrate radiographic sharpness, and is a measurement of the contrast reduction, or blurring, imposed by the system as a function of spatial frequency. It is more convenient to measure the response to discrete functions for radiographic imaging, such as bar patterns and square waves. The response to a square wave as a function of frequency or wavelength is referred to as the Contrast Transfer Function, CTF. It is a function that relates how a bar pattern is transferred to an imaging system as a function of the dimensions of the bars [58]. In this research, the CTF was determined experimentally for a test pattern, which was used for the quantitative evaluation of print clarity on paper or textile substrate. Contrast of image, C_{image}, which characterizes the print clarity of gap-bar-gap set test pattern, was compared for different conditions.

The test pattern is a set of increasing sizes of bars with aggregate distance between lines and was created in Adobe Photoshop™ to be printed in both the woven fabric's warp and weft directions as shown in Figure 5.7.

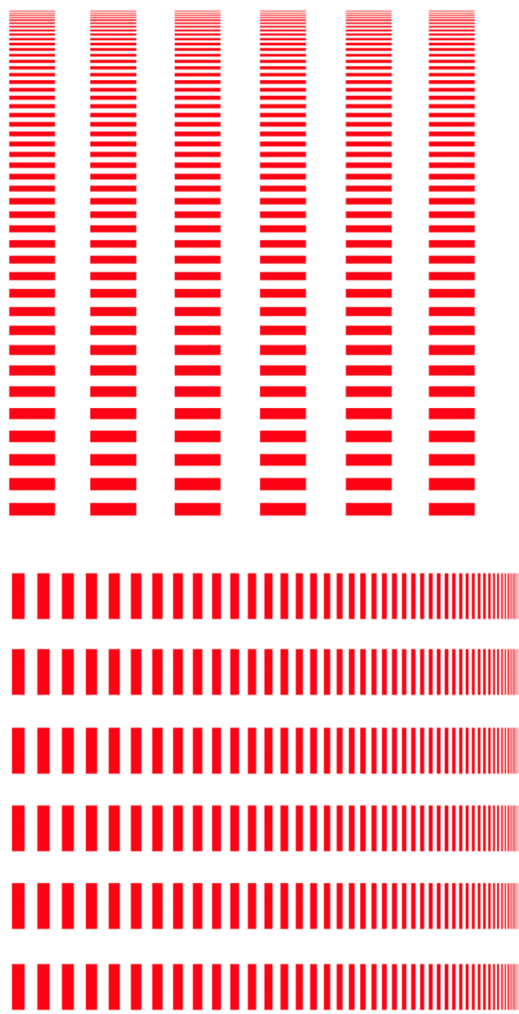


Figure 5.7 Test Pattern in Adobe Photoshop™

The finest bar is 0.4333-inch-long and 0.002-inches-wide. The finest yarn in this research is 2/145/36 denier filament polyester, its diameter is 0.0084 inch. The smallest bar is far finer than the yarn diameter.

The width of each line increased by 0.001 or 0.002 inch compared to the previous line, the distances between two lines were the same as the width of the previous line.

Six channels for six colors CMYKRB (cyan, magenta, yellow, black, red, and blue) were created for the comparison of six color inks.

5.3.2 Design of Experiment

Understanding the substrate factors impacting print clarity of digital printing will contribute to the quality and efficiency of digital printing. Four parameters were considered in the design of experiment:

Color

Six colors: cyan, magenta, yellow, black, blue and red, were digitally printed in this test pattern on selected woven polyester samples. Different colors may have different results in print clarity due to diverse chemicals in the ink formulation. Black and yellow were predicted to be the best and worst in visual assessment of print clarity, respectively, by the digital printing companies. Using the quantitative test method to compare the print clarity of CMYKRB colors is crucial.

Direction

Two types of directions were considered. The orientation of the design allows for a comparison of printing across the warp and across the filling yarns.

The direction of test pattern printing is compared with the motion of print head: the direction of test pattern is the same as the print head motion and the direction of test pattern is perpendicular to the print head motion.

The direction of test pattern was also analyzed with warp or weft direction: the direction of test pattern lines paralleled with warp yarns and the direction of test pattern lines paralleled with weft yarns.

These two types of directions may have impact on print clarity.

Fabric (Substrate)

Yarn type, yarn size, yarn density, fabric construction are important factors lead that may lead to different results in wet pickup, fabric basis weight, cover factor and fabric texture, which influence the print clarity.

Four designed fabrics (A52F, A52S, B28F, B28S) and three selected commercial fabrics (NC_WM15_012, NC_WM15_014, NC_WM16_016) as well as a cotton-cotton/linen blended commercially available fabric specifically designed for digital print (from Springs Creative) were evaluated in this case.

Husky® Copy30 (30% post-consumer recycled content) Paper was digitally printed first as the control, and the result of test pattern clarity on paper was also compared with multiple fabric samples.

Identification of the relationships between print clarity and substrate properties would benefit the digital printing industry and the market.

Print Mode

Droplet size (ink volume) of pigment ink is from 4 to 72 pl, which is varied by the Print Mode setting in MS-JP5 Evo digital printer. Each mode has a different droplet range as seen in Table 5.5.

Table 5.5 MS JP5 Print Modes and Drop Sizes [57]

A	4	7	12												
B	7	12	18												
C	4	7	11	14	16	19	24								
D	4	8	12	16	19										
E	4	8	12	15	19	21	26	31	36						
F	4	8	16	19	22	25	28	33	38	43	48				
G	4	8	12	16	20	28	36	42	48	54					
H	4	8	12	16	20	24	28	32	36	40	48	54	60	66	72

The print mode setting may change the final print quality on different substrates. The optimum print mode of each substrate may differ due to the fiber type, yarn size, yarn type, fabric construction and other properties. Three printing modes on the MS printer: B2, C2 and D2 were applied on the fabrics for assessment based on the suggestions from suppliers and industry experts.

5.3.3 Experimental Work

Print

In order to maintain the consistency of pigment ink in this research, a MS JP7 printer in a commercial or industrial production setting was used. The MS JP7 printer has the same technical specifications or capabilities in dpi resolution, gray levels, drop size and printing width as the MS JP5 Evo printer, but with a higher production speed, which doesn't impact print clarity of the experimental samples.

Seven woven polyester samples prepared for digital printing, along with a paper substrate, were printed with the identical pigment inks. At least five repeated test patterns were printed under each condition to ensure accuracy of the print clarity evaluation.

A preliminary trial of the digitally printed test pattern on paper substrate was run as a control test. Different results in print clarity in two directions could be observed: the test pattern is clearer when the direction of the test pattern line is the same as the motion of print head, which is likely due to the motion of the print head. The factor of the head's printing direction was considered in the design of experiments and specifically in the design of experiments in this research.

To eliminate the impact of print head motion on print clarity, woven polyester samples were placed on the printer's belt in two directions: fabric warp is either parallel or perpendicular to the adhesive belt, to ensure the direction of the test pattern line is the same as the motion of print head. Samples were carefully labeled with the sample name, direction and print mode to identify different situations.

Digitally printed woven polyester samples were cured at 320°F to 340°F for 25 seconds. All the samples for evaluating print clarity were printed and cured on the same day with the same procedure. After completing the printed test pattern on multiple substrates, samples were cut and scanned.

Scan

An EPSON Expression 11000XL Photo Scanner was used to scan multiple samples.

Settings of the scanner were adjusted in the EPSON Scan software to obtain the optimum image for evaluating print clarity. The brightness and contrast were set to 0, and the images were saved as Color image type and at 1200 dpi, which is the highest resolution. All the samples were scanned in the same scanner with the same settings and saved as TIFF files to ensure the integrity of the files. The TIFF files were labeled with sample name, direction, pigment color and print mode.

5.3.4 Work Data Processing

Data processing is a vital part of this analysis after scanning all the digital printed samples. Several software packages, such as Image-Pro and MATLAB, were used to process data to analyze and compare image contrast of test pattern under different conditions.

Image-Pro

Image-Pro Premier in the lab at Department of Forestry in the College of Natural Resources at NCSU was used to extract data from the TIFF files.

Its technique for performing Automatic Measurements is claimed to be the foremost solution for gathering data from images by segmentation systems [59]. Image-Pro provides a sample step-wise approach to the problem, exporting data from the TIFF image files to Excel and Text files.

TIFF files of the test pattern were opened in Image-Pro Premier software as Figure 5.8 shows.

It can be observed that from the 16th line of the test pattern, the printed image starts to become clear by visual assessment by the human eye. To compare the print clarity under different conditions, analyzing the first 16 lines of test pattern was required.

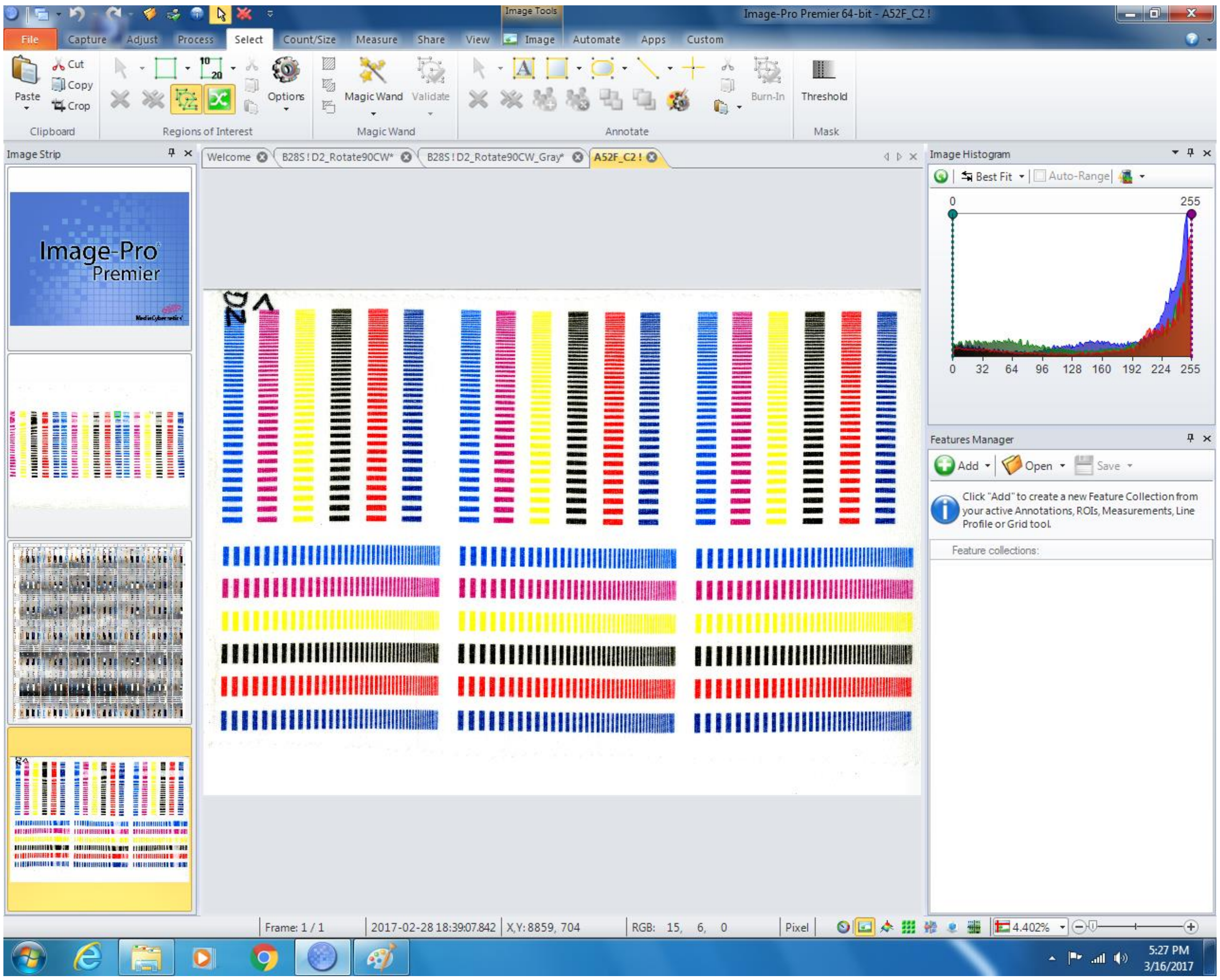


Figure 5.8 Test pattern image file in Image-Pro Premier

The region of interest in the test pattern was selected by drawing a rectangle around the selected area and cropping the image to contain only this area as shown in Figure 5.9. The selected area of the image was converted to gray scale by adjusting the image into Mono 8bpp. Multichannel color images were converted into single channels in gray scale digital images where the value of each pixel is a single number and carries only luminous intensity information. It is also referred to as black-and-white and is composed exclusively of shades of gray, varying from black at the weakest intensity to white at the strongest [60].

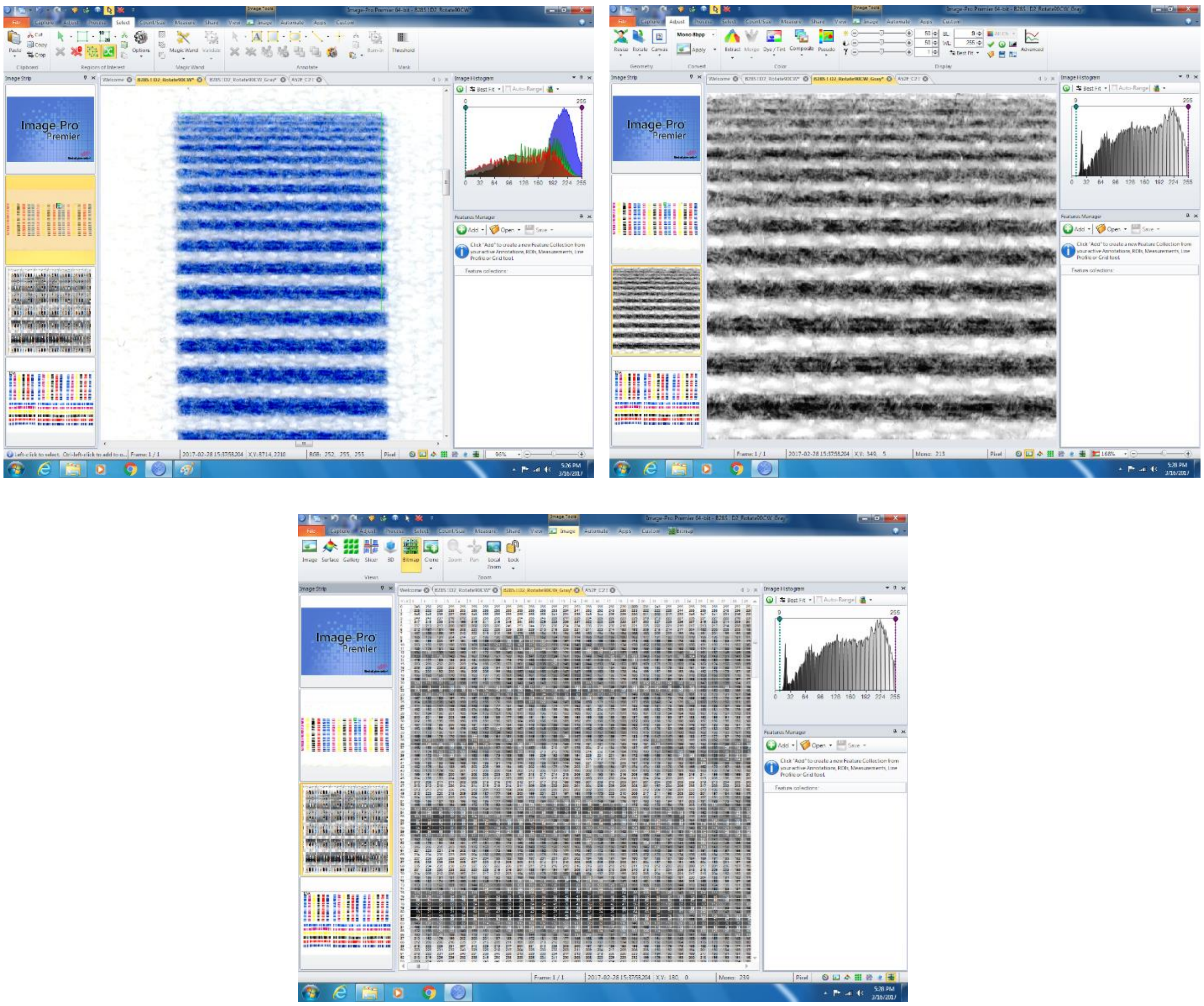


Figure 5.9 Process test pattern in Image-Pro Premier

The intensity threshold needed to be adjusted before converting the image to Mono 8bpp. In some cases, for example the colors red and magenta, it was necessary to make the gray scale image represent the print clarity of test pattern sufficiently.

The gray scale of the selected area TIFF images was converted to Excel or Text format by applying “Bitmap” in the “Image” command. Each pixel in the TIFF files was converted to a number range from 0 to 255, which reflects the luminance of the color. Excel files need to be formatted into number format instead of general.

Each line of numbers in Excel or Text files was averaged to represent the luminance of the pixel at this specified position.

MATLAB

MATLAB® was applied to analyze and compare the data extracted from Image-Pro. According to the literature review, a scanning electron micrograph along the edge of the coarse scale of the standard target is shown in Figure 5.10 [58].

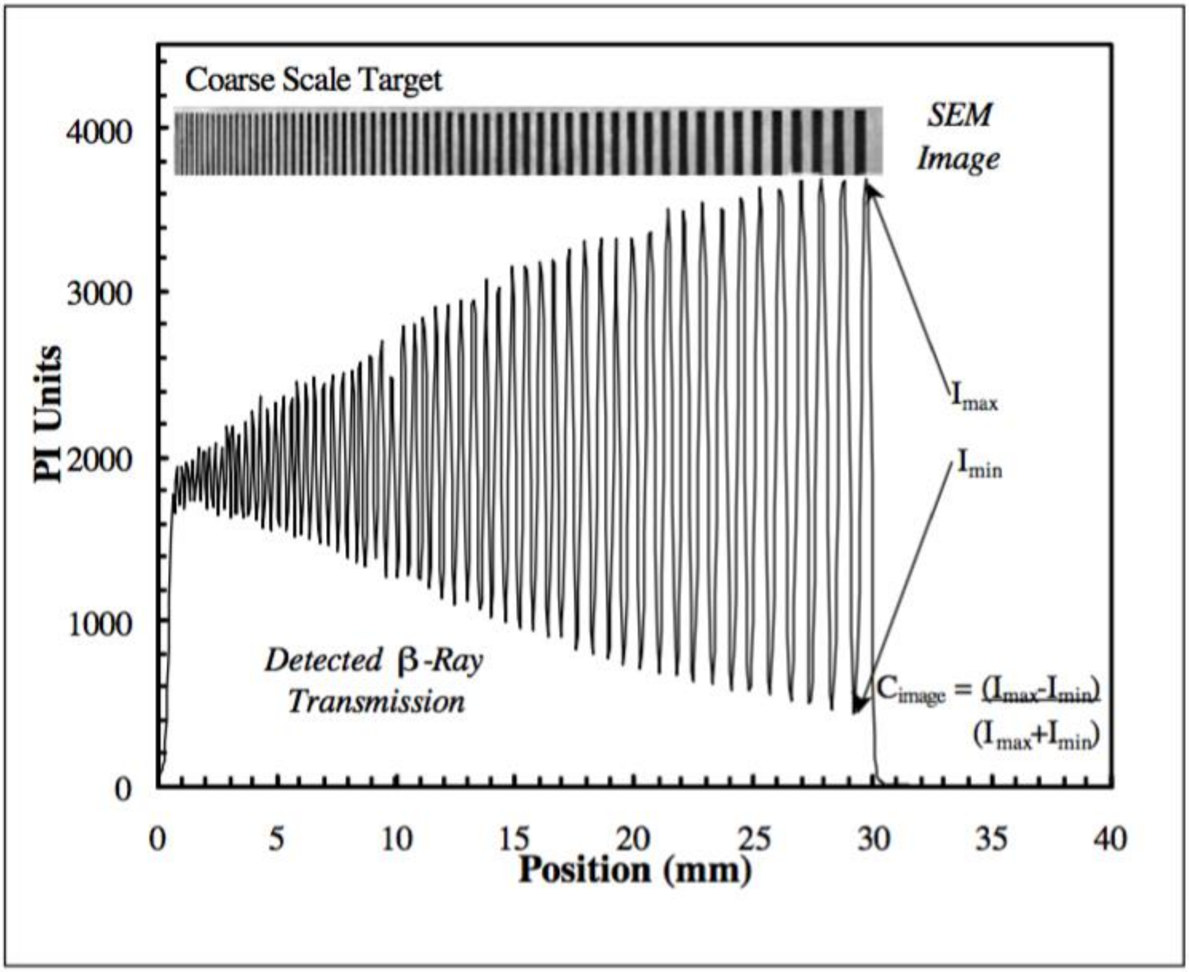


Figure 5.10 Scanning electron micrograph and coarse scale of the standard target [58]

This figure also illustrates the pattern of transmission showing the intensity that is detected when imaged using the storage phosphor system.

C_{image}, the image contrast, is given by

$$C_{image} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

where I_{max} and I_{min} are intensities for a corresponding gap-bar-gap set [58].

In this study, the average luminance value of each line in the Excel or Text files in MATLAB is plotted as shown in Figure 5.11, which is similar to the scanning electron micrograph in Figure 5.10.

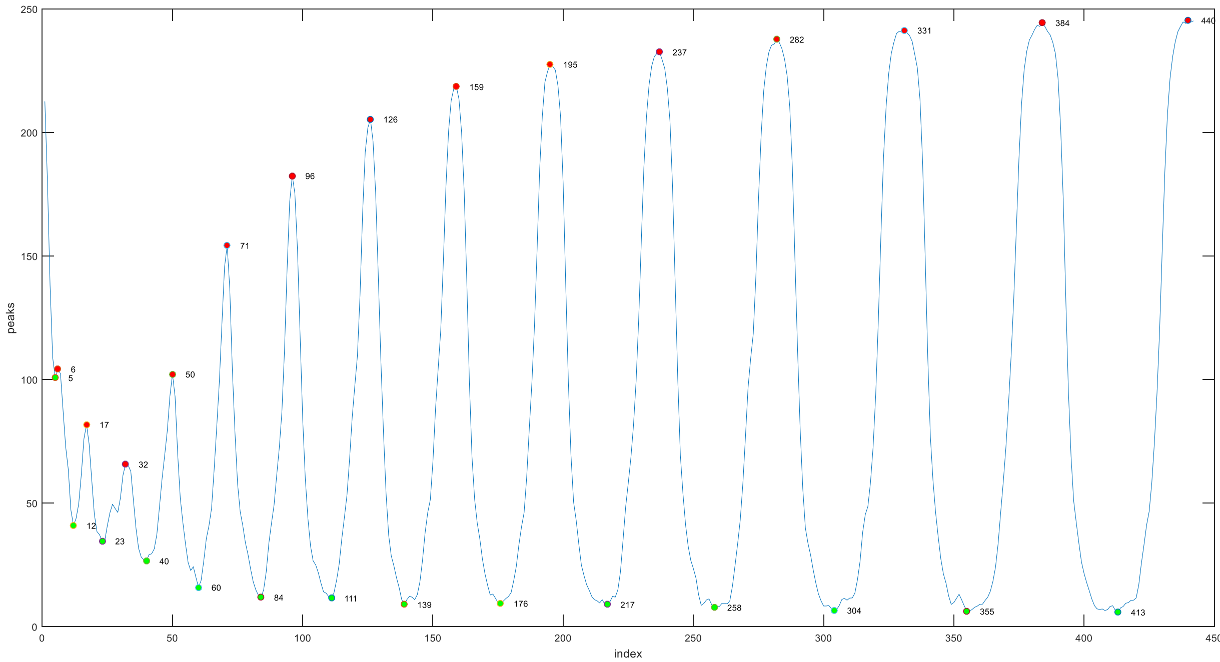


Figure 5.11 Average luminance value of each line (test pattern on paper in color red)

X axis represents the number which is the position of each averaged luminance value pixel, Y axis is the luminance value range from 0 to 255, which also demonstrates the intensity I of the corresponding gap-bar-gap test pattern set.

It can be observed that I_{max} and I_{min} are close to 255 and 0, respectively. In this case, the maximum difference between I_{max} and I_{min} is 255. (I_{max} - I_{min}) was used to calculate the maximum difference between I_{max} and I_{min}.

C, the contrast of a corresponding gap-bar-gap test pattern set is

$$C = \frac{I_{max\lambda} - I_{min\lambda}}{I_{max} - I_{min}}$$

where $I_{max\lambda}$ and $I_{min\lambda}$ are intensities for a corresponding bar width in a gap-bar-gap test pattern set, λ is wavelength which characterizes each bar width in gap-bar-gap test pattern set.

$(I_{max} - I_{\mathrm{min}})$ is the maximum difference between I_{max} and I_{min} in the whole gap-bar-gap test pattern set; while $(I_{max\lambda} - I_{min\lambda})$ is the difference between two adjacent I_{max} and I_{min}. MATLAB was applied to find $I_{max\lambda}$ and $I_{min\lambda}$, and calculate C.

The curve of average luminance in Figure 5.11 is not smooth because of the unevenness or roughness of textile and paper substrate surfaces, which add difficulties in finding the $I_{max\lambda}$ and $I_{min\lambda}$ in the equation.

The Findpeaks function is used to find local maxima or local peak, which is a data sample that is larger than its two neighboring samples. $I_{max\lambda}$, which is the peak in the plot, can be found by the Findpeaks function and is labeled red in the figure; $I_{min\lambda}$, which is the trough in the plot, can also be obtained by the Findpeaks function, labeled green in the figure. Data was preprocessed with the Findpeaks function to label peaks and troughs.

However, multiple peaks and troughs were found since there is noise around $I_{max\lambda}$ and $I_{min\lambda}$, which prevents the evaluation of the contrast value correctly. Filters in the X axis and Y axis were created to eliminate noise.

From the observation of several average luminance value plots, the X axis can be divided into two parts:

Part One: small peaks and troughs without noise around $I_{max\lambda}$ and $I_{min\lambda}$, do not require a filter in the Y axis.

Part Two: big peaks and troughs with noise around $I_{max\lambda}$ and $I_{min\lambda}$, need a filter in the Y axis.

A threshold a was set to separate Part One and Part Two to determine whether to use filter in Y axis or not. A threshold b times ($I_{max\lambda} - I_{min\lambda}$) was programed to screen the noise around $I_{max\lambda}$ and $I_{min\lambda}$, with a radius of search c.

The threshold a, threshold b and radius c need to be adjusted based on the data obtained in different situations. This program can find $I_{max\lambda}$ and $I_{min\lambda}$ correctly after a minor adjustment. Then the peaks and troughs were put into the equation to calculate the image contrast value. The contrast of gap-bar-gap test pattern set, C, in CMYKRB colors on multiple substrates in B2, C2, D2 mode in two directions were evaluated and exported into Excel files.

Six colors, CMYKRB, on the same substrate in the same mode and direction, were plotted in one figure along with the average contrast value of six colors in the bold or coarse blue line. The average contrast value of all six colors of each substrate in the different directions and print modes were saved and labeled in a separate Excel by MATLAB for further comparison.

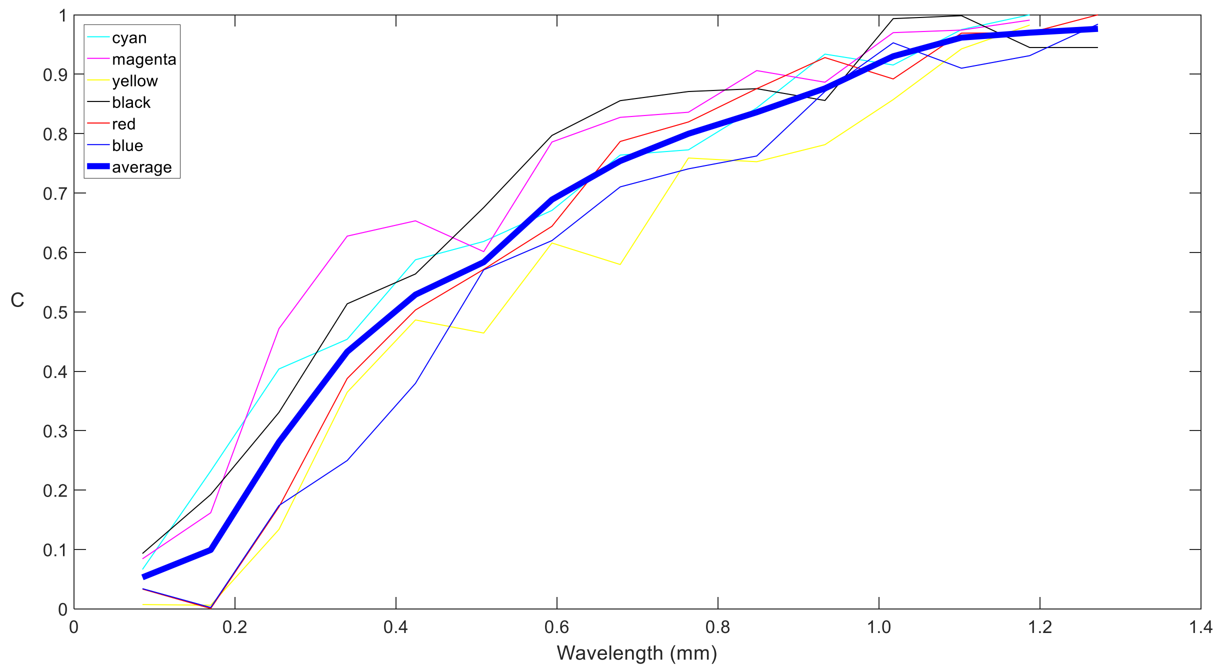


Figure 5.12 Contrast of six colors and average (A52S C2-)

X axis, λ, Wavelength, which is the bar width of test pattern, starts from 0.002-inch-wide with an increase of 0.001 or 0.002 inch. The unit of X axis was converted from inch to millimeter. X axis was labeled from 0.2 mm to 1.4 mm based on this relationship in MATLAB.

Y axis, C, contrast of a corresponding gap-bar-gap test pattern set is used to represent the print clarity. It can be observed that the plots of contrast C are rough. The Smooth function was used to smooth the curves and maintain the accuracy of the comparison of contrast C. MATLAB codes are shown in the Appendix B.

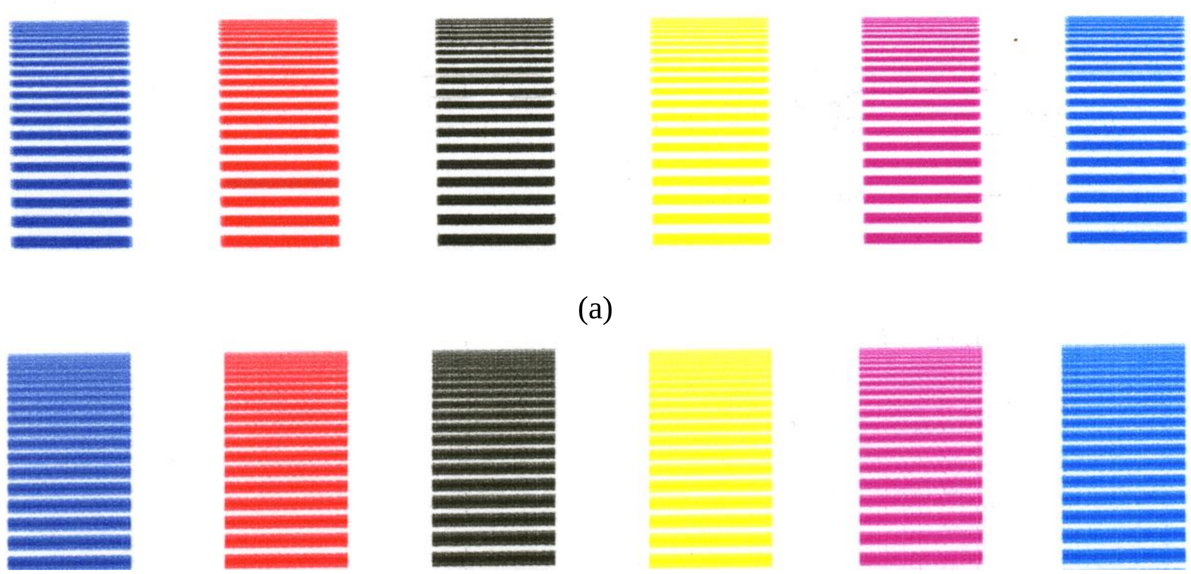
5.3.5 Results and Discussion

The marks “–” and “|” refer to the directions of test pattern, – means the test pattern is parallel to weft yarn and | means the test pattern is parallel to warp yarn. Thus, “A52F C2 –” means: Sample A52F, C2 print mode, the test pattern is parallel to weft yarn.

Direction (motion of print head**)**

A preliminary trial of the digitally printed test pattern (Figure 5.7) on Husky® Copy30 paper was run as a control test. Husky® Copy30 paper was placed in two directions: parallel and perpendicular to its machine direction with the adhesive belt to exclude the impact of paper substrate factors.

It can be observed that different results in print clarity occur in the two directions: the test pattern is clearer when the direction of test pattern line is the same as the motion of print head regardless of whether the paper is paralleled or perpendicular to adhesive belt.



(a)

(b)

Figure 5.13 Test pattern (a) same as and (b) different from the print head motion

This is likely due to the motion of the print head, which is one factor that was to be compared in this study.

TIFF files of the test pattern on paper were processed by Image-Pro and evaluated by MATLAB. Contrasts of a corresponding gap-bar-gap test pattern set of six colors (CMYKRB) on paper in two directions was plotted in Figure 5.14 and Figure 5.15 shown below.

When the test pattern is the same as the print head motion, all six colors have similar contrast value with a slightly better contrast in the magenta pattern. However, when the test pattern was printed perpendicular to the print head motion, each of the six colors has a different result in the contrast value as shown in Figure 5.15. The print clarity (Contrast C) is in the order Magenta $>$ Red $>$ Cyan $>$ Yellow $>$ Black $>$ Blue.

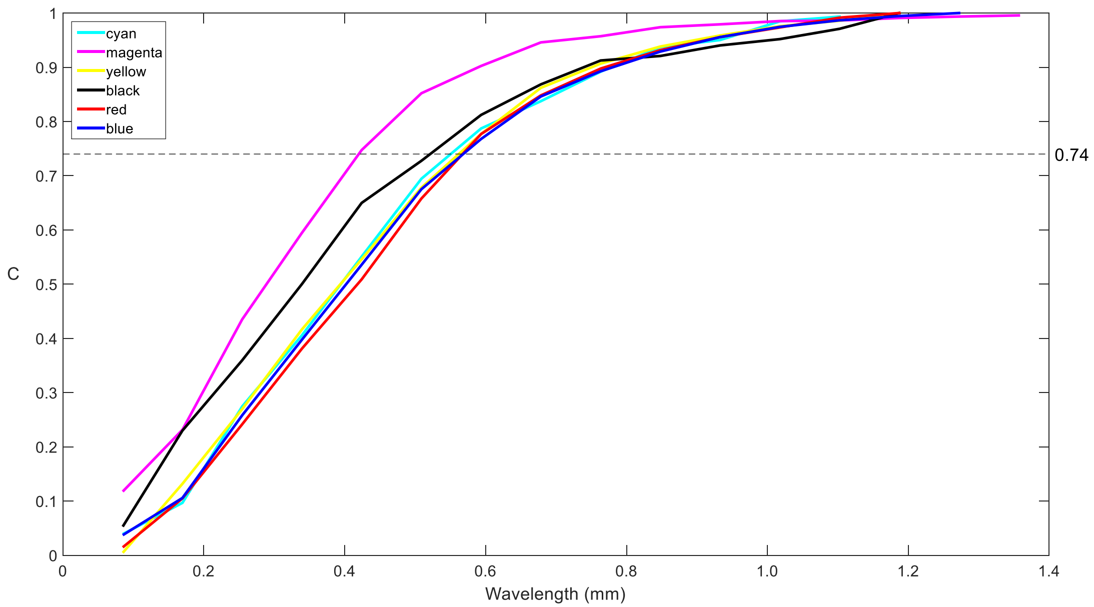


Figure 5.14 Contrast C of Paper C2 printed in the same direction as the print head motion

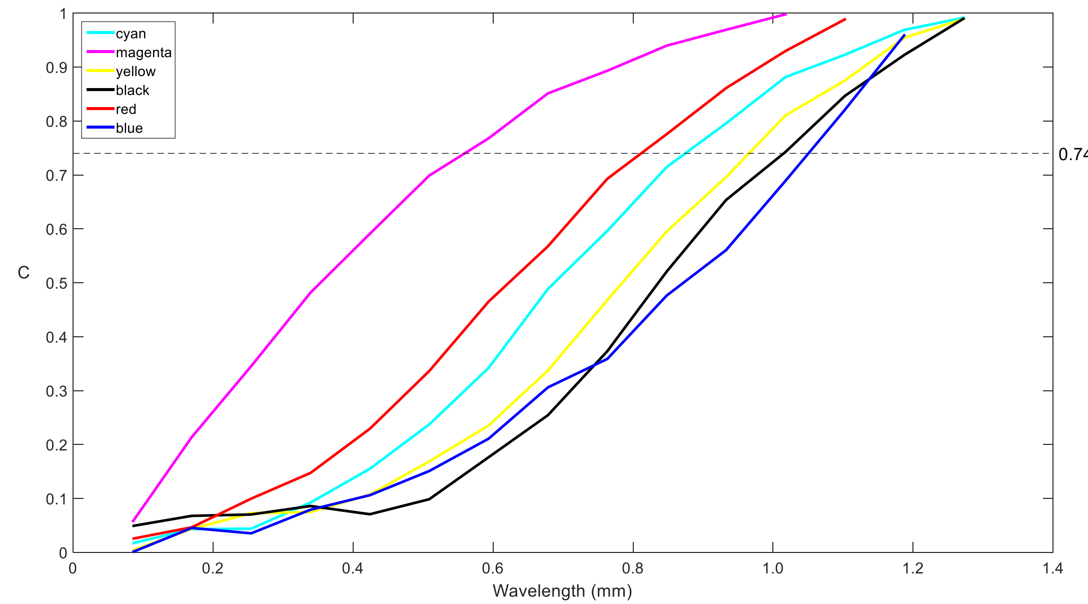


Figure 5.15 Contrast C of Paper C2 printed perpendicular to the print head motion

To eliminate the impact of print head motion on print clarity, woven polyester samples were placed in two directions: fabric warp paralleled and perpendicular with the adhesive belt, to keep the direction of the test pattern line the same as the motion of print head. Samples were carefully labeled with the sample name, direction and print mode to identify different situations.

Comparison of Contrast C (Print Clarity)

The resolution of a system is based on the minimum distance γ at which the points can be distinguished as individuals [61]. Several standards are used to determine quantitatively, whether or not the points can be distinguished. The method used to define resolution of a microscope specifies that, on the line between the center of one point and the next, the contrast between the maximum and minimum intensity should be at least 26% lower than the maximum. This corresponds to the overlap of one Airy disk on the first dark ring in the other. This standard for separation is also known as the Rayleigh criterion [61]. The distance is expressed as:

$$\gamma = \frac{1.22\lambda}{2n \sin\theta} = \frac{0.61\lambda}{NA}$$

where γ is the minimum distance between resolvable points, λ is the wavelength of light, n is the index of refraction of the media surrounding the radiating points, θ is the half angle of the pencil of light that centers the objective, and NA is the numerical aperture [61].

According to the Rayleigh criterion, the contrast value of a corresponding gap-bar-gap test pattern set should be no more than 0.74 to determine whether two neighboring bars are distinguishable from each other. To compare the print clarity of gap-bar-gap test pattern, contrast C of CMYKRB six colors on nine substrates, in B2, C2, D2 mode and two directions were plotted using MATLAB programs. When the contrast C reaches 0.74, the wavelength (bar width) of all the colors in different situations were documented through MATLAB shown in Table 5.6 below. A horizontal line was drawn at which the contrast C is 0.74 for easier comparison.

Table 5.6 Wavelength or bar width (mm) when Contrast C is 0.74

Sample No.	Mode+ direction	Cyan	Magenta	Yellow	Black	Red	Blue	Average	SD
Paper	C2 –	0.551	0.420	0.562	0.521	0.567	0.568	0.532	0.06
	C2 |	0.875	0.559	0.966	1.015	0.812	1.051	0.879	0.18
A52F	C2 –	0.719	0.625	0.699	0.629	0.609	0.906	0.698	0.11
	C2 |	0.640	0.523	0.499	0.569	0.575	0.662	0.578	0.06
A52S	C2 –	0.687	0.592	0.838	0.579	0.679	0.762	0.689	0.10
	C2 |	0.570	0.505	0.652	0.599	0.712	0.602	0.607	0.07
B28F	C2 –	0.600	0.520	0.543	0.672	0.599	0.667	0.600	0.06
	C2 |	0.625	0.531	0.583	0.697	0.579	0.600	0.603	0.06
B28S	C2 –	0.616	0.518	0.641	0.551	0.580	0.590	0.582	0.04
	C2 |	0.589	0.575	0.637	0.627	0.697	0.648	0.629	0.04
12	C2 –	0.629	0.484	0.625	0.527	0.647	0.583	0.582	0.06
	C2 |	0.611	0.606	0.554	0.461	0.566	0.710	0.584	0.08
14	C2 –	0.547	0.503	0.605	0.432	0.548	0.657	0.549	0.08
	C2 |	0.682	0.519	0.617	0.488	0.653	0.656	0.603	0.08

Table 5.6 Continued

16	C2 –	0.740	0.917	0.634	0.650	0.868	0.947	0.793	0.14
	C2 |	0.644	0.615	0.512	0.579	0.684	0.646	0.613	0.06
SC	C2 –	0.539	0.542	0.592	0.549	0.527	0.622	0.562	0.04
	C2 |	0.554	0.490	0.640	0.463	0.459	0.629	0.539	0.08

Wavelength or bar width (when Contrast C is 0.74) means the bar width of the test pattern can be distinguished from neighboring bars, i.e. the print clarity is good through optical observations. If the wavelength or bar width is small (for Contrast C = 0.74), it indicates that the digitally printed pattern is clear even though the bar or line is very fine.

Color

It can be observed that six colors (CMYKRB) can have various results in print clarity (contrast value) as shown in Figure 5.15. The different print clarity in all six of the colored pigment inks was evaluated in this study. As discussed in the **Direction (**motion of print head**)** section, the motion of the print head has a great impact on the print clarity of different colored pigment inks. When the direction of the test pattern bar changed from paralleled to perpendicular to the motion of the print head, the standard deviation of CMYKRB colors' contrast increased from 0.06 to 0.18. It can be observed from the preliminary trials on paper, that the motion of the print head has obvious impact on print clarity. To eliminate the motion of the print head factor, all the directions of the gap-bar-gap test pattern analysis was the same as the motion direction of the print head.

The average wavelength in millimeters of different colored pigment inks on textile substrates were calculated and compared:

Magenta (0.566) ≤ Black (0.567) < Yellow (0.617) < Cyan (0.624) = Red (0.624) < Blue (0.68)

Standard deviation of wavelengths of CMYKRB colors on textile substrates varies from 0.04 to 0.14. CMYKRB colors' wavelength with a standard deviation larger than 0.07 were evaluated to validate the average wavelength results.

In conclusion, black and magenta, especially black visually has the best print clarity; blue has the worst print clarity. Other colors are in between these extremes.

The colored inks' properties may impact the print clarity. The different colored inks are essentially formulated with the same chemistry, but different pigments. The binder and additive packages are the same with slightly different ratios of the components according to the company providing pigment inks. However, the pigment particle sizes vary in the different inks. They are nano-milled in a bead mill and shapes are irregular crystals that approach square or low aspect rectangles. According to the company that provided the pigment inks in this study, the color yellow is perhaps the largest (150 nm) and the pigment used in the blue ink is the smallest (80 nm), the other colors are in between these two in size. Although the particle size might be expected to influence the print clarity, this was not observed in this study. The blue ink had the smallest particle size while it has the worst print clarity. Yellow had better print clarity even though it was the largest particle. This suggests that particle size is not important in this case.

For the black ink, however, it is different as it is made from carbon black pigment, which is not a crystal but rather a fractal structure of primary particles fused together during the synthesis of the carbon black particles, which may lead to a good print clarity result.

Fabric (Substrate)

Four types of fabrics: A52F, A52S, B28F, B28S, were specially designed and woven to analyze the impact of fabric factor on print clarity. Three similar selected commercial fabrics (NC_WM15_012, NC_WM15_014, NC_WM16_016) as well as a cotton-linen blended commercial fabric specifically designed to be digital printed were compared in the research. To compare the print clarity of all the substrates, the contrast of nine substrates in two directions were plotted in Figure 5.16 and Figure 5.17.

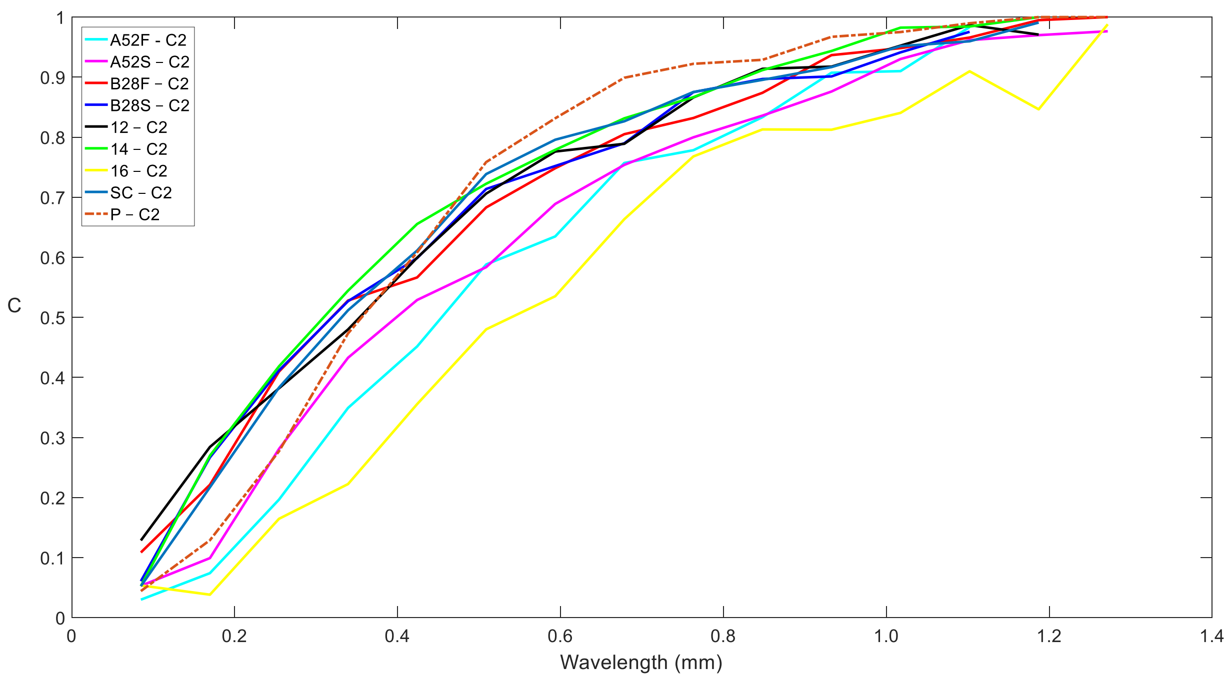


Figure 5.16 Print clarity of all the substrates when the test pattern is parallel to weft yarn

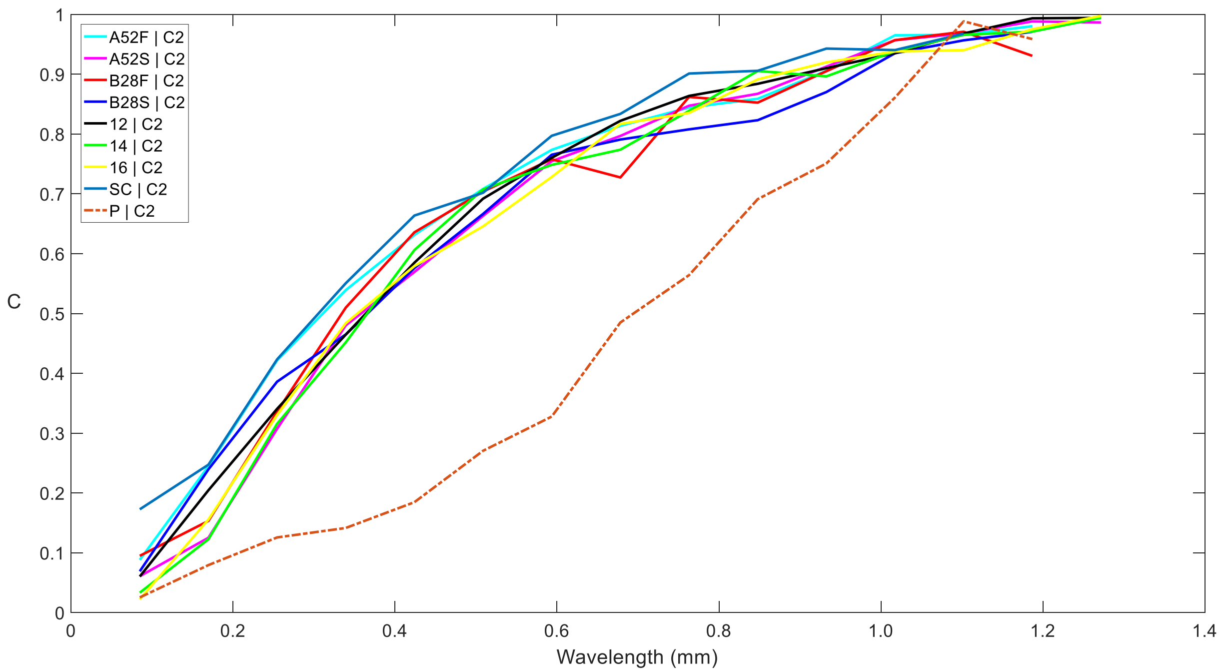


Figure 5.17 Print clarity of all the substrates when the test pattern is parallel to warp yarn

Wicking yarn: warp vs. weft

Two sets of Test Pattern were printed in the substrate samples: parallel to warp yarn and parallel to weft yarn. The impact of print head motion on print clarity was eliminated by rotating the fabric to make sure the direction of test pattern bars was the same as print head motion, the only variable in this comparison is the direction of gap-bar-gap set Test Pattern on the substrates.

Table 5.7 Wavelength or bar width (mm) (when Contrast C is 0.74) of all the substrates when the test pattern is parallel to weft yarn

Sample No.	Mode+ direction	Wicking yarn	Average	SD	CV
14	C2 –	warp spun 12.4/1 OE	0.549	0.08	0.14
SC	C2 –	warp 10s	0.562	0.04	0.07
12	C2 –	warp filament 2/150/48	0.582	0.06	0.11
B28S	C2 –	warp spun 16/1	0.582	0.04	0.08
B28F	C2 –	warp spun 16/1	0.600	0.06	0.10
A52S	C2 –	warp 2/145	0.689	0.10	0.14
A52F	C2 –	warp 2/145	0.698	0.11	0.16
16	C2 –	warp filament 280	0.793	0.14	0.17

Wavelength or bar width (when Contrast C is 0.74) means the bar width of the test pattern can be distinguished from neighboring bars, i.e. the print clarity is good through optical observations. If the wavelength or bar width is small (for Contrast C = 0.74), it indicates that the digitally printed pattern is clear even though the bar or line is very fine.

Table 5.8 Wavelength or bar width (mm) (when Contrast C is 0.74) of all the substrates when the test pattern is parallel to warp yarn

Sample No.	Mode+ direction	Wicking yarn	Average	SD	CV
SC	C2 |	weft 10s	0.539	0.08	0.15
A52F	C2 |	weft filament 2/145/36	0.578	0.06	0.11

Table 5.8 Continued

12	C2 |	weft spun 30/2	0.584	0.08	0.14
14	C2 |	weft spun12.4/1	0.603	0.08	0.13
B28F	C2 |	weft filament 4/150/34	0.603	0.06	0.09
A52S	C2 |	weft spun 19/1	0.607	0.07	0.12
16	C2 |	weft spun 10/1	0.613	0.06	0.10
B28S	C2 |	weft spun 8/1	0.629	0.04	0.07

Wavelength (when Contrast C is 0.74) of warp and weft yarn as wicking yarn shown in Figure 5.18.

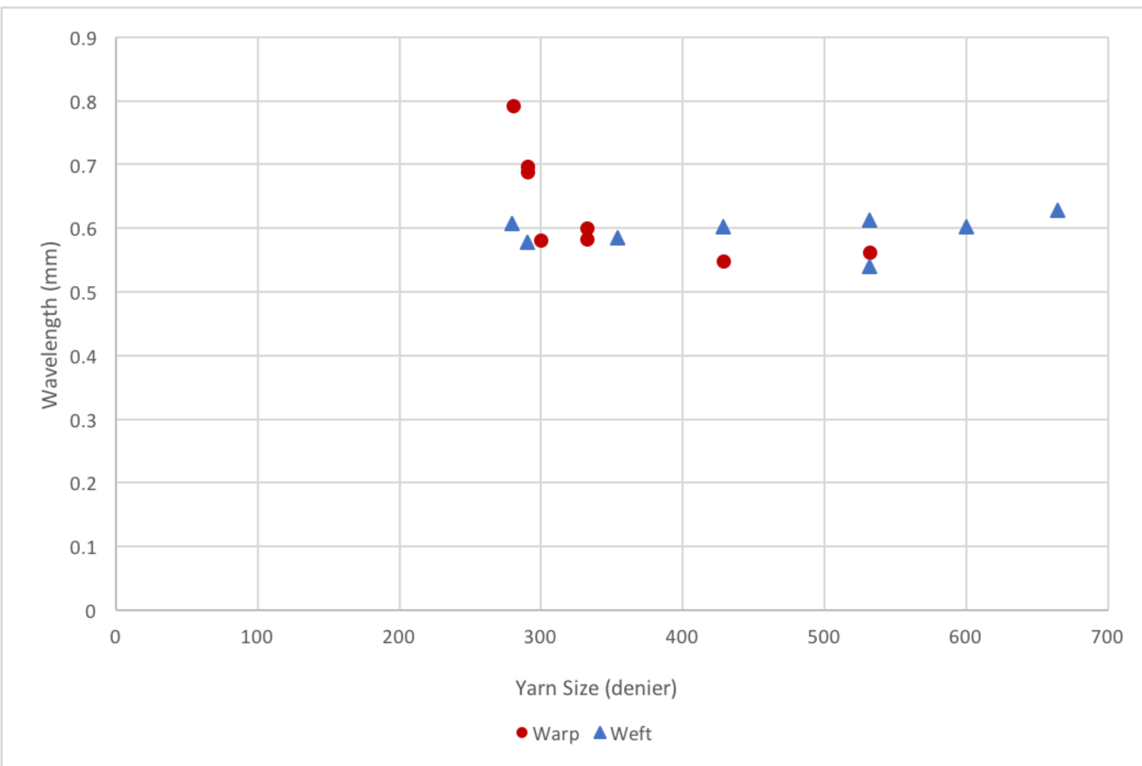


Figure 5.18 Wavelength or bar width (mm) (when Contrast C is 0.74) of warp and weft yarn as wicking yarn

This suggests that there is a critical size for optimum contrast – around Ne 17 or 300 denier – for these fabrics.

Based on the tables and graphs above, wavelength (when Contrast C is 0.74) of all the substrates when the test pattern is parallel to weft yarn had a range of 0.549 to 0.793 with an average of 0.632. It tended to decrease while yarn diameter increased when yarn size was smaller than 300 denier, and tended to be stable around 0.575 when yarn size was bigger than 300 denier.

Wavelength (when Contrast C is 0.74) when the test pattern is parallel to warp yarn had a range of 0.539 to 0.629 with an average of 0.594, which is smaller, and it appears to be nearly independent of yarn size as yarn diameter increases.

According to the literature, when the test pattern (digitally printed lines) is parallel to weft yarn, print clarity indicates the wicking behavior in the warp yarn. Wavelength or bar width (mm) (when Contrast C is 0.74) decreased while the warp yarn diameter increased when the warp yarn size was smaller than 300 denier, which implies the print clarity increased, and the wicking behavior occurred less in the warp yarns. However, wicking behavior in the weft yarn remained within a relatively small range and with a smaller average.

Different wicking behavior in warp and weft yarns might be due to the weaving process. During the weaving process, warp yarns are held tight on the loom when the weft yarns are inserted into the openings of warp yarns, and the warp yarns are held under more tension than the weft yarns. The capillary pressure for wicking increases in the closely packed multifilament yarn structure and in the high density of warp yarns in a woven fabric[18]. High tension in warp yarns packs warp yarn more closely, leads to an increase in the capillarity for wicking in the warp yarn, especially when the warp yarn diameter decreases. The print clarity declined as warp yarn diameter decreased when the yarn size was less than 300 denier.

However, in the comparison above, the warp yarns were crossed with different weft yarns, and there were spun yarn and filament yarns in the warp and weft direction, which makes it difficult to draw a conclusion in this complicated situation.

Wicking yarn: spun vs. filament

Print clarity of Test Pattern on spun and filament yarn were compared. Designed woven fabric samples A52F, A52S, B28F, B28S along with commercial fabrics 12, 14, 16 and SC were evaluated in this part. A52F, A52S as well as B28F, B28S were designed and woven with the same warp yarn (one is filament, one is spun), interlaced with the similar yarn count spun and filament yarn as shown in Table 5.9 below. C2 |direction of test patterns showed the wicking behavior in weft yarns, which were compared to evaluate spun and filament filling yarns when warp yarn was the same and other factors were controlled.

Table 5.9 Textile substrates for print clarity test

<table>
<tr><th>Sample No.</th><th>Supplier</th><th>Warp Yarn</th><th>Weft Yarn</th><th>Count epi× ppi</th><th>Weave</th><th>Weight (osy)</th><th colspan="2">Wavelength (mm) (when Contrast is 0.74)</th></tr>
<tr><td rowspan="2">A52F</td><td rowspan="4">Designed</td><td rowspan="2">2/145 PET (18.3 Ne)</td><td rowspan="2">2/145/36 PET (18.3 Ne)</td><td rowspan="2">64×52</td><td rowspan="2">Plain</td><td rowspan="2">7.4</td><td>C2 –</td><td>0.698</td></tr>
<tr><td>C2 |</td><td>0.578</td></tr>
<tr><td rowspan="2">A52S</td><td rowspan="2">2/145 PET (18.3 Ne)</td><td rowspan="2">19/1 PET (280 den)</td><td rowspan="2">64×52</td><td rowspan="2">Plain</td><td rowspan="2">6.8</td><td>C2 –</td><td>0.689</td></tr>
<tr><td>C2 |</td><td>0.607</td></tr>
</table>

Table 5.9 Continued

B28F		16/1 PET (332 den)	4/150/34 PET (8.8 Ne)	84×28	2/1 duck	8.64	C2 –	0.600
							C2 |	0.603
B28S		16/1 PET (332 den)	8/1 PET (664 den)	84×28	2/1 duck	7.87	C2 –	0.582
							C2 |	0.629
12	B	2/150/48 stretch textured PET (17.7 Ne)	30/2 ring spun PET (354 den)	61×48	Plain	6.16	C2 –	0.582
							C2 |	0.584
14	A	12.4/1 OE PET (429 den)	12.4/1 OE PET (429 den)	64×41	2/1 duck	7.44	C2 –	0.549
							C2 |	0.603
16	D	280 denier PET (19 Ne)	10/1 spun PET (531 den)	40×31	Plain	5.52	C2 –	0.793
							C2 |	0.613
SC	C	10s carded cotton slub (531 den)	10s cotton/linen slub (531 den)	70×30	Plain	7.37	C2 –	0.562
							C2 |	0.539

The wavelength (when Contrast C is 0.74) of A52F is 0.578, which is smaller than 0.607, the wavelength of A52S. Same result in B28F and B28S, the wavelength (when Contrast C is 0.74) of B28F is 0.603, which is smaller than 0.629, the wavelength of B28S. The smaller the wavelength (when Contrast C is 0.74), the clearer the digitally printed test pattern is. This indicates that when the warp yarn and the other factors were carefully controlled, filament yarn provides a slightly better print clarity result than spun yarn, which conflicts with result in literature review where yarns were not matched.

However, a different result was found when comparing commercial fabric samples # 12, 14 and 16. Samples number 12 and 14 had similar weft yarns (# 12's weft yarn is 15 cotton count while # 14's weft yarn is 12.4 cotton count), and comparable yarn density. C2 – direction on samples number 12, 14 and 16, when the warp yarn was wicking yarn, were evaluated. The wavelength (when Contrast C is 0.74) of 14 is 0.549, which is smaller than 0.582, the wavelength of 12. Sample number 12 had a filament warp while sample number 14 had a spun warp, which showed that spun yarn had better print clarity result than filament yarn.

Similar results were obtained in samples 14 and 16. Samples 14 and 16 had similar weft yarns (sample 14's weft yarn is 12.4 cotton count while sample 16's weft yarn is 10 cotton count), and comparable yarn density. The wavelength (when Contrast C is 0.74) of 14 is 0.549, which is much smaller than 0.793, the wavelength of 16. Warp yarn of sample number 16 is 280 denier filament yarn. Warp yarn of sample number 14, 12.4/1 open end spun polyester gave a better print clarity than filament yarn.

Results in the commercial fabric samples is the same as the results discussed in the literature review. However, the polyester woven samples in that article were commercial fabrics, and the author didn't control the warp yarn or weft yarn and yarn density. Yarn sizes in that research were similar but not the same, which is the reason that commercial fabrics number 12, 14, 16 had the same result as the (named) article in the literature review.

Yarn type has a slight impact on the print clarity of the test pattern. Filament yarns provide a better image clarity when the other factors are strictly controlled. Compared to spun yarn, filament yarn made by the single polyester filaments, grouping together and then twisting or entangling, gave a more uniform surface than staple yarn, provideed ink droplets land on a relatively smooth surface to show the detail of printed patterns. The stretch textured filament yarn in the samples also created bulk and a degree of stretch.

However, the wavelengths (when Contrast C is 0.74) of the compared fabrics or yarns are overlapped when the standard deviation is considered.

Black and magenta were chosen when comparing single colors since they provided the best print clarity of the different pigments and particle sizes.

Table 5.10 Wavelength (when Contrast C is 0.74) of filament and spun yarn in black and magenta

Color	Wavelength comparison	Yarn with better print clarity
Black	A52F<A52S	Filament
	B28S<B28F	Spun
Magenta	A52S<A52F	Spun
	B28F<B28S	Filament

It can be observed from Table 5.10 that print clarity appears to be nearly independent of yarn types (spun or filament yarn).

List of Abbreviation and Symbols

C – Contrast of a corresponding gap-bar-gap set.
C_{image} – Contrast of the image.
I_{max} – Maximum intensity of the corresponding gap-bar-gap set.
I_{min} – Minimum intensity of the corresponding gap-bar-gap set.
λ – Wavelength, bar width.
$I_{max\lambda}$ – Maximum intensity of the corresponding bar width in a gap-bar-gap test pattern set.
$I_{min\lambda}$ – Minimum intensity of the corresponding bar width in a gap-bar-gap test pattern set.

CHAPTER 6 SUMMARY AND CONCLUSIONS

6.1 Survey (Industry interviews)

The purpose of this research is to improve the substrate (basecloth) for digital printing and understand the factors (processes and materials) that affect digital printing. Industry interviews were conducted in order to validate the contributing factors discovered in this research and reveal any new factors.

6.1.1 Development of Interview questions

Potential participants were identified by the author through contacts in industry and academia.

The author developed a set of interview questions based on literature review and field study research.

The interview questions included two parts. The first part consisted of a consent form that followed the requirements of the PI's Institutional Review Board (IRB). The second part was the questionnaire which contained 27 questions; 24 multiple choice questions and 3 open-ended questions, which included questions on 1) substrate content and structure, 2) dyes and chemicals, 3) professional background. Specifically, participants were asked to provide their valuable input on relevant factors from fiber, yarn, structure, selvedge, width and weight to dyes/inks, which cover the whole process to capture the participants' experience in digital textile printing. The three open ended questions sought to gain further insight into the participant's understanding of digital textile printing and reveal any new factors affecting printed fabric manufacturing and quality of finished fabrics. Participants were asked to provide suggestions for this research and recommendation of other experts who could provide valuable input.

6.1.2 Selection of experts

The author limited the participants to those who had expertise in the following areas: substrate manufacturing, dyestuffs & chemicals, printing, or finishing. These areas represent the whole process of digital textile printing which offered diverse and comprehensive product and procedure quality preferences from the different area's experts.

The interview response rate was 62%, a total of 37 emails were sent to experts in digital textile printing field. Of the 37 respondents, 23 started the interview process and 20 completed the interview. The 20 participant experts were contacted during the period from July 2016 to February 2017. In total, 37 experts were contacted, 23 confirmed their willingness to participate, 3 individuals were considered to not have sufficient experience, 11 completed the survey by face-to face interviews and 9 completed the questionnaire via email.

6.1.3 Interviews with experts

Study participants were contacted via email (see Appendix C for a copy of the cover letter)and asked to participate in the study by completing the interview. All correspondence and the interview questionnaire were prepared in compliance with North Carolina State University's Institutional Review Board (IRB). The IRB determined that this study was exempt from full review. Participants were asked to answer a questionnaire through email, or face-to-face interview in their working place or if possible, were invited to interview at North Carolina State University, College of Textiles (see Appendix E for interview questionnaire). Collected data was recorded by handwritten notes and electronic notes, during a face to face interview, responses was noted by the interviewer and reviewed with the interviewees to confirm their accuracy.

The information in the study records were kept strictly confidential. Data was stored securely on the author's hard drive (password protected). Code numbers were created for participants' name and company; these code numbers were the only identifiers stored with the data. The master list linking codes to the subject was kept in a separate location from that of the data in order to minimize the potential of linking the data to the participant and participant's company. In addition, any identifying information was removed when reporting the data. No reference was made in oral or written reports which could link participant to the study.

The study participants were not compensated. An indirect benefit to participants of the study was the knowledge that they were contributing to an enhanced body of knowledge about the digital printing process and related technologies. This study identifies the impacts of textile substrates (basecloth), dyes and chemicals and other factors that influence digital printing. Understanding the factors impacting digital printing will contribute to the quality and efficiency of digital printing.

6.1.4 Results and Discussion

Data was collected and analyzed from the interviews. Multiple choice questions provided more answers.

Experts' information showed in Figure 6.1 and Figure 6.2.

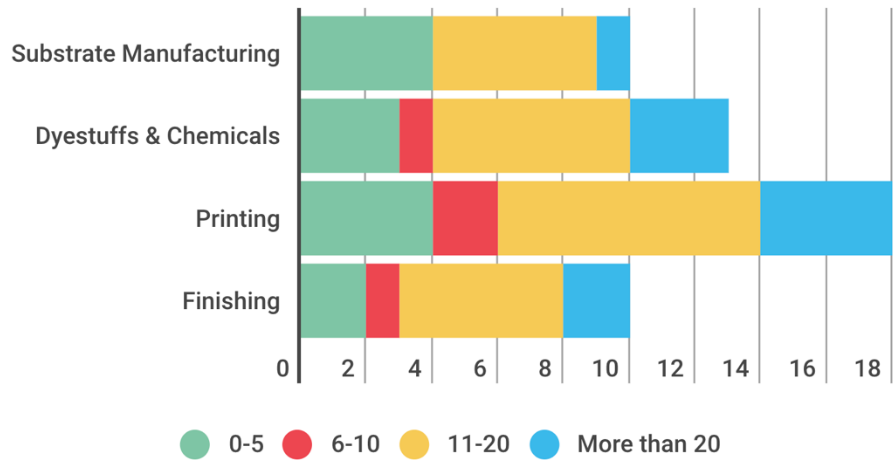


Figure 6.1 Experience years and areas of experts

The 20 experts in substrate manufacturing, dyestuffs and chemicals, printing and finishing field with various years' experience participated in the survey. Most of them had printing experience, working in the roles of research, development, manufacturing, marketing and purchasing.

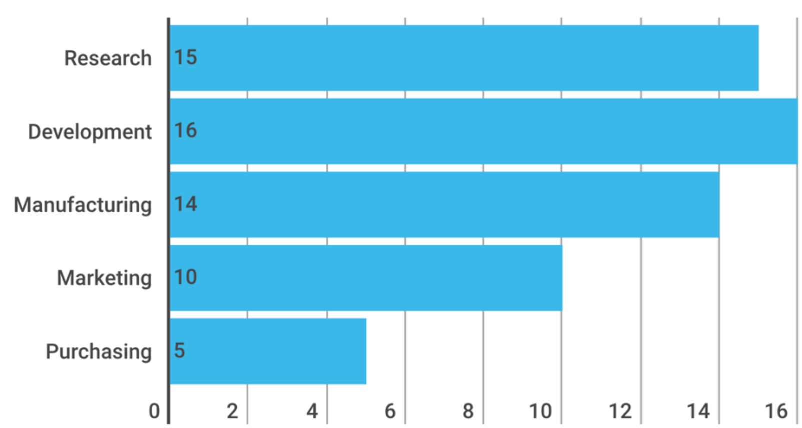


Figure 6.2 Roles in textile and related industries

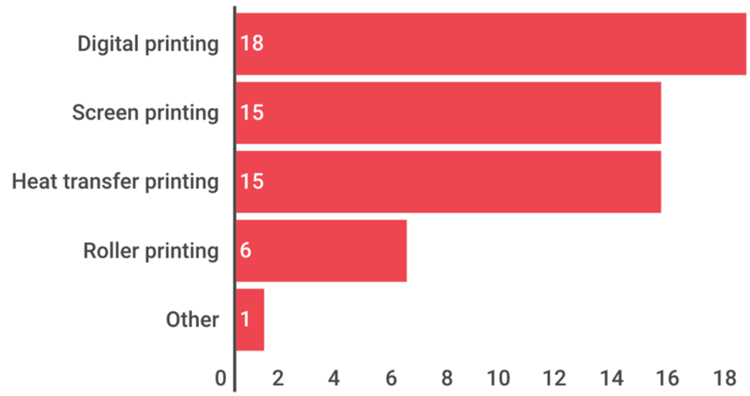


Figure 6.3 Experience in type of printing

Among the 20 experts, 18 stated that they had experience in digital printing, 15 had screen printing or heat transfer printing experience, see Figure 6.2 and Figure 6.3.

Polyester, cotton, poly/cotton blend were the most common fiber content in the fabrics which have printed by the experts, followed by nylon and poly/nylon blend.

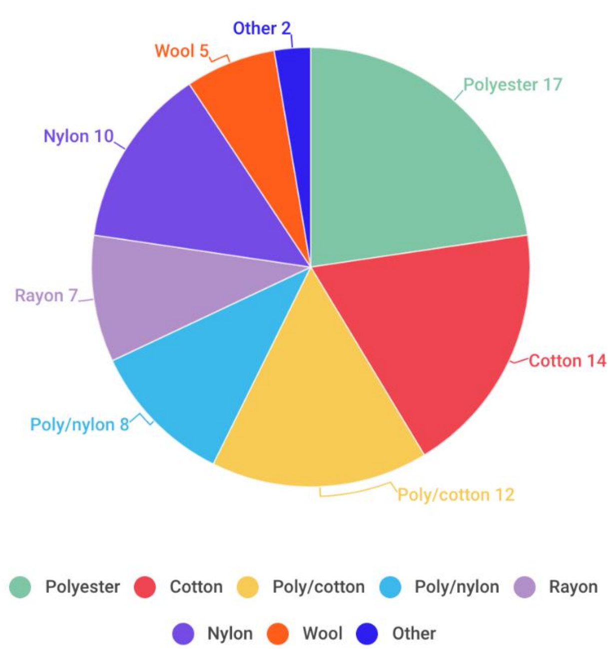


Figure 6.4 Fiber content in the fabrics have printed by experts

The end-use of the printed fabric shown in Figure 6.5.

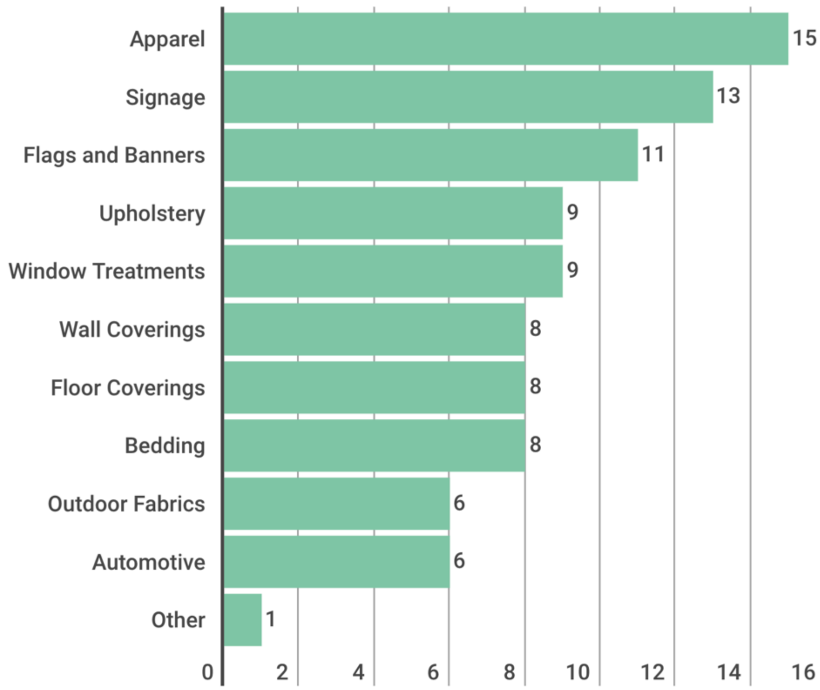


Figure 6.5 End-use of the printed fabric

For the types of yarn used in the substrate, the experts showed no preference in choosing spun and filament as warp and weft in woven or in knit, tufted. However, ring spun was more popular than open end, air jet, or recycled yarn in the spun yarn category; textured filament was preferred in filament yarns.

When it came to the most successful printed woven structure, 13 experts found plain weave provided good print results while 12 experts preferred satin weave. However, according to the literature review, satin weave would lead to a poor print quality.

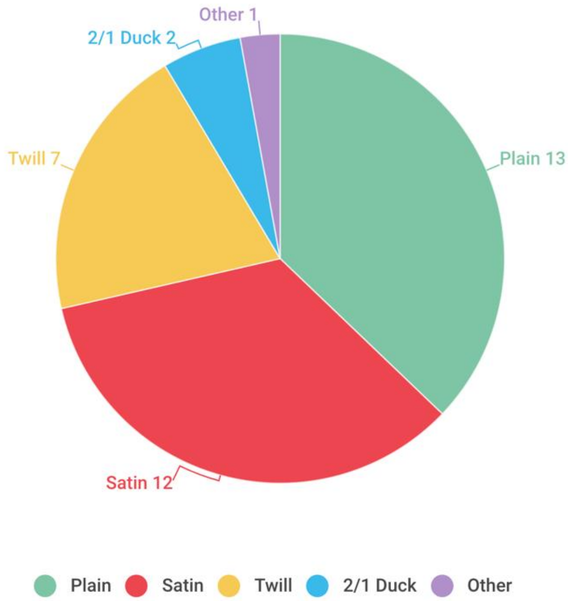


Figure 6.6 Preferred woven structure in printing

10 of the experts noted that there was size (starch, oil, acrylic, PVC) on the PFDP substrate, and all of them removed the size before printing; 7 of the experts observed no size on the basecloth.

Half of the participants responded that they check wet pickup percentage before pretreatment or printing, seven of them stated that they do not check wet pickup.

For the selvedge questions, 14 of the experts claimed that their substrates had selvedges, 5 of them removed the selvedges before printing while 9 of them didn't remove the selvedges.

15 out of 20 experts believed selvedges have impact on digital printing quality. They believed selvedges are the maintain control of the fabric, if selvedge is too tight or loose or thick then the fabric ripples, which causes fabric feed problems and creates print head strikes. Selvedges with long fringe can brush print heads or catch on the printer carriage, which can lead to print quality issues. Hairy selvedges can also make contact with the print heads

causing nozzles to clog/misfire or create unwanted ink splotches. The risk is greater the faster the printer is running and the closer the print heads are to the fabric. The fabric needs to lay flat and crease free on the belt – trimming selvedges improves the material movement. Slitting or cutting apparatus could be attached to the printer. Selvedge should be discarded before end-use.

Only three participants thought selvedge did not impact printing since the selvedge can be excluded from the printed area. Most experts realized the impact of selvedge.

17 experts considered shrinkage as a critical factor in preparing substrates for printing. 10 of the participants reported the preshrinking of the substrates to control shrinkage; 11 of them purchase preshrunk fabric directly and 2 of them do not control shrinkage.

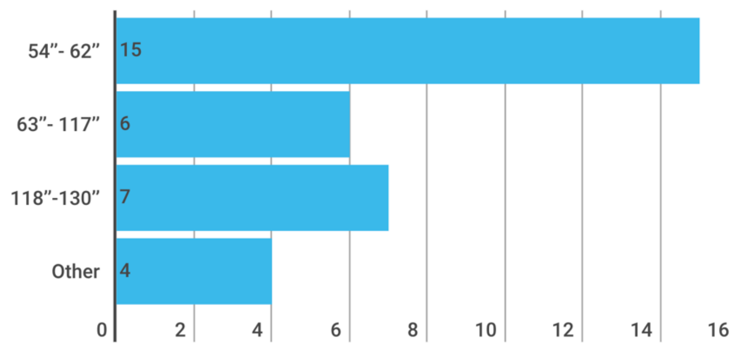


Figure 6.7 Width of substrates

54’’- 62’’ was the most common woven width of purchased pfp substrate or it was the most widely used loom wide range of weaving basecloth in the experts’ companies according to Figure 6.7.

To provide better performance and print quality, most experts chose relatively heavy weight (five to ten ounces per square yard) to print.

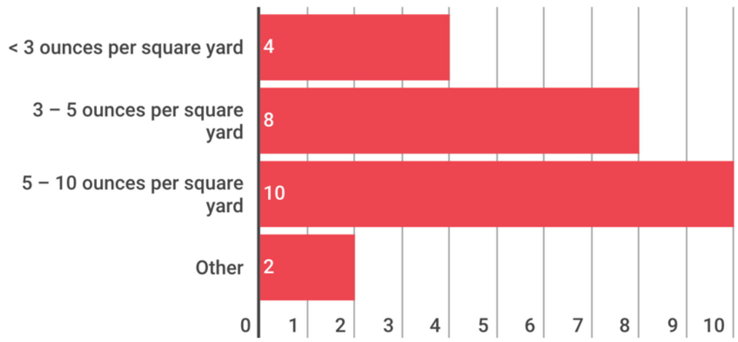


Figure 6.8 Preferred substrate weight for performance and print quality

Pigment and disperse ink are widely used among the 20 experts.

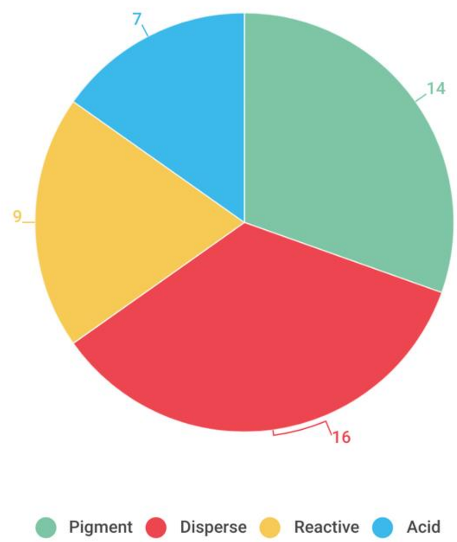


Figure 6.9 Types of dyes/inks used in printing

Most of the experts pretreated substrates before printing and post treated (such as wash, heat set, chemical finish, steam) substrates after printing.

When it came to standards for print clarity used during quality inspection, seven experts used evaluation strike-off, four experts chose printed test pattern and 6 experts applied production standard, one expert from digital printing field suggested G7 method.

12 experts had encountered bow and bias issues during the process, they provided several reasons:1) bow and bias occurred during the knitting or weaving process; 2) the weave of the fabric is affecting how the fabric moves through the printer or heat press calendar which is a particular issue with satin weaves since it’s less stable; 3) poor pretreatment and handling: fabrics are pulled too tight in some areas after being padded and dried with pre-treatment on a Tenter frame, or are not framed correctly, or the frame speed has not been adjusted. Bow and bias is a critical problem in manufacturing.

Among the 18 experts who had experience in digital printing, 8 of them had a printer with a continuous adhesive belt while 2 of them had non-adhesive belts. 4 of them cleaned the adhesive belt every 1 to 6 months, which typically took 4-8 hours; the other four experts’ adhesive belt required cleaning every 7 to 12 months which took longer number of hours. The frequency of cleaning a continuous adhesive belt depended on the production run. Half of the experts digitally printed short run sampling (less than 100 yards per style/colorway); 3 experts printed more than 100 yards per style/colorway while 6 experts run both sampling and production yardages.

Question 23 and question 24 are open-ended questions. In question 23, the experts were asked to provide other substrate or processing issues affecting printed fabric manufacturing or the quality of finished fabrics. Most experts considered substrate preparation as the most critical factor affecting printed fabric quality; 1) roll preparation is critical. Fabric with rolls that are evenly tensioned and free of wrinkles lead to better finished quality. Cardboard tubes need the correct tube size and length for the print machine and not be broken or crushed; all aspects of fabric processing are important such as desizing and pretreatment; 2) A high-quality yarn is important (yarn that is not overly hairy) to ensure a high print quality. Prints will look crisper, more detailed, darker and more saturated. If a roll of fabric is hairy and it is affecting print quality it may need to be enzyme washed/bio polished to knock down the fuzziness; 3) defects in fabric with loose fibers or units, selvedge type and construction in fabric affect printed fabric performance and quality; 4) oligomer content in polyester, degree of mercerization of cotton, heat history/crystallinity of polyester also determine the properties of substrates; and 5) scouring and heat setting 100% polyester for transfer dye sublimation are critial, applying ink receptive coating for direct dye sublimation printing. Many applications require NFPA 701 and the FR used can affect the print quality and hand of the fabric. 6) Softeners are not good for pigment printing. 7) lack of standard is also an issue in digital textile printing field.

For the question 24, the experts described the characteristics of an ideal woven substrate for digital printing:

1) fabric would lay completely flat with no wrinkles during shipping, and with a uniform winding of the fabric roll on the core

2) fabric would have a smooth surface, surface fiber could be singed, fabric PFP also mercerized

3) fabrics should be clean/ no selvedges, or leno selvedges, or closed evenly tensioned selvedges or selvedges that have been trimmed to less than 3mm

4) fabrics should consist of stable and balanced weaves; tight and flat construction warp knits or woven materials since texture and dimensions cause issues with appearance and consistent quality.

5) fabrics should be well scoured, with no contamination

6) preferred fabrics would be Inexpensive, opaque, well filled, long piece lengths, and durable.

7) fabrics would have a high fiber density

8) fabrics should have a perfect pH acidity value.

It can be observed in the survey that preparation is the key factor that affect digital textile printing. The experts showed their concern about shrinkage and selvedge. These factors have obvious impacts on printing quality. The fringes or loose selvedge threads or the selvedges also might stand up and pause the printer during printing. Fiber from fringes sometimes stick on the adhesive belt, which is hard to remove and cause issues during printing. repeated earlier in the paragraph.

6.2 Summery and Conclusions

Tear strength across the warp is slightly higher than tear strength across the weft. When the warp is spun yarn, tear strength is twice as high as any other fabric.

Tensile strength in the warp direction is higher than tensile strength in the weft direction. Tensile strength is related to fabric basis weight; the higher fabric weight, the higher the tensile strength.

Four commercial samples have similar seam strengths. However, for the designed polyester woven samples, spun warp fabric has the lowest seam strength.

Yarn type has an impact on abrasion. The filament yarn fabrics have better abrasion performance than spun yarn fabrics.

Polyester woven fabric with filament yarns shrinks up to 13% during scouring while it's only 5% shrinkage when the warp and weft are both spun yarn. The spun-spun fabric has the lowest percentage shrinkage. As long as there is filament yarn in the fabric, the fabric shrinks twice as much as the 100% spun or spun-spun fabrics.

Shrinkage also occurs during heat setting due to the high temperatures, and is noted at approximately 2% shrinkage in both directions. These shrinkage results are vital for fabric preparation, especially for designing the greige fabric and predicting the size, weight and thread density of certain polyester woven fabric after scouring and heat setting.

GS stain value of dry crock fastness is slightly better than wet crock fastness. Designed polyester woven fabrics had better performance in dry and wet crocking than the commercial fabrics evaluated in this researcch. The best crock fastness was achieved when the warp and weft were both filament yarn. Filament polyester warp fabric had better crock fastness.

In this research, print clarity of digitally printed images on various substrates was considered as image sharpness. A quantitative test method to evaluate print clarity was created based on the estimation of image sharpness by analyzing MTF.

The motion of the print head has impact on print clarity. It provided better sharpness when the motion of print head was the same as the direction of test pattern.

The average wavelength (when Contrast C = 0.74) in millimeters of different colored pigment inks on textile substrates were calculated and compared: Magenta (0.566) $\leq$ Black

(0.567) < Yellow (0.617) < Cyan (0.624) = Red (0.624) < Blue (0.68). Black and magenta, especially black visually has the best print clarity; blue has the worst print clarity. Other colors are in between these extremes. The particle size of pigment was not found to be important to print clarity.

Print clarity appears to be nearly independent of yarn types (spun or filament yarn) and yarn direction (warp or weft).

CHAPTER 7 FUTURE RESEARCH RECOMMENDATIONS

Due to the limited time, not all aspects of digital textile printing could be investigated in depth. Following suggestions for future work evolved:

Key chemical factors in pretreatment, printing and posttreatment affecting digitally printed fabric qualities such as reliable performance and attractive appearance for the market application should be studied.

Factors affecting other fibers such as cotton and structures like knit in digital printing need be identified.

Practical application of gap-bar-gap set test pattern to typical commercial patterns (single or multi colored geometric, floral and novelty) should be explored.

The factors that affect the print clarity of CMYKBR pigment ink need to be studied.

Optimum print mode for matching woven fabrics or other kind of substrates should be considered.

Disperse ink need to be studied in comparison of pigment ink.

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APPENDICES

Appendix A

Table 1. Minimum Fabric Yardage Requirements to Complete Basic Testing for research fabrics

Test Description	**Test Method**	**Performance Requirements**	**Fabric**	**Length**
Fabric Defects	ASTM D3990	No major defects, such as stains, holes, slub yarns, mis-stitches, etc.		
Fabric Weight (oz/sq yd) (g/sq m)	ASTM D3776	As specified in Product Specification or Previous Testing(±5%)	20”2	4.5”
Thread Count(Woven)	ASTM D3775	As specified in Product Specification or Previous Testing(±5%)	3”×3”	3”
Evenness of Color	Visual	Uniform and even color within a sample and between samples		
Pilling Resistance	AATCC 135/150(3 washings/ dryings)	Minimum of Grade 3.0.	15”×15”	15”
Tensile Strength(lb) Outdoor Cushions	ASTM D5034	Warp 200.0 lbs Fill 100.0lbs	2”×2”	2”
Tear Strength(lb) Outdoor Cushions	ASTM D2261	Warp 10.0 lbs Fill 8.0lbs	3”×8”×10	15”
Yarn Slippage(Woven)	ASTM D434	Min.at 1/4 Seam Separation 15.0 lbs		
Dry Crocking	AATCC 8	Minimum of: Grade 4.0	2”×5.1	2”
Wet Crocking	AATCC 8	Minimum of: Grade 3.0.	2”×5.1	2”
Lightfastness	AATCC 16.3	Good Better Best	2.75”×4.7” ×3 1.2”×1.2”× 3	10”
			561.5 in2	53.5”

Table 2 Woven fabric A (warp 2/145/36 denier PET)

Length (yard)	Filling	Content	Yarn count	ppi	Body weave	Selvedge weave
1	Spun	100% Polyester	19/1 cc	52	Plain	Plain
1	Filament	100% Polyester	2/145/36 dnr	52	Plain	Plain
3	Filament	100% Polyester	2/145/36 dnr	52	Plain	Plain
3	Filament	100% Polyester	2/145/36 dnr	52	Plain	Basket
3	Filament	100% Polyester	2/145/36 dnr	52	Plain	Twill
3	Spun	100% Polyester	19/1 cc	52	Plain	Plain
3	Spun	100% Polyester	19/1 cc	52	Plain	Basket
3	Spun	100% Polyester	19/1 cc	52	Plain	Twill
2	Spun	100% Polyester	19/1 cc	48	Plain	Plain
2	Filament	100% Polyester	2/145/36 dnr	48	Plain	Plain
1	Filament	100% Polyester	2/145/36 dnr	48	Herringbone	Plain
1	Filament	100% Polyester	2/145/36 dnr	48	Herringbone	Twill
1	Spun	100% Polyester	19/1 cc	48	Herringbone	Plain
1	Spun	100% Polyester	19/1 cc	48	Herringbone	Twill
1	Spun	80/20 Poly/cotton	20/2 cc	32	Plain	Plain
5	Filament	100% Polyester	2/145/36 dnr	48	Plain	Plain
5	Spun	100% Polyester	19/1 cc	48	Plain	Plain

Table 3 Woven fabric B (warp 16/1 cc PET)

Length (yard)	Filling	Content	Yarn count	ppi	Body weave	Selvedge weave
4	Spun	100% Polyester	8/1 cc	28	2/1 duck	2/1 duck
3	Spun	100% Polyester	8/1 cc	28	2/1 duck	Basket
3	Spun	100% Polyester	8/1 cc	28	2/1 duck	Plain
4	Spun	100% Polyester	8/1 cc	25	2/1 duck	2/1 duck
4	Filament	100% Polyester	638.2 dnr	28	2/1 duck	2/1 duck
3	Filament	100% Polyester	638.2 dnr	28	2/1 duck	Basket
3	Filament	100% Polyester	638.2 dnr	28	2/1 duck	Plain
4	Filament	100% Polyester	638.2 dnr	25	2/1 duck	2/1 duck
1.5	Filament	100% Polyester	638.2 dnr	25	Herringbone	2/1 duck
1.5	Spun	100% Polyester	8/1 cc	25	Herringbone	2/1 duck
3	Spun	100% Polyester	8/1 cc	25	2/1 duck	2/1 duck
2	Spun	80/20 Poly/cotton	20/2 cc	28	2/1 duck	2/1 duck
1	Spun	80/20 Poly/cotton	20/2 cc	25	2/1 duck	2/1 duck

Appendix B: Color calibration and creation of CTB profile

There are three stages for printer calibration and so three different steps are needed to generate the print file for each stage. Each stage will require and then a spectrophotometer reading.
Stage 1: Channel page – measure ink density
Stage 2: Virtual Channels – measures the percentage of any light inks. For example, grey for the nano-pigments and light magenta and light cyan for the reactive inks.
Stage 3: Main pages – measures the percentage of all eight inks,
Three are three Calibration Choices:

- Standard – most typically used, will create 3-6 Main pages
- Condensed – only used for Windows desktop printers
- Enhanced – rarely used, will create 30-36 Main pages

Both Standard and Enhanced will allow the entire printable gamut to be used, however, when color matching with the spectrophotometer, the enhanced will sometimes provide a more accurate match.

<u>STEP 1: Directions for Creating the Channels Page</u>

1. Click on the ProfileMaster tab to open the RipMaster software.
2. Click on the "create new calibration" icon, and provide a distinct new name for the calibration
3. Choose Standard from the pull down menu
4. Click on the Printer tab and select the correct printer
5. Check the box for Use Virtual Channels, Mode: 8 colors
6. Click in the box that says Ink 1 and type in the name of the colors that corresponds to the ink location in the printer. Ex. Ink 1 should be re-named Cyan. Continue to rename Ink 2-8.
7. Tab through when finished and make sure that the Printer Slots are renamed with each ink color in the correct position.
8. Tab to the grey printer slot, and check the box Light Ink.
9. Tab to the black printer slot, and check the box Black.
10. Hit OK.
11. Click on the Format tab to change the size of the color table chips so that they fit in one page. Change from .65 to .6. When asked to apply settings choose: Yes.
12. Click on the Pages icon to send the color table to the print windows.
13. When in the Print windows, hit the "test", make sure Calibration is not checked. Hit Print to send the files to the printer.

Note:
Duplicate the color table file in the printer window so that you have 3-4 files set-up to print. Printing more than one color table file will ensure that you have at least one good quality print should you have a wrinkle in the fabric, head-strikes, fabric feed issues, etc.

STEP 2: Directions for Measuring the Channels Page with the Spectrophotometer

1. Remove the fabric from the printer and trim so that the printed Channel page fits on the spectrophotometer table.
2. Position the printed Channel page so that the image is straight. Tape down any edges that are curling. Turning on the electrostatic charge on the calibration table will help most fabrics to lie smoothly.
3. Click on the Measuring tab in RipMaster.
4. Select the appropriate spectrophotometer: 1)Gretag (xy) Eye-One i0 (USB) when using the spectrophotometer with the reading Table, 2)Gretag Eye-One when using the spectrophotometer only.
5. Hit Apply. Hit Spectro Reset (will take a few seconds to process). Then hit White Calibration (will also take a few seconds to process). It will come out with “insert white standard”, then hit “OK.
6. In RipMaster, select the Measure xy icon and check Use defined page size.
7. On the reading table, manually position the clear plastic crosshair over the top right color chip. In RipMaster, a number representing the top left position should now appear in the box next to Top left (1/1). Click OK to the right of Top left (1/1).
8. On the reading table, manually position the clear plastic crosshair over the top right color chip. In RipMaster, a number representing the top left position should now appear in the box next to Top left (1/24). Click OK to the right of Top right (1/24).
9. On the reading table, manually position the clear plastic crosshair over the top right color chip. In RipMaster, a number representing the top left position should now appear in the box next to Bottom left (1/24). Click OK to the right of Bottom left (1/24).
10. On the reading table, manually position the clear plastic crosshair over the top right color chip. In RipMaster, a number representing the top left position should now appear in the box next to Bottom Right (1/24). Click OK to the right of Bottom Right (1/24).
11. Click OK at the bottom of the RipMaster page.
12. The Spectrophotometer will begin reading in the color chips, which will take around 12-15 minutes.

STEP 3: Directions for Creating the Virtual Channels Page

1. After the spectrophotometer reading of the Channel page is complete, a new image will be added Measurement Channel page 1. By clicking on the color chip in the file, the LAB value will be shown.
2. Click on the darkest color chip on the Grey ink value scale and note the “L” value. Ex. 42.47.
3. Locate the closest “L” value on the Black ink value scale. Ex. Two close matches were 43.87. We choose position 224, but either would work.
4. Locate the calibration file on the C drive, for example, Users\Public\Public documents\RipMaster Data Folder\Printer\Calib\Profiles\Nano Cotton Sateen

0114\Chan 01. cpt.

5. Open this file by choosing Notepad
6. In the notepad, locate the line for 224 and write down the formula, note the number for Black=64.

0	0	0	64	0	0	0	0
Cyan	Magenta	Yellow	Black	Orange	Red	Violet	Grey

7. Change the black and the grey to the correct percentage. To calculate percentage, divided 64 by 256, =25%.
8. Click on the virtual Channels Tab, select "black" in the virtual channel drop-down menumenu, click on the add New Step icon and enter 25.
9. Select the 25 Step line.

	Cyan	Magenta	Yellow	Black	Orange	Red	Violet	Grey
0								
25	0	0	0	64	0	0	0	0
100								

10. In the Physical channel drop-down menu, change the Black to 0 and the grey to 100.
11. Select Pages icon to send the light color blanket, select "channel page 2"
12. After printing it out, follow step 2.

<u>STEP 4: Directions for creating a color blanket</u>

1. Click Pages icon and there will be four main pages formed, send them to printer and follow step 2, reading main pages one by one into computer.
2. After reading all of the main pages, the software will show CTB icon. Click on the CTB icon.
   Color Table Type: From LAB to printer COL8, include gamut data (check)
3. Click on Gamut mapping details. Check the white in the paper tab.
   Gamut mapping: absolute Colorimetric, then click OK.
4. Click calculate and the calculation will last for a while
5. Click RipMaster, then color tab, select color catalog, then check LAB parameters under Options/creation parameters
6. Load calibration—load the CTB file
7. Create LCH catalog, enter catalog name, check limit to device gamut
8. Click "Device Calibration", then load the CTB file into device calibration
9. Click OK, save.
10. Click on "load catalogue", select the "pcf" file. Create a new folder for your calibration file, export RGB catalog to the new folder.
11. Under printer's window, load the new CTB file to the calibration

Appendix C: MatLab code

MATLAB Contrast of a corresponding gap-bar-gap test pattern set (text version)

```
clear;clc;close all;

%text document
rawdata = readtable('12_C2_C.txt');
data=rawdata{:,2:end};
l=size(data);
%calculate average
for i=1:l(1)
    y(i)=mean(data(i,1:end));
end

%filter
[peak, ~] = find_peak(y,1);   % peak
[trough, yy] = find_peak(y,2);  % bottom

%without filter
[Maxima,MaxIdx] = findpeaks(y);%peak
DataInv = 1.01*max(y) - y;
[Minima,MinIdx] = findpeaks(DataInv);
% The true minima will then be:
Minima = y(MinIdx);            %bottom

%Threshold for using filter or not
thres=32;
%Whole peak
peak_a=find(MaxIdx<=thres);
peak_b=find(peak>thres);
peak_fir=MaxIdx(1:length(peak_a));
peak_sec=peak(peak_b(1):end);
peak_pos=[peak_fir,peak_sec];
%Whole bot
bot_a=find(MinIdx<=thres);
bot_b=find(trough>thres);
bot_fir=MinIdx(1:length(bot_a));
bot_sec=trough(bot_b(1):end);
bot_pos=[bot_fir,bot_sec];

for i=1:length(peak_pos)
    p=y(peak_pos(i));
```

```
    Maxima(i)=p;
end

for i=1:length(bot_pos)
    q=y(bot_pos(i));
    Minima(i)=q;
end

%output
disp('index of peaks')
disp(peak_pos);
disp('index of bottoms')
disp(bot_pos);

%Calculate C
b=max(Maxima)-min(Minima);
 len=length(peak_pos);
for i=1:len
    ctemp=Maxima(i)-Minima(i);
    C(i)=ctemp/b;
end

figure;
%plot C
x=linspace(1,len,len);
plot(x,C);

figure;
% plot original figure
h = plot(1:size(yy,2),yy);
xlabel('index');
ylabel('peaks');
hold on;
for i=1:size(peak_pos,2)  % the position of peak
    tmpx = peak_pos(i);
    tmpy = yy(tmpx);
    h = plot(tmpx,tmpy,'o');
    set(h,'MarkerFaceColor',[1 0 0])
%     text(tmpx+2,tmpy,['(' num2str(tmpx) ',' num2str(tmpy) ')'],'FontSize',7);
     text(tmpx+5,tmpy, num2str(tmpx),'FontSize',8);
end
for i=1:size(bot_pos,2)  % the position of bottom
    tmpx = bot_pos(i);
```

```
    tmpy = yy(tmpx);
    h = plot(tmpx,tmpy,'o');
    set(h,'MarkerFaceColor',[0 1 0])
%     text(tmpx+2,tmpy,['(' num2str(tmpx) ',' num2str(tmpy) ')'],'FontSize',7);
    text(tmpx+5,tmpy, num2str(tmpx),'FontSize',8);
end
xlswrite('_C.xls',C);
```

MATLAB Find peaks

```
function [peak yy] = find_peak(y,flag)
% find the peak and bottom of data 'y'
% y: input data
% yy: data after filter
% peak:index of peak
% flag: 1-->peak;2-->bottom

% step 0: data pre-processing
if (flag==2)
    y = y .* -1;
end

% step 1: filter
% yy = median_filter(y,5);
% yy = mean_filter(y,6);
yy=y;
% yy = median_filter(yy,9);

% step 2: max data
[~, tmp_peak] = findpeaks(yy);

% step 3: index of threshold
max_y = max(yy);
e = (max(yy)-min(yy))*0.8;    %threshold
R = 10;      %radius of search
peak=[];
for i=1:size(tmp_peak,2)
    if(max_y - yy(tmp_peak(i)) <= e) %whether meet the threshold
        found = 1;
    else
        continue;
    end
    for j = tmp_peak(i)-R:tmp_peak(i)+R
       if(j<1 || j>size(yy,2))
```

```
            continue;
        end
        if(yy(tmp_peak(i))<yy(j))
            found = 0;
        end
        if(yy(tmp_peak(i))==yy(j) && sum(peak==j)==1)
            found = 0;
            break;
        end
    end
    if(found==1)
        peak = [peak tmp_peak(i)];%record the index of peak
    end
end

if(flag==2)
    yy = -1.*yy;
end
```

MATLAB CMYKRB six colors and average

```
clear;clc;close all;

C1=xlsread('_C');
C2=xlsread('_M');
C3=xlsread('_Y');
C4=xlsread('_K');
C5=xlsread('_R');
C6=xlsread('_B');
A={C1;C2;C3;C4;C5;C6};

%the length of the file
L(1)=length(C1);
L(2)=length(C2);
L(3)=length(C3);
L(4)=length(C4);
L(5)=length(C5);
L(6)=length(C6);

base=min(L);

for i=1:base
    aver(i)=(A{1}(i)+A{2}(i)+A{3}(i)+A{4}(i)+A{5}(i)+A{6}(i))/6;
```

```
end

%one more
pos1=find(L>=(base+1));
num1=length(pos1);
total1=0;

if num1~=0
    for i=1:num1
        total1=total1+A{pos1(i)}(base+1);
    end
    aver(base+1)=total1./num1
end

%two more
pos2=find(L>=(base+2));
num2=length(pos2);
total2=0;

if num2~=0
    for i=1:num2
        total2=total2+A{pos2(i)}(base+2);
    end
    aver(base+2)=total2./num2
end

%three more
pos3=find(L>=(base+3));
num3=length(pos3);
total3=0;

if num3~=0
    for i=1:num3
        total3=total3+A{pos3(i)}(base+3);
    end
    aver(base+3)=total3./num3
end

%four more
pos4=find(L>=(base+4));
num4=length(pos4);
total4=0;
```

```
if num4~=0
   for i=1:num4
      total4=total4+A{pos4(i)}(base+4);
   end
   aver(base+4)=total4./num4
end

% for i=1:base
%     aver(i)=(C1(i)+C2(i)+C3(i)+C4(i)+C5(i)+C6(i))/6;
% end
%
% len1=find(L=base+1);
% len2=find(L=base+1);

figure

lw1=1;
lw2=6;
plot(C1,'c','linewidth',lw1);
hold on;
plot(C2,'m','linewidth',lw1);
plot(C3,'y','linewidth',lw1);
plot(C4,'k','linewidth',lw1);
plot(C5,'r','linewidth',lw1);
plot(C6,'b','linewidth',lw1);
plot(aver,'B','linewidth',lw2);
set(gca,'fontsize',18);

set(gca,'Xtick',([0 2.359 4.718 7.077 9.436 11.795 14.154
16.513]),'Xticklabel',[{'0','0.2','0.4','0.6','0.8','1.0','1.2','1.4'}]);
xlim([0 16.513])
xlabel('Wavelength (mm)','fontsize',20);
ylabel('C','fontsize',20,'rot',0);
set(get(gca,'ylabel'), 'Units', 'Normalized', 'Position', [-0.05, 0.5, 0]);

legend('cyan','magenta','yellow','black','red','blue','average','FontSize',16,'Location','northwest'
)

xlswrite('16_C2_aver.xls',aver);
```

Appendix D: Cover letter

June 6, 2016

Mr. X

Dear Mr. X ,

I am a doctoral student at the College of Textiles, North Carolina State University (NCSU) conducting research under the supervision of Professor Nancy Powell. In order to better understand the requirements of the industry in the area of digital printing and discover potential improvements I am seeking valuable input from experts. We are requesting your assistance in this study related to the factors impacting digital printing quality.

This research seeks to improve fabric (substrate) for digital printing enhancements, but also to develop an optimum base cloth that could be supplied by a U.S. manufacturer. Improved print substrates or prepared for digital printing base materials will contribute to the final product's qualities in meeting performance, styling and cost requirements. Each step in the general process from fiber to finished product for a woven substrate and digitally printed product impacts the final performance and aesthetic appearance of the printed products.

Specifically, I am requesting your assistance by completing the attached questionnaire to confirm research results. Your participation in this study will provide critical input for the characteristics and preparation of substrates for digital printing. The information in the study records will be kept confidential. No reference will be made in oral or written reports which could link you to the study. Notes taken from person-to-person interviews would be confirmed for accuracy by interviewees. This dissertation will be available for your review through the NCSU Library Electronic Theses & Dissertations (ETDs) at the expected completion of the research in 2017. If you have any questions or require more information, please do not hesitate to contact me. I would also be glad to schedule a phone or SKYPE interview if you would prefer to discuss the completion of the questionnaire in that manner.

Sincerely,

Xingyu Li
Graduate Research Assistant, PhD student
Fiber and Polymer Science
College of Textiles
North Carolina State University (NCSU)
xli39@ncsu.edu
919-413-6610 (mobile)

Appendix E: Informed consent form for research

North Carolina State University
INFORMED CONSENT FORM for RESEARCH

FACTORS IMPACTING DIGITAL PRINTING ON TEXTILES

Principal Investigator: Xingyu Li Faculty Sponsor: Nancy B. Powell

What are some general things you should know about research studies?

You are being asked to take part in a research study. Your participation in this study is voluntary. You have the right to be a part of this study, to choose not to participate or to stop participating at any time without penalty. The purpose of research studies is to gain a better understanding of a certain topic or issue. You are not guaranteed any personal benefits from being in a study. Research studies also may pose risks to those that participate. In this consent form you will find specific details about the research in which you are being asked to participate. If you do not understand something in this form it is your right to ask the researcher for clarification or more information. A copy of this consent form will be provided to you. If at any time you have questions about your participation, do not hesitate to contact the researcher(s) named above.

What is the purpose of this study?

The purpose of this study is to improve the substrate (base cloth) for digital printing and understand the factors (processes and materials) that affect digital printing on textiles. This was done by printing on different types of polyester woven fabrics and analyzing physical properties of printed fabrics. The fabrics were analyzed for dry and wet crock fastness, light fastness, color gamut, tensile strength, tear strength, seam strength and clarity of printed test patterns. Following the analysis stage, industry interviews (such as this) will be conducted in order to validate the contributing factors discovered in this research and reveal any new factors.

What will happen if you take part in the study?

If you agree to participate in this study, you will be asked to answer a series of questions about your professional observations of fibrous substrates and dyes and chemicals that maybe applied in digital printing. The length of the interview session will vary. It is predicted that the session will take no longer than 30 minutes. During a face to face interview, responses will be noted by the interviewer and reviewed with the interviewees to confirm the accuracy.

Risks

Possible legal risks exist due to disclosure of potentially confidential information; however, subject responses will be coded and any information that could identify subjects will be removed in the reporting of the information. Please do not divulge any information that you are uncomfortable sharing.

Benefits
This study is intended to benefit companies interested in the digital printing process and related technologies. This study identifies the impacts of textiles substrates (base cloth), dyes and chemicals and other factors that influence digital printing. Understanding the factors impacting digital printing will contribute to the quality and efficiency of digital printing.

Confidentiality
The information in the study records will be kept strictly confidential. Data will be stored securely on the researcher's hard drive (password protected). Code numbers will be created for your name and company; these code numbers will be the only identifiers stored with the data. The master list linking codes to the subject will be kept in a separate location from that of the data in order to minimize the potential of linking the data to you and your company. In addition, any identifying information will be removed when reporting the data. No reference will be made in oral or written reports which could link you to the study.

Compensation
You will not receive anything compensation for participating.

What if you have questions about this study?
If you have questions at any time about the study or the procedures, you may contact the researcher, Xingyu Li, at the College of Textiles, Campus Box 8301, Raleigh, NC 27695, xli39@ncsu.edu, or 919.413.6610.

What if you have questions about your rights as a research participant?
If you feel you have not been treated according to the descriptions in this form, or your rights as a participant in research have been violated during the course of this project, you may contact Deb Paxton, Regulatory Compliance Administrator at dapaxton@ncsu.edu or by phone at 1-919-515-4514.

Consent To Participate
"I have read and understand the above information. I have received a copy of this form. I agree to participate in this study with the understanding that I may choose not to participate or to stop participating at any time without penalty or loss of benefits to which I am otherwise entitled."

Subject's Signature__________________________________**Date**____________________

Subject's Printed Name:________________________ _____________________________

Investigator's Signature______________________________Date ____________________

Appendix F: Questionnaire for industry survey

FACTORS IMPACTING DIGITAL PRINTING ON TEXTILES

The purpose of this study is to improve the substrate (base cloth) for digital printing and understand the factors (processes and materials) that affect digital printing. Industry interviews (such as this) are being conducted in order to validate the contributing factors discovered in this research and reveal any new factors.

Please complete the following questions by checking the appropriate boxes from your experience and expertise. During a face to face interview, responses will be noted by the interviewer and reviewed with the interviewees to confirm the accuracy. The interviewee will never be identified or linked to the comments in any results report or publication.

NOTE: If a particular question does not apply to your situation, please skip that question.
You may check more than one box for each question if appropriate.

1. In which type of printing have you had experience?

☐ Digital printing
☐ Screen printing
☐ Heat transfer printing
☐ Roller printing
☐ Other: ________________

Substrate Content and Structure

Fiber:

2. Identify the fiber content in the fabrics you have printed.

☐ Polyester	☐ Cotton
☐ Poly/cotton blend	☐ Poly/nylon blend
☐ Rayon	☐ Nylon
☐ Wool	☐ Other: ________________

End use

3. Identify the use of the printed fabric application.

☐ Apparel	☐ Floor Coverings
☐ Automotive	☐ Window Treatments
☐ Upholstery	☐ Outdoor Fabrics
☐ Bedding	☐ Signage

☐ Flags and Banners ☐ Wall Coverings
☐ Other: ____

Yarn:
4. Which types of yarn are used in the substrate and where?

Yarn	Application
☐ Spun	☐Warp ☐Filling ☐Knit ☐Tufted
☐ Filament	☐Warp ☐Filling ☐Knit ☐Tufted

5. Describe the spinning process for the yarns used in the preparation of the substrates?

☐ Spun	☐Open end	☐Ring spun	☐Air jet	☐Recycled	☐Other: _______
☐ Filament	☐Textured	☐Recycled	☐Flat	☐Other: _______	

Structure:
6. Which woven structures have you found to be the most successful in printing?
☐ Plain ☐ Satin
☐ Twill ☐ Other: ______________________
☐ 2/1 Duck

Scouring:
7. Is there a size on the substrate? Is the size removed before printing?
☐ Yes Type: _____________________________________
☐Removed ☐Not removed
☐ No

8. Do you check wet pickup percentage before pretreatment or printing?
☐ Yes
☐ No

Selvedge:
9. Do your substrates have selvedges?
☐ Yes Are they removed before printing? ☐Removed ☐Not removed
☐ No

10. Do you think selvedges have any impact on printing quality?
☐ Yes Reason: ____
☐ No Reason: ____

Shrinkage of substrate:
11. Is shrinkage a critical consideration in preparing substrates for printing?
☐ Yes ☐ No

12. If so, what steps do you take to control shrinkage?
☐ Preshrink ☐ Purchase fabric preshrink
☐ Do not control
☐ Other: ____

Width:
13. How wide do you weave or specify in purchasing substrates?
☐ 54''- 62''
☐ 63''- 117''
☐ 118''-130''
☐ Other: ____

Weight:
14. For fabric performance and print quality which finished fabric weights do you prefer?
☐ < 3 ounces per square yard
☐ 3 – 5 ounces per square yard
☐ 5 – 10 ounces per square yard
☐ Other: ____

Dyes and chemicals

15. What type of dyes/inks have you used for printing?
☐ Pigment ☐ Reactive
☐ Disperse ☐ Other: ____________________

16. Are your substrates pretreated before printing?
☐ Yes
☐ No

17. Are your substrates post treated (after printing)?
☐ Yes ☐ Wash ☐ Heat setting (curing) ☐ Chemical finish ____________
☐ Other: ____________________________________
☐ No

18. Please check any standards for print clarity used during quality inspection

☐ ASTM F1944-98 ☐ Evaluation strike-off

☐ Printed Test Pattern ☐ Production Standard

☐ Other: ______________________

19. Have you encountered any bow and bias issues at any point during the process?

☐ Yes Reason: ____

☐ No Reason: ____

Printer Belt:

20. Are you digital printing? Does your printer have a continuous belt?

☐ Yes ☐ Adhesive Belt ☐ Non-adhesive belt

☐ No

21. If so, how often does the adhesive need to be reapplied to the belt? How long does the process take?

Frequency:	Duration:	
☐ 1-6 months	☐ 4-8 hrs	☐ more than 8hrs
☐ 7-12 months	☐ 4-8 hrs	☐ more than 8hrs
☐ Other: ______	☐ 4-8 hrs	☐ more than 8hrs

22. Are you digitally printing long-run production or short-run sampling?

☐ Long run production (more than 100 yards per style/colorway)

☐ Short run sampling (less than 100 yards per style/colorway)

☐ Both sampling and production

23. Are there any other substrate or processing issues affecting printed fabric manufacturing or quality of finished fabrics?

____

____

____

24. If you could design an ideal woven substrate for digital printing, what type of characteristics would you include?

Professional Background

25. In which of the following areas have you had experience? How many years of experience do you have in the related area?

- ☐ Substrate Manufacturing ☐0-5 ☐6-10 ☐11-20 ☐more than 20 years
- ☐ Dyestuffs & Chemicals ☐0-5 ☐6-10 ☐11-20 ☐more than 20 years
- ☐ Printing ☐0-5 ☐6-10 ☐11-20 ☐more than 20 years
- ☐ Finishing ☐0-5 ☐6-10 ☐11-20 ☐more than 20 years

26. In which of the following roles in the textile and related industries have you had experience?

- ☐ Research
- ☐ Development
- ☐ Marketing
- ☐ Purchasing
- ☐ Manufacturing

27. Could you recommend other experts who could provide valuable input?

THANK YOU FOR YOUR PARTICIPATION

Appendix G: Thank you letter

Date

First Last Name
Company Name

Dear X,

Thank you for participating in the material assessment phase of my research at NC State University's College of Textiles. Your professional contribution was vital to the success of my dissertation research project, "*FACTORS IMPACTING DIGITAL PRINTING ON TEXTILES*". I and my doctoral committee sincerely appreciate you taking time out of your busy schedule to participate in this session. The dissertation will be available for your review through the NCSU Library Electronic Theses & Dissertations (ETDs) at the expected completion of the research in 2017.

Thank you for your time and your valuable insights.

Xingyu Li
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