Grading zero waste design using digital and virtual methods

by

Sahar Hassan Ejeimi

B.S., King Abdul-Aziz University, 2008
M.S., Colorado State University, 2016

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Apparel, Textiles and Interior Design
College of Health and Human Sciences

KANSAS STATE UNIVERSITY
Manhattan, Kansas

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Abstract

Traditional practices of pattern cutting within the apparel industry result in a considerable portion of fabric waste that negatively impacts the environment. Currently, garment manufacturers make responding to fashion trends, at the lowest possible cost, the main priority, regardless of fabric waste, to ensure economic profit. Besides, one of the sustainable challenges when working with zero waste design (ZWD) is the feasibility of pattern grading under the current apparel production system. Thus, the purpose of this experimental study was to explore the feasibility of grading zero waste garments for industry production using digital and virtual methods. The main research questions in this study were: What pattern piece adjustments and marker layouts achieve both 100% marker efficiency and accurate virtual visual appearance? Can digital 3D simulation be used as an effective and sustainable sizing and fit assessment tool? Does attachment and appreciation of ZWD influence expert judges' evaluation of visual accuracy?

The first research question was answered through a functional design process that included three phases: sample development, grading and marker making, digital and virtual testing of marker adjustments, and marker refinement. The application of typical and novel marker making and design tactics for functional utilization of the cuts offs resulting in no fabric waste of the mixed marker of the graded sizes was explored. As a result, a system of four different adjustment methods were applied to reach 100% marker efficiency while maintaining visual accuracy. Multiple challenges regarding the use of 3D simulation to create virtual samples were encountered.

To answer the second and third research questions, an online questionnaire was utilized to collect assessment related to the efficiency of the graded virtual samples compared to the physical based on particular design criteria. Two judge groups participated in this study, zero waste design academic researchers and industry technical designers. The judges compared the samples via video, between and across groups. The findings indicated that the use of 3D simulation was mostly challenging for grading ZWD while maintaining 100% marker efficiency and visual accuracy. Judges suggested that the 3D simulation would be a useful, sustainable tool for fit and appearance assessment to decrease the number of physical samples; however, major improvements for the software were recommended before the physical sample could be eliminated. These findings contribute to understanding the effectiveness of sizing zero waste design and use of 3D virtual simulation as an assessment method, which promotes sustainable development through pattern making within the production methods in the apparel industry. Technical judges had more agreement than ZWD judges regarding the similarity between virtual and physical samples, and the sufficiency of information provision by virtual samples that would replace physical samples. Thus, ZWD judges had higher expectations for virtual technology. This finding indicated a relationship between attachment and appreciation of sustainability in fashion with the adoption of advanced practices to develop sustainable fashion design through the functional design process.

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Approved by:

Major Professor
Sherry Haar

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Acknowledgment

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CHAPTER I

INTRODUCTION

Since the emergence of the First Industrial Revolution, as well as the Technological Revolution in the last third of the nineteenth century, the world has been facing growing issues of industrial waste resulting from different industrial fields. Pre-consumer textile waste has been globally caused via the production of textile, clothing, and home textile products, as well as through various other industrial textile products including streams of fiber, textile, and clothing manufacturing (Reverse Sources, 2016). Excessive production and consumption of clothing has been increasing waste during recent decades making the apparel industry the world's second largest polluter, right behind the oil industry (Eco Watch, 2015). Although production in the apparel industry results in numerous waste categories including water, energy, and solid waste such as packaging materials, the current study specifically focused on the solid textile waste produced from cutting garment pattern pieces out of fabric.

Traditional practices of pattern cutting within the apparel industry result in a considerable portion of fabric waste that negatively impacts the environment. In fact, fabric waste resulting from the fabric cutting process generates 10% of solid, apparel industry waste (Fletcher, 2014; Reverse Sources, 2016). Fast fashion has been playing a primary role in speeding up fashion consumption, thereby, creating more waste (Lau, 2015). Ultimately, this waste creates negative environmental and economic impacts, as well as contributes to the risk of global warming.

To mitigate the negative environmental impacts created by various industry sectors, Cradle-to-Cradle (hereafter referred to as C2C), a sustainable concept that utilizes various waste management strategies, addresses the three pillars of sustainability: environmental sustainability, economic sustainability, and social sustainability (McDonough & Braungart, 2002). The apparel industry has been adopting the C2C concept throughout the life cycle of garments, starting from the initial stages of fiber manufacturing all the way to garment disposal. Apparel waste across its life cycle within C2C is categorized as either pre- or post-consumer waste (McDonough & Braungart, 2002). Post-consumer waste emphasizes consumer awareness of global environmental problems. Thus, strategies to manage waste are focused on recycling practices such as purchasing up-cycled apparel products, donating for the use of second-hand apparel, or recycling materials for making new products.

Managing pre-consumer waste in C2C, on the other hand, is considered the industry's responsibility in order to decrease the amounts resulting from pre-production and production processes, such as marker-making (the process of arranging pattern pieces on a rectangular shaped block, used as a cutting guideline in the cutting process), fabric cutting, and garment construction. Decreasing textile waste during the pre-consumer phase is usually realized through the three Rs (recycling, reusing, and reducing). Improving marker (i.e., garment pattern piece layout) efficiency is one of the most crucial technical steps in the apparel industry to reduce waste. However, preventing pre-consumer waste is more efficient than managing waste (Rissanen & McQuillan, 2016). Zero waste design (ZWD) is the practice of eliminating pre-consumer waste through pre-production processes. Currently, ZWD is at the top of the pyramid of waste management strategies (Aakko & Sivonen, 2013; Rissanin, 2013).

Although ZWD is not a new concept, it is considered a shift from waste management to waste elimination (Zero Waste International Alliance, 2009). According to Fletcher (2014), "zero waste pattern cutting is alternative formats of clothing configuration and construction in which the layout and shape of pattern pieces is altered to reduce to zero any waste from the layout and cutting process" (p. 130). Rissanen (2013) suggested that although waste elimination is a small contribution towards sustainable fashion design, it is one that has significant impact on the amount of fabric waste created by the apparel and textile industries.

Creating zero waste contributes to environmental protection (Rissanen, 2013). Most research on sustainable practices that examine the environmental impacts of pre-consumer waste are focused on the initial phases of fabric production. Previous research included examination of the challenges of using renewable materials, non-harmful materials, and long-life materials regarding fibers and production stages (Roos, Posner, Jönsson, & Peters, 2015; Wong, Ng, & Cai, 2018). Researchers also have investigated promoting fiber and fabric recycling processes (L'Abbate, Dassisti, Cappelletti, Nicoletti, Russo, & Ioppolo, 2018). While use of sustainable materials are crucial for reducing the harm of waste fabric, eliminating waste is significant for maintaining natural resources and valuing the embedded cost and labor of manufacturing textiles. Furthermore, there is a lack of research regarding ZWD, especially in relation to pattern sizing and fabric cutting in apparel manufacturing.

One significant reason behind the lack of research about ZWD is due to the current apparel production system. Currently, garment manufacturers make responding to fashion trends, at the lowest possible cost, the main priority, regardless of fabric waste, to ensure economic profit. Therefore, as long as the economic profit is higher than the loss resulted from the waste, fabric waste is not regarded. In addition, marker efficiency is traditionally a technical procedure during the pre-production process that is a reaction to pre-determined designs. ZWD, however, considers the amount of fabric usage from the initial stages of design. This limits ZWD to studio-level practice and thus the research tends to be focused on creative pattern cutting and aesthetic investigation. This study used an original zero waste design in which pattern cutting was determined through the initial stage of the design process, not as a reaction to a finalized design idea. Thus, this allows investigation of fabric waste within the current industry practice through the marker-making process.

Another research challenge when working with ZWD is the feasibility of pattern grading (i.e., sizing of pattern pieces) under the current apparel production system. In fact, grading zero waste garments is considered the main limitation for producing zero waste design for large-scale manufacturing (Carrico & Kim, 2014; Rissanen & McQuillan, 2016). Zero waste patterns are designed based on specific fabric widths or shapes cut within determined dimensions, thereby making grading to smaller or larger sizes problematic for maintaining zero waste. Therefore, in order for more adoption of zero waste garments within the apparel industry, the feasibility of grading ZWD in a manner similar to current, conventional grading practices within the industry is crucial (Rissanen & McQuillan, 2016).

Currently, grading ZWD might be feasible with the utilization of the Jigsaw ZWD approach. Jigsaw is a zero-waste design method in which garment patterns and their layout on fabric (i.e., a marker) are created based on a specific width of fabric. Similar to conventional pattern design, the Jigsaw method includes a variety of pattern shapes. However, Jigsaw pattern pieces are interlocked by mutual lines, unlike the negative space between pattern pieces and resulting fabric waste of conventional markers (Carrico & Kim, 2014). As mentioned above, the Jigsaw approach proves problematic when it comes to grading patterns, while maintaining zero waste. However, since this approach is similar to the traditional two-dimensional pattern cutting method, it has the most potential for use in large-scale manufacturing of varied sizes, using current grading and marker-making practices.

Various marker-making factors influence achieving high marker efficiency, including marker layout and marker type. Dumishllari and Guxho (2015) conducted an experimental study to investigate how different marker layouts influenced the percentage of fabric consumption. The study examined an order of 200 jackets composed of various sizes with a different order quantity for each size. The researchers stressed that marker lengths have a direct impact on fabric consumption; they determined using a longer marker resulted in higher efficiency. Another study by Haque (2016) compared efficiency between three differing marker types for a particular style, and found that the mixed marker, which includes all sizes mixed within the layout, was the most efficient approach.

Even though marker-making practices could result in efficient utilization of fabric and saving time and cost, visual accuracy across graded sizes is another important element that is associated to the challenge of fit in grading. However, three-dimensional simulation technology has been used to view the accuracy of fit and appearance after grading. This technology has been used by apparel companies to save time and cost by reducing the number of physical prototypes as well as to improve communication across pre-production (Salmon, 2014; Papahristou & Bilalis, 2017). Two-dimensional grading practice has been occurring in conjunction with 3D technology to better understand measurement change across body sizes. Bye, LaBat, McKinney, and Eun Kim (2008) used 2D Optitex for grading and generating digital body outlines, and 3D scans and rotation technology as methods to analyze traditional grading with fit-to-shape (i.e., custom fit) grading.

Optitex software, including 2D and 3D solutions, is being used by 7000 companies around the world including Under Armor, one of the apparel companies that consider adopting sustainable practices for athletic wear manufacturing. This fact supports the potential feasibility of implementing the outcomes of this study. According to Meng, Mok, and Jin (2012), the interactive style edits in both 2D and 3D garments were efficient when altering pattern. However, although 3D virtual simulation is widely used for its advantages, some researchers found that virtual fit does not precisely depict the accurate fit of the garments (Baytar & Ashdown, 2015; Lin & Wang, 2014; Lee & Park, 2017; Song & Ashdown, 2015). Song and Ashdown (2015) found that in comparing the fit of garments between real and virtual models, the simulations did not accurately depict ease or stress folds on poor fitting items. In addition, the researchers found that there was an inaccuracy of waist placement and silhouette width on investigated items. Similarly, Lee and Park (2017), who examined 3D virtual fit simulation as an assessment tool to analyze fit between actual and virtual garments, found that actual fitting showed smaller variation than the 3D simulation across the sizes.

Song and Ashdown (2015), used a multidimensional body shape analysis which utilized a large anthropometric data set and statistical methods to classify shapes based on a comparison of multiple body dimensions. They found that 3D showed less ease on a virtual model than on the actual model for the pants. They also found the virtual fit did not display the small stress folds of the fabric caused by small amounts of tightness and looseness, which, according to the researchers, requires both improvements in the software and caution when assessing prototypes.

The challenge of assessing accurate fit issues using 3D simulation is related to in-depth analysis of fit rather than basic fit issues (Baytar & Ashdown, 2015; Lee & Park, 2017; Meng, Mok, & Jin, 2012; Song & Ashdown, 2015). Song and Ashdown (2015) stressed that having expert fit judges, who worked as designers or technical designers, evaluate the similarities between the real and the virtual fit gave more accurate fit assessment. Lee and Park (2017) also found that preliminary fit analysis, using 3D simulation technology, was a useful tool to check for major fit issues of overall length, width, and silhouette of a prototype, which indicates the importance of experts' evaluation for in-depth assessment such as assessing the hang of the garment and accurate proportion between garment parts. Thus, this study included 3D simulation technology interactively for the evaluation of constructed garment images and virtual through the design process to asses and/or resolve fit issues.

Purpose

The overarching purpose of the study was to improve the sustainability of production methods of sustainable fashion design. This study explored the feasibility of grading ZWD for industry production using digital and virtual methods. A ZWD jigsaw dress, size 8, was developed and served as the control. The process included: a) grading the Jigsaw ZWD dress pattern to sizes 4 and 12 using industry software Optitex, b) establishing an initial marker with the graded sizes, c) making pattern piece adjustments to establish 100% mixed marker efficiency (no fabric waste), d) view best markers on the virtual avatar, e) construct control and best adjustment result in fabric, and f) have expert judges evaluate graded sizes against the control across both constructed and avatar images.

The results may provide a guide for grading similar ZWD Jigsaw patterns in order to contribute to solving a crucial issue regarding grading ZWD garments within current practices in apparel design and manufacturing. Researchers agree that sizing ZWD patterns does vary from one ZWD method to another (Carrico & Kim, 2014; Rissanen & Mcquillan, 2016). Since the standard rule for grading in the apparel industry keeps the features of design that are successful (Lin & Wang, 2014), experimental research regarding grading Jigsaw patterns may uncover findings that address sizing issues of ZWD garments made of Jigsaw patterns, which could lead to more utilization of ZWD manufacturing for mass production as a sustainable design practice.

Following are definitions of the key terms used in the research questions and later in the methods chapter.

- Control: is size 8 in this study.
- Graded: are sizes 4 and 12 in this study.
- Virtual: is the 3D simulated garments that were stitched and draped by the researcher using Optitex.
- Constructed: is the actual garments that were constructed by the researcher

Research Questions

Question One

1. What pattern piece adjustments and marker layouts achieve both 100% marker efficiency and accurate virtual visual appearance? Specifically,

   a. What pattern piece adjustment methods, for the two graded sizes of the selected ZWD Jigsaw style result in 100% marker efficiency and visual accuracy?

   b. What is the most efficient pattern piece adjustment method and marker layout that maintains visual accuracy as compared between the virtual control garment and the graded virtual garments?

Marker arrangements were experimented with the two sizes before applying any pattern adjustments. This step was important for reaching the maximum marker efficiency for the initial marker to assure minimum adjustments for achieving zero waste for the graded Jigsaw pattern pieces.

Different adjustment methods were applied to pattern pieces, as a means of increasing marker efficiency and eliminating waste. Each adjustment method had a different order of the following adjustment techniques (Glock & Kunz, 2005).

- adjusting visible pattern dimensions (pattern division; pattern extending/shortening or widen/narrow; seam; fullness by ease, gather, fold)
- adjusting non-visible pattern dimensions (hem width or length, seam allowance, facing, internal support)
- modifying specified grainline (tilt, rotate)
- utilizing negative space (create garment parts such as inner pockets and facing).

When 100% marker efficiency was established, the pattern pieces then moved into three-dimensional virtual garments to evaluate visual accuracy. The process continued until an acceptable digital solution was determined. Records and screen shots were kept to document how pattern adjustments influenced the fit and silhouette of the virtual garment. To answer the second part of the first question, three-dimensional simulation was used to examine the best pattern adjustments plan that resulted in minimum change of the appearance between graded sizes and the control size.

Question Two

2. Can digital 3D simulation be used as an effective and sustainable sizing and fit assessment tool? Specifically,

   a. What is the visual accuracy between the physically constructed control garment and the virtual control garment?

   b. What is the visual accuracy between the physically constructed control garment and the two graded physically constructed garments?

c. What is the visual accuracy between the virtual control garment and the two graded virtual garments?

d. What is the visual accuracy between the two graded physically constructed garments and their corresponding virtual simulation?

Although 3D virtual models have been widely used in the apparel industry, especially in initial phases of apparel manufacturing, researchers have stressed the importance of the utilization of actual garments to achieve precise results in comparison to the virtual models (Bye et al., 2007; Song & Ashdown, 2015). Thus, silhouette, drape, fit and ease, location of internal seamlines, distribution of gathers and overall acceptability were assessed across the sizes in both physically constructed garments and 3D virtual garments by expert judges. The first group was comprised of six ZWD designers, while the second group was comprised of six technical apparel designers. The virtual and physical garments were viewed on dress forms of corresponding sizes via video. Judges' answers informed the researcher about the efficacy of the 3D virtual simulation compared to actual garments, which answered the second research question.

Question Three

3. Does attachment and appreciation (to be explained in framework) of ZWD influence expert judges' evaluation of visual accuracy? Specifically,

a. Are evaluations by ZWD designers similar or different from technical designers regarding the visual accuracy between the control garment and the sized garments for both constructed and virtual garments?

Three approaches were utilized to analyze the results for each research question. First, the design data analysis for the first research questions included multiple meetings between the researcher and Dr. Haar and Dr. Wu to evaluate the results through the functional design process.

In addition, the researcher communicated the technical support for the software company to solve issues. Lastly, the feedback from the pilot survey provided further analysis of the design process results. On the other hand, to answer the second and third research questions, descriptive statistical analysis was utilized to examine the judges' responses through an online survey, while the content analysis approach (Julien, 2008) was utilized for analyzing the qualitative comments.

Theoretical Framework

Two frameworks that have been utilized in sustainable design practice are the Cradle-to-Cradle Apparel Design and Production model (C2CAD) (Gam, Cao, Farr, & Heine, 2009) and the model of Sustainable Fashion Design (Aakko & Sivonen, 2013). The C2CAD model was developed through the integration of McDonough and Braungart's (2002) C2C model into other pre-existing apparel design and production models. The C2CAD provides practical guidelines for addressing the three pillars of sustainable development: economic development, social development, and environmental protection. The C2CAD model is focused on recycling and reusing practices for textile products; therefore, it was not the ideal model to use in the current study due to its focus on waste elimination.

The model of Sustainable Fashion Design (Askko & Sivonen, 2013), on the other hand, is a framework that integrates the elements of sustainability and fashion design to guide the sustainable practices from different dimensions in apparel industry. The core concept of this design model is the exchangeable balance between the materials consumed from the environment for manufacturing purposes and the amount returned to the environment after manufacturing without incurring any form of harm on either end (see Figure 1.1). Functional design is one of the key elements for the core concept in this model. Through the production methods, as a major category for sustainable practices, ZWD is a patternmaking practice that would contribute to the development of sustainable fashion design through functional design process.

In addition to the production methods included in this model, the “Attachment and Appreciation” category, along with its subcategories, serve as a bridge between the “Considered Take and Return” concept and other categories in the model including “Production Method.” This indicates the importance of the factor of attachment and appreciation of sustainability in the efficiency of addressing any of the model part categories. Thus, this study included a comparison between the evaluations of the ZWD designers and the technical designers, in order to examine the influence of attachment and appreciation of ZWD in the evaluation of visual accuracy between the control and graded sizes of the ZWD style. Further discussion of the model of Sustainable Fashion Design can be found in chapter two.

Justification

Managing textile waste is considered as one of the major sustainable challenges the apparel and textile industry encounters. Pre-production waste is more challenging to manage than post-consumer textile waste because most pre-production waste is not in a form of finished products. ZWD is one approach to address waste management that occurs in the pre-production phase. However, grading ZWD is one of the obstacles to extend the production of ZWD in addition to minimal research on grading for ZWD mass production. Digital and virtual methods would allow for experimentation with grading and viewing on an avatar that could reduce sampling and thus fabric waste. A digital means of communication between design, technical design, and a manufacturer’s sampling may reduce the pre-production carbon footprint. This would be achieved by saving natural resources including energy consumption and raw materials being consumed for making, mostly, non-used physical samples.

Definition and Terms

The following list of definitions and terms referenced throughout the study:

Apparel Pre-Production Processes

Processes conducted before garment mass production; these can include: patternmaking, pattern grading, marker making, and sample making.

Bundle

The bundle includes all the pattern pieces in a marker for a particular size.

Cardinal Point

Points where changes are made along the perimeter of a pattern piece (Mullet, 2015).

Cloth Files (*. **clt**)

It is a cloth file format in Optitex.

Cut off or fall out

The fabric pieces not included in the marker that usually be thrown away after cutting the marker.

Embedded Jigsaw

Patterns from two or more outfits designed to interlock perfectly on fabric and leave no waste (Rissanen, 2013) (see Figure 1.2).

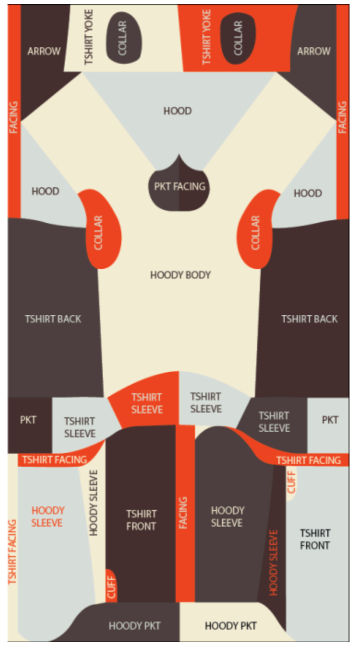


Figure 1.2 Embedded Jigsaw by Holly McQuillan. The layout includes three garments, a hoody and two t-shirts (Rissanen & McQuillan, 2016).

Fast Fashion

The fast fashion system combines quick response to the latest fashion trends with exploiting minimal production times to match supply with unpredictable demand (Cachon & Swinney, 2011).

Grading

The process of systematically increasing and decreasing the size of a master pattern to create a range of sizes (Mullet, 2015). The example below shows the base size (the center pair) as the front and back of a bodice, where the blue lines indicate locations for width change and the orange lines for length changes. The pair on the left indicate decreases in size, while the pair on the right show increases (see Figure 1.3).

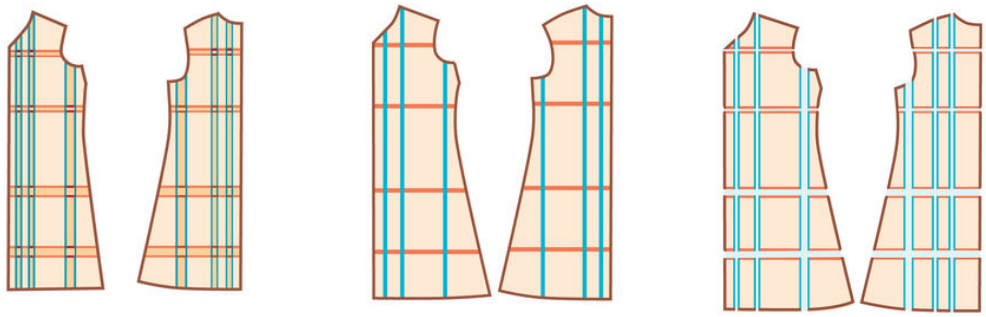


Figure 1.3 Graded patterns of front and back bodice (control size in the middle, smaller size on the left, and larger size on the right) (Boston, 2008).

Grade Rule (see Appendix 1 for example)

The amount of required change at each cardinal point for each size (Mullet, 2015).

Jigsaw Method

Patterns are designed to interlock perfectly on fabric and leave no waste. This method can be applied to two-dimensional flat patterns or three-dimensional draping (Rissanen, 2013) (see Figure 1.4).

Figure 1.4 An example of Jigsaw pattern for a hoodie jacket (O’Neill, n.d.).

Marker

A combination of pattern pieces arranged on a rectangular shaped block, used as a cutting guideline or pattern in the cutting process (Puasakul & Chaovalitwongse, 2015); the unused area between, or among, patterns is considered cut-offs or waste areas (Rissanen, 2013) (see Figure 1.5).

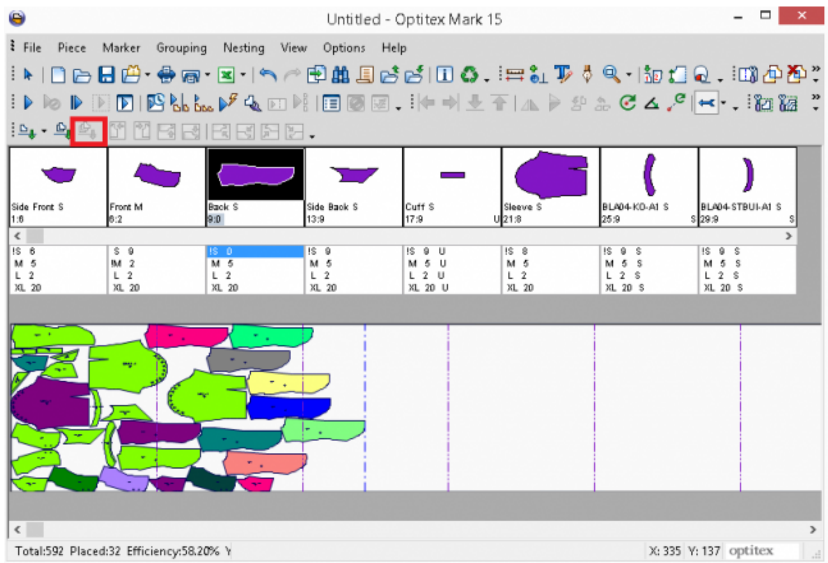


Figure 1.5 An example of a marker layout on Optitex software (Optitex, n.d.).

Mixed marker. Includes an equal number of all possible sizes (Haque, 2016) (see Figure 1.6).

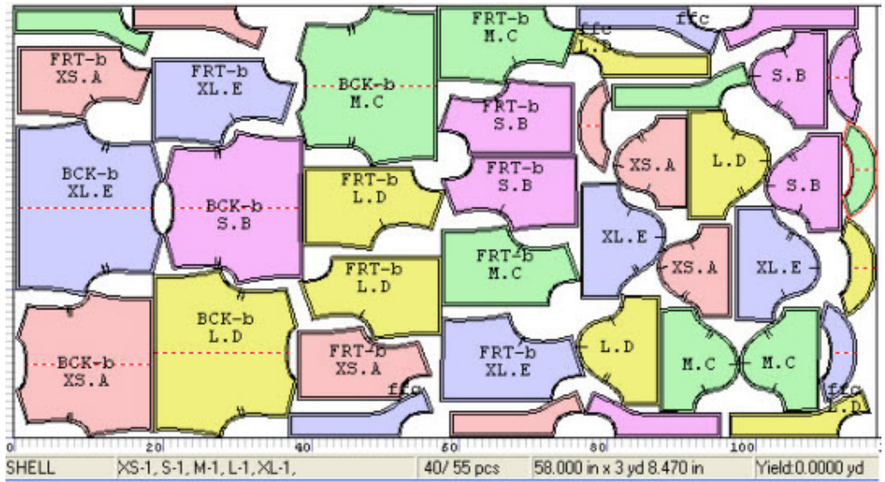


Figure 1.6 An example of a mixed marker that includes different sizes (Fashion-incubator, 2012).

Solid marker. A solid marker includes different sizes with each size blocked separately from the other sizes (Haque, 2016) (see Figure 1.7).

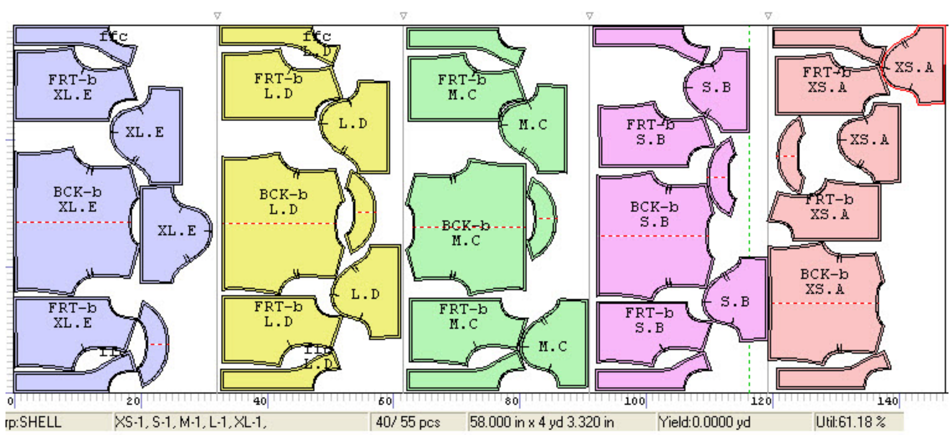


Figure 1.7 An example for solid (blocked) marker that include the layout of each size separately (Fashion-incubator, 2012).

Negative spaces

Negative spaces in the marker are the areas not utilized by any pattern pieces, which usually considered as cut off or fall out.

Nested Grade

All selected graded sizes from the basic blocks stacked together facilitating the observation of the incremental differences (Mullet, 2015) (see Figure 1.8).

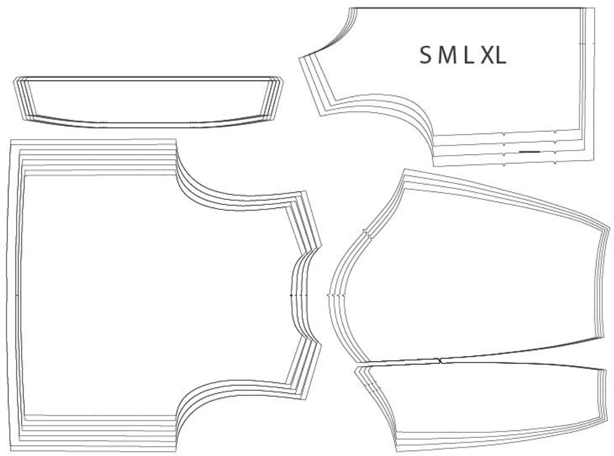


Figure 1.8 An example of a grade nest including four sizes (clothes design resource, n.d.).

Optitex

It is a leading provider of 3D Virtual Prototyping & 2D CAD/CAM software solutions for the apparel and other textile products.

PDS file

It is a system module in Optitex for pattern design and drafting

Post-Consumer Textile Waste

Refers to fabric waste resulting from garments and other textile products after purchase or use by the consumer.

Pre-Consumer Textile Waste

Pre-consumer fabric waste as fabric loss during the marker-making process and outside the marker process, such as fabric waste occurred due to unsatisfied embroidery results or such as sample garments.

Sustainability

Sustainability refers to human activity or behavior's impact on maintaining and protecting the environment to avoid the long-term depletion of natural resources (Robertson, 2014).

Sustainable Development

The process of considering the current generations needs along with the consideration of future generations' economic, environmental and social needs being fulfilled (Robertson, 2014).

Technical Design

Includes the processes that follow the initial drawing of the designs including flats development, fabric selection, and specification sheets (Lee & Steen, 2010).

Three Pillars of Sustainability

Environmental sustainability considers satisfying the needs of human society without exceeding the ability of natural resources to regenerate or result in human harm to the environment (Robertson, 2014).

Economic sustainability refers to the fair distribution of resources in human society, as well as all individuals' ability to meet their basic human needs.

Social sustainability refers to equal access of basic needs (food, water, employment, education and healthcare), and the freedom from unhealthy living conditions for all humans.

Total Grade (see Appendix 1 for example)

Measurement of the difference between two or more different sizes distributed throughout the pattern (Mullet, 2015).

3D simulation

A tool used to design a three-dimensional garment from two-dimensional pattern pieces on a virtual model, using both virtual stitching and computer simulated draping techniques (Sayem, 2015).

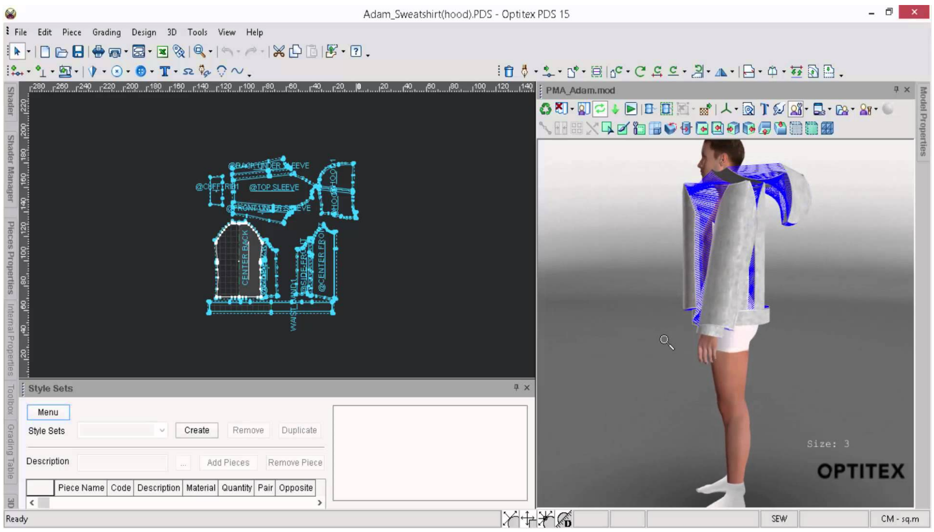


Figure 1.9 An example of 3D garment simulation. Left: pattern pieces; right: 3D model (OptTex, n.d.).

CHAPTER II

REVIEW OF LITERATURE

The following literature review describes the triple bottom line of sustainability as the base of sustainability. In this review, the triple bottom line of sustainability (Robertson, 2014) guides the discussion of environmental waste issues in apparel pre-production processes as a considerable contributor to global environmental issues. The literature review also includes the discussion of zero waste design (ZWD) as a solution for eliminating garment fabric pre-production waste. The review addresses grading (i.e., sizing) challenges, marker making(i.e., garment pattern layout) challenges, and pre-production technical design challenges in ZWD. Since the ultimate aim of this study is to contribute to the improvement of sustainable practice of the production methods of sustainable fashion design, a discussion of the sustainable fashion design model is also included in this review.

The Triple Bottom Line of Sustainability

The triple bottom line of sustainability is the base of the three pillars of environmental, economic, and social sustainability. In order to meet current and future generation needs, Theis and Tomkin (2012) emphasized considering the triple bottom line of sustainability as people, profit and planet. According to Robertson (2014), the planet is related to environmental integrity, which includes preserving and restoring the health of living systems. It also includes ecosystem services, which relates to processes provided by the natural environment (e.g., purifying air and water, pollinating crops, providing foods). In addition, the planet as a sustainability element includes the carrying capacity of biological species, which are the environmental limits the eco systems can support without significant negative impacts to the environment.

The other two elements of the triple bottom line are profit and people (Robertson, 2014). Profit includes economic vitality that considers fair and just distribution of resources and the ability of all individuals to meet basic human needs. This element aims toward the provision of long term prosperity for all; thus, profit works against economic growth that drains natural resources, pollutes the environment, depletes ecosystem services, and leads to an eventual decline in quality of life for the human population. People are the third element of the triple bottom line of sustainability; this element references social equity for all individuals. Social equity refers to freedom from unhealthy living conditions; equal access to food, water, employment, education, healthcare, and the provision of opportunity for all people.

To achieve sustainability, the consideration of the interconnection among the three bottom lines of sustainability is crucial (Theis & Tomkin, 2012) (see Figure 2.1). The three pillars of sustainability are: social equity, economic development and environmental protection. Social sustainable development must be environmentally acceptable and its profits distributed equally. In a similar manner, economic sustainable development must maintain environmental sustainability and be addressed equally to all people. Furthermore, sustainable environmental development practices must be socially acceptable to be utilized as a source of profit.

Figure 2.1 The interaction between the three pillars and triple bottom line of sustainability (Theis & Tomkin, 2012).

As mentioned previously, the interconnection between the three pillars of sustainability is crucial in order to fulfill the requirements for the triple bottom line of sustainability. Thus, the consideration of one element while disregarding the two other elements leads to a deficiency in realizing sustainability. The apparel industry is one industry sector that has been prioritizing economic (profit) over the environmental and social elements, which has been contributing to crucial global sustainability issues.

Climate Change

Although there are many environmental issues related to the concept of sustainability, such as water pollution, water scarcity, droughts, etc., climate change is considered one of the most threatening environmental issues due to its major influence on other sustainability issues and the complexity of solving its causes. There are many factors that contribute to climate change. These factors include a change in the solar cycle every eleven years, big volcanoes, the hole in the ozone layer, and deforestation (Claussen, Cochran, & Davis, 2001). However, greenhouse gas emissions are the dominant factor that increases the issue of climate change (Anderson, LeHew, Hiller Connell, Sutheimer, & Hustvedt, 2016).

Since the mid twentieth century, the emission of greenhouse gases has been drastically increasing. As a result, carbon emission increased by three percent a year since 1990, while currently there are five times available more oil, coal, and gas than safe to burn (Anderson, et al., 2016). Two factors influence the continuous increase of the emissions of greenhouse gases. The first factor is the increased use of machines, such as refrigerators, that emit hydroflourocarbon. Second is the increase of carbon dioxide levels in the atmosphere resulting from burning coal, oil, or natural gas (Anderson et al., 2016). These emissions contribute to climate change resulting in many negative impacts.

Environmental, Economic, and Social Impacts

The emission of greenhouse gases is the impetus of many environmental issues such as warming oceans. This results in harm to sea life by decreasing the population of fish and other marine species. For example, in the northeast Atlantic, the heat of the ocean has been leading fish and other marine species to move to the North Pole to escape from the heat of the ocean. Moreover, weather changes, like the change in the pattern of rainfall, has been causing droughts in many areas across the globe. These environmental issues have direct negative social and economic impacts.

The environmental impacts of climate change have both social and economic impacts (Anderson et al., 2016). For example, ninety-nine %of people who work in the fishing industry are people who come from poor countries. The movement to other locations or disappearance of fish from the locale is a direct threat to their livelihood. In addition, fish are a main food source for people in many regions of the world, such as Columbia and West and Central Africa, which makes their disappearance or movement impact food security in the affected areas. Similarly, drought also has a negative impact on food security, due to not only the lack of plants, but the impact it has on agriculture practice, which is the main source of income for many people around the world.

The Risk of Climate Change

The increase of global demand for energy, which has been rising with the increase of the global economy and manufacturing, is what makes climate change a threatening sustainability issue (Anderson et al., 2016). Energy generation relies on the burning of fossil fuels (oil, coal, natural gas) to produce hydrocarbons, which are required for manufacturing, making fossil fuels a significant source of climate change (Anderson et al., 2016). For example, oil is the key raw material for various essential fuels such as gasoline and diesel. Both of which provide a large contribution to increasing greenhouse gas emissions. In addition, burning of coal to generate electricity is a huge contributor to global greenhouse emissions. Apparel and textile is considered as one of the major industries that consume huge amounts of electricity through all manufacturing processes (Anderson et al., 2016).

In addition to the increase of the global demand of energy, the global economy is dependent on consuming hydrocarbons to the extent that makes replacing fossil fuels with any other alternative impossible for two reasons (Anderson et al., 2016). First, even renewable sources of energy, such as wind and water, that could be a solution to the problem, are dependent on hydrocarbons for manufacturing. Second, the adoption of alternative energy options is difficult as global communities are primarily developed by planning for long-term investment. Long-term community investment accounts for the availability and affordability of using petroleum fuels as the main source of energy for various systems. For example, the building of long distance miles of high-speed interstate highways requires fueling for gasoline powered vehicles.

Following is a discussion of the apparel and textile industry’s dependency on consuming hydrocarbons through various processes of apparel manufacturing to the extent that they are contributing to climate change.

Apparel and Textile Industry Contribution to Climate Change

Almost all garment-making processes affect climate change, from fiber production to disposal processes (Hiller Connell, 2015; Muthu, 2014). An estimated ten percent of the overall global effect of carbon emissions has been caused by the apparel and textile industry (Zaffalon, 2010). Following are examples of processes found throughout different phases of the garment life cycle in which the apparel and textile industry contributes to climate change.

The process of fiber production starts with the consumption of raw materials and energy, and ends with solid waste and gas emission (BSR, 2009; Hiller Connell, 2015). In fact, manufacturing both synthetic and natural fibers involves various processes that consume fossil fuels. Polyester, for example, the most common manufactured fiber, requires up to 127,000 megajoules of energy for manufacturing one ton of polyester. In terms of natural fibers, large amounts of oil are required for cotton cultivation in order to run farm machinery for harvesting and fuel planes for aerial spraying. All of which contributes to greenhouse gas emissions by the textile and apparel industry (Hiller Connell, 2015).

In addition to fiber production, other processes within the garment life cycle consume excessive energy; including the production, retailing, and distribution processes (Muthu, 2014). In fact, 132 million tons of coal is consumed annually to meet the energy demands of the global apparel and textile industry. For example, there is excessive energy use in high bath temperatures used for dying. In addition, high energy consumption is required for processes such as spinning, weaving, and knitting machinery, in addition to sewing machines, irons, etc. Moreover, transportation throughout the supply chain is another significant process that consumes energy within retailing and distribution activities, where the primary energy source for transportation mechanisms is found in fossil fuel.

The previous examples represent the consumption of apparel and textile industry of energy for operating some of the processes during apparel manufacturing. With the increase in energy consumption to meet the production demand, GHG emission will increase and subsequently contribute to the threatening impacts of global warming. Thus, grading zero waste garments is considered an effort to decrease the GHG emission from two aspects. First, the feasibility for grading zero waste design would decrease the excessive amount of pre-production fabric waste to reach landfills and generate methane (one of the GHG) (further discussion in chapter 2). Second, grading zero waste garments would decrease the need for adopting recycling pre-production textile waste, whether recycling into new textile products or into new fabrics. This is due to the energy requirements for recycling textile waste into new products (further discussion in chapter 2).

Because this study focuses on pre-consumer textile waste in the apparel industry, following is further discussion of textile waste issues occurring in apparel pre-production processes. Apparel pre-production includes processes that are conducted before garment mass production such as patternmaking, pattern grading, and sample making (Bubonia, 2017).

Textile Waste Issues in Apparel Pre-Production Processes

It is widespread practice within the apparel industry to send textile waste to the landfill. Statistics show that industrial waste is generally either included in sanitary landfills used for municipal solid waste or sent to separate industrial waste landfills (Robertson, 2014). Apparel factories either arrange their own waste disposal services or deal with waste management services and pay landfill fees based on the amount of discarded waste; these waste strategies include both woven and knit fabric waste (Nordic fashion, n.d.).

Generation of Pre-Production Solid Textile Waste

Various processes cause pre-consumer textile waste within the apparel industry. The literature notes pre-consumer fabric waste as fabric loss during the marker-making process and outside the marker process. According to Kavitha and Manimekalai (2014), there are various fabric losses outside the marker process that can be broadly classified into separate groups including ends of fabric roll losses, piece losses, edge losses, etc. The authors further add fabric loss also happens during the dying and washing of the fabric, as well as during transportation; furthermore, pieces could also be lost or misplaced in the factories. Kavith and Manimekalai (2014) also reported that during printing and embroidery pieces might not meet the standards or are not meeting the desired look, which also results in fabric loss. Finished or partly-finished garments, such as clothing samples and unsold clothing, are also considered pre-consumer waste and include other waste materials such as metal and plastic from findings such as interfacing, zippers, snaps, etc. However, Textile Exchange (2012) emphasized that among the various processes of garment production, cutting is the main area in which fabric waste is generated, with approximately fifteen percent of fabric intended for clothing ending up on the cutting room floor. This percentage of cutting waste has contributed to the overall impact of sustainability issues increased by the waste resulting from the apparel industry.

Environmental Impacts of Pre-Production Solid Textile Waste

According to Rissanen (2014), in developed countries, the growing levels of unsustainable use of clothing production and consumption are concerning and need attention; the negative economic and environmental effects have been more negatively impacting the developing countries where clothing production has largely increased because of trade openness due to globalization. Apparel manufacturing processes adds to the depletion of natural resources because it does not just cause continued air and water pollution, but it also generates more solid waste (Hiller, 2015; Ecochic, 2014); landfills also consume valuable land that could be better served for other purposes, such as agriculture and construction. Based on statistical data, Rissanen (2013) assumed that if only five percent is the estimated amount of fabric waste then approximately 50,000 tons of fabric waste would result during apparel manufacturing in the UK alone, since one million tons of clothes are consumed annually in the UK.

Worldwide, the increasing amounts of textile waste negatively impact ground water supplies. According to Caulfield (2009), textile waste in landfills contaminates groundwater because textile decomposition contributes to the generation of the leach (dissolved solid materials created by the action of a percolating liquid) that reaches the groundwater. Rissanen (2005) and Fletcher (2014) argued that regardless of the materials fabrics are made from (natural or synthetics), treatments in fabrics with various finishing chemicals, as well as dyes, result in harmful impacts to both soil and underground water when decomposed. This is especially true of gases such as methane, a significant contributor to global warming.

Along with soil pollution, textile waste also cause air pollution. Sending waste to landfills resulted in waste decomposition and the generation of leaching toxic chemicals including ammonia and methane, which contributes to global warming (Caulfield, 2009; Fletcher, 2014). Rissanen (2005) and Caulfield (2009) argued that synthetic chemical fibers are even more harmful than natural fibers to the environment because they take more time to decompose and are not biodegradable in comparison to natural fibers; subsequently, they have more damaging and more prolonged effects in terms of leachate and gas production.

Economic Impact of Pre-Production Solid Textile Waste

Pre-consumer textile waste not only has a threatening environmental impact, it also has a considerable economic impact. Sending textile waste, which makes up approximately fifteen percent of the cost price of a garment (Rissanen, 2013), to landfills has both a direct and embedded economic costs. According to Caulfield (2009), space for landfills has become scarce due to the increasing need for waste disposal, which increases the cost of landfill maintenance in some developed countries.

Along with the cost of the fees paid for waste disposal, textile waste also has an embedded cost. Rissanen (2013) mentioned in his critiques of current practices regarding pre-consumer textile waste, manufacturers do not consider the amount of fifteen percent waste as economically threatening if it is at or below the yield cost. Rissanen argued the loss of pre-consumer textile waste included the loss of economic investment as well, since fabric is a precious and sophisticated product with numerous embedded labor costs, occurring through various processes, such as knitting or weaving. These costs comprise twenty percent of total garment cost. These embedded costs also make fabric higher than fibers in terms of the embodied energy consumed during manufacturing.

In terms of non-solid waste, Rissanen (2013) suggested that wasting a part of the fabric is not only wasting the solid materials, but also wasting the embodied time and labor of people who worked on fiber extraction, spinning, textile design, weaving and/or knitting of the fabric. In addition, Rissanen (2013) mentioned two categories of non-solid waste. One category of non-solid are natural raw materials embedded in fabric such as water and energy. The other category of non-solid waste includes human resources investment including fiber and fabric research for development and design. Both categories subsequently increase the negative environmental impact created by pre-production textile waste.

In order to mitigate the environmental impacts caused by the apparel industry, the industry has been adopting various sustainable practices. Since this study focuses on the practices related to reducing pre-production textile waste, the next section reviews some of the current common practices.

Apparel and Textile Industry Responses to Pre-Production Textile Waste

The three R's (referred to reusing, recycling and reducing) waste management strategies have been widely adopted during different stages of the garment life cycle (Fletcher, 2014). Recycling and reducing are the two main strategies that have been utilized for managing pre-consumer waste. On the other hand, reusing is a common strategy in managing post-consumer waste besides recycling and reducing strategies. Following is a discussion of recycling and reducing waste management strategies for pre-consumer textile waste.

Recycling Pre-Production Textile Waste

Recycling has been increasingly adopted within the apparel industry to deal with pre-consumer textile waste by recycling fabric remnants as a solution for the high-cost of raw materials for apparel products, and the energy intensive polluting processes textiles go through during the manufacturing of virgin fibers. According to Lau (2015), recycling pre-consumer textile waste within the apparel and textiles supply chain directs waste away from landfills and incinerators. Lau suggested that pre-consumer textile waste is easier to handle and recycle than post-consumer waste, since fabrics can be sorted by color, to be either manufactured into different textiles or recycled to new products. Lau also argued it is easier to recycle pre-consumer waste since there is no challenge with hygiene issues such as those found in recycling post-consumer waste.

While there is consideration given to the environmental benefits of recycling pre-consumer textile waste, most of the literature emphasizes the economic benefits of recycling. Reverse Sources (2016) indicated that new business opportunities can be explored by re-using waste fabric. The authors claimed that at least 15 billion new products could be produced, globally, out of pre-consumer textile waste if manufacturers circulated the resources efficiently.

For example, according to Phys Org (2014), there are methods of separating the cellulose molecules from natural textile waste to reuse fibers, such as cotton, in addition to recycling synthetic fabrics, such as polyester. In addition, Reverse recourses (2016) suggested that using ten %of the textile waste resulting from apparel manufacturing in China, Bangladesh and India, alone, would make it possible to produce at least six billion apparel items worth $20 billion.

However, recycling is not the ideal solution to solve the problem of excessive textile waste. One argument against recycling pre-consumer textile waste is that fabric loses its primary function of being used in the garment by the industry, like in using denim fabric for housing insulation (Rissanen, 2013). Rissanen has also criticized the use of by products for their difficulty in manufacturing. He argued it is difficult to handle and store wasted fabric from garments, for later use in smaller items when using conventional mass-production cutting methods. The difficulty of storing wasted fabric in layers is due to the size and cut shape of cut off pieces that require to be managed after the cutting stage of production (Rissanen, 2013).

Along with the loss of the fabric's function, due to recycling, there is another challenge that makes recycling not the most efficient solution for pre-consumer textile waste. Rissanen (2013) and Fletcher (2014) mentioned that blended fabrics are one of the most difficult to recycle in regards to sorting fabric waste by fiber type (natural and synthetic). Not only is fiber type a challenge when sorting fabric waste, but color also presents a challenge since the resulting color from recycling different colored fabrics cannot be predetermined, thereby creating a necessity to consume more resources for re-bleaching and dyeing.

Reducing Pre-Production Textile Waste

Even though numerous efforts have been spent on reducing waste, pre-consumer waste is still a crucial contributor to overall textile waste, especially with the increasing pace of apparel production and consumption. Currently, reducing pre-production textile waste mostly occurs during the marker-making process; however, it has not been feasible to eliminate all waste through marker-making for non-ZWD patterns. Thus, researchers found that ZWD, which is the maximum level of reducing waste, is a viable solution for preventing textile waste (Aakko & Sivonen, 2013; Rissanen, 2013).

Current Marker-making Practices

Waste production occurs in the cutting room when laying out garment pattern blocks and discarding cut-loss. The cutting process, either manually or through laser cut, generates more waste than the amount of waste produced during both the sewing and quality control processes (Fletcher, 2014; Rahman & Haq, 2016; Reverse Sources, 2016). However, the waste produced from the cutting process is not a production problem, but rather one of planning during the marker-making process. Marker-making is a judicious process of arranging garment pattern pieces with different sizes according to fabric width, while considering the maximum usage of fabric and the narrowest gap between pattern pieces, a consideration referred to as marker efficiency (Reverse Sources, 2016; Rissanen, 2014). Both manual and digital (CAD system) markers have been used in the apparel industry; however, efficiency of markers is different from one factory to another because efficiency is dependent upon the mathematical skills of the marker maker and the ability to concentrate (Rissanen, 2014).

Measuring Pre-Production Textile Waste

The fabric waste resulting from apparel production ranges between 10 to 30% of the original fabric yardage (Rissanen, 2005). However, the literature does not mention common approaches of measuring pre-consumer textile waste within apparel factories. According to

Textile Exchange (2012), the pre-production textile waste rate has been ignored for years and throughout the industry; however, there are some approaches used to measure the approximate amount of waste produced. Cut order plans is planning fabric cut, which is determined by the quantity of garment order sets. Cut order plans is considered one of means for measuring textile waste by multiplying the waste resulted from one marker in the number of fabric layers.

The literature mentions other factors, besides cut order plans, that influence methods of textile waste measurement resulting from the cutting process. Reverse Sources (2016) suggested that bigger production, whether in quantity or in size (S, M, L, XL, etc.), results in larger amounts of textile waste per product. On the other hand, Rissanen (2013) estimated the amount fluctuates depending upon garment type; for example, the waste percentage for both pants and jeans is lower, somewhere around ten percent, but then the percentage goes slightly higher for blouses, jackets, and underwear. According to Rissanen (2005), even with up-to-date computer technology, garment styles with unpredictable pattern piece shapes are the primary issue in reducing waste during marker making. Variables in a garment's style that influence marker efficiency include: number of pattern pieces, size of the garment, and the shape of pattern pieces in relation to fabric width, as well as the expertise of the marker-maker (Haque, 2016; Pamuk & Yildiz, 2016; Rissanen, 2013; Utkun, 2016). Reverse Sources (2016) stated there are two requirements to assess the amount of cut-off waste from the garment industry: knowing both the average waste amount that resulted from one garment, and the quantity of garments produced in a specific geographical area.

In order to decrease waste amounts or increase marker efficiency of pattern layouts, marker makers have adopted multiple procedures to ensure more efficient fabric use. Glock and Kunz (2005) mentioned some pattern adjustments that may be applied in order to reach maximum marker efficiency; these pattern adjustments include splitting pattern pieces by creating a seam, reducing seam allowances and/or hem width, adjusting either pattern dimensions without noticeable change to fit and style or grainline for hidden garment parts, and modifying grainline specified by the designer. These adjustments are further discussed in the methods chapter, during the pre-production technical design stage.

Zero Waste Design

Background

Contemporary practices of garment pattern cutting, within the apparel industry, are extremely wasteful compared to historical methods that included efficient use of fabrics. Rissanen (2005) mentioned that pre-industrial societies regarded fabric as a valuable resource and worked toward the elimination of waste to zero during the cutting process. Rissanen claimed the decrease of textile valuation after the Industrial Revolution was due to developments in weaving and spinning technology in Europe. The development of weaving and spinning yarns influenced the cutting process as a result of the Industrial Revolution, and the increased speed of textile production, all of which resulted in fabrics being more affordable and, therefore, not as precious as they were prior to the industrial revolution. Rissanen (2013) mentioned that Zandra Rhodes, a textile and fashion designer from the UK, believes that fashion designers might be more concerned about the designs, and not the people for whom they are designing. She maintained that whether they are textile designers or textile engineers both contribute to the production of every fabric, so wasting even a small proportion of fabric is wasting part of the embodied time and effort of textile design.

The contemporary attitudes regarding textile wastefulness are mostly formed by culture and social constructionism (Binotto & Payne, 2017; Henninger, Aelvizou & Oates, 2016). Binotto & Payne (2017). In their discussion of contemporary wastefulness practice in the context of fashion, Binotto and Payne (2017) stated that some of the recycled fashion designs made with waste being visible are work that has an influence of culture on fashion and materiality. For example, the author quoted Rovine (an African designer) (2005) says: " it's an African- and any Third World nation's- philosophy to use things up. You don't waste any-thing, but create new from old". This perception of recycling or upcycling of textile waste would interpret the role of culture on the current variation of valuing of zero waste design. On the other hand, Henninger, Alevizou, and Oates (2016) in their examination of the understanding for the term sustainable fashion found that that social constructionism, which refers to realty being constructed through social interactions (Shotter, 2002), that people perceive reality in different meanings of different situations/ circumstances. Thus, while some people perceive sustainable fashion, including zero waste design, as a non-mainstream phenomenon in the fashion world (Henninger, Alevizou, & Oates, 2016), others perceive it as a crucial shift in apparel industry.

However, the ZWD design process sequence differs from the conventional design processes (see Figure 2.1). As indicated in the figure, final design decision-making is made after sketching for conventional design, while ZWD final decisions occur after the pattern cutting, sketching, or draping phases. Subsequently, rethinking the responsibilities of fashion designers on a larger scale within the apparel industry is recommended and crucial to reach the feasibility of adopting ZWD. The efficiency of fabric use is part of marker-maker responsibilities; however, Rissanen (2005) argued that designer responsibilities should also include efficient practices of fabric use. Doing so does not imply a shift of roles within the apparel industry; rather, it addresses the importance of collaboration between designers and pattern cutters to produce contemporary garments with environmental considerations that contribute to the ecological footprint of contemporary apparel production, all while considering the aesthetic aspects of design (James, Roberts, & Kuznia, 2016; Rissanen, 2013; Saeidi, 2015).

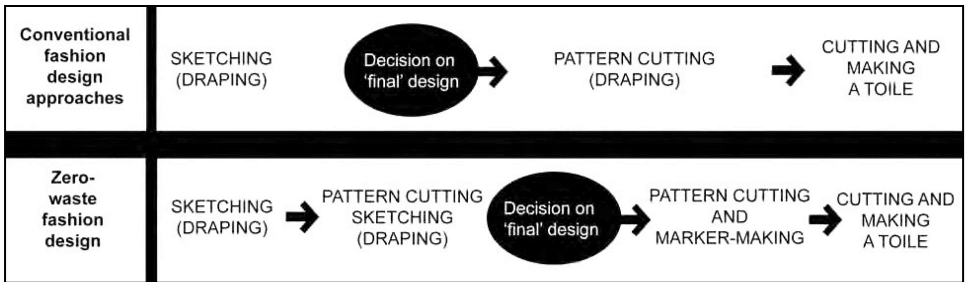


Figure 2.2 Comparison of the conventional design process and the ZWD process (Rissanen, 2013).

ZWD as a Practice of Creative Pattern Cutting

The current practice of ZWD is considered a creative pattern cutting method, not just a practice for eliminating waste (Rissanen & Mcquillan, 2016; Townsend & Mills, 2013). One of the challenges of ZWD is the designer handling the total amount of fabric when creating a garment design. However, there are various ZWD approaches that have been investigated by researchers to manage the process of ZWD (Carrico & Kim, 2014; Han & Suh, 2016; Niinimarki, 2013; Townsend & Mills, 2013). Carrico and Kim (2014), utilizing practice-based research, investigated three distinct ZWD practices, tessellation, embedded Jigsaw, and the multiple cloth approach, along with traditional Jigsaw methods. In this review the classification of ZWD approaches by Carrico and Kim (2014) only includes fabrics; knitting and weaving are not considered in this study nor is the use of other non-fabric materials.

No cut and minimal cut. The no cut method of design practice involves completing the outfit without cutting by using a 3D dress form to shape the design (Carrico & Kim, 2014). This method had been utilized in some historical garment designs, such as the Indian sari, in which one rectangular piece of fabric is hung and folded, thereby shaping the design around the body. This approach provides structural flexibility, as the design is not fully determined before draping the fabric (Cho & Lee, 2015).

The minimal cut method, however, minimizes the number of times the fabric is cut; this method is similar to no cut, but in using this method the designer can make slits in the fabric to shape the design (Carrico & Kim, 2014). An example of this method is "Untitled" (see Figure 2.2). Created using draping techniques, with no plan for the outcome, the final design included only two cuts and three slits (Carrico & Kim, 2014). The standard grading techniques used in mass production might not be suitable for either the minimum cut or the no cut approach if one desires to achieve the same final look when sizing the design (see Figure 2.2).

Figure 2.3 Untitled Dress by Carrico and Kim (2014) using the minimal cut method of Zero Waste Design. Front and back views and garment pattern (Carrico & Kim, 2014).

Tessellation and layering. The tessellation method or tessellation pattern consists of one shape that repeats to fit together perfectly on fabric (Carrico & Kim, 2014). The size of the shape can remain the same or vary. After the repeating pattern is generated, pattern pieces can be cut, pinned together, or placed on the dress form to allow the pieces to overlap and shape around the dress form, resulting in a creative, aesthetically pleasing texture and silhouette. One of the representative designers of this method, Holly McQuillan, designed a dress cut with laser cuts so the pieces of the tessellation pattern could be re-sculpted into a new zero waste design (see Figure 2.4), (Rissanen & McQuillan, 2016).

Figure 2.4 Hyperbolic tessellation pattern and dress by Holly McQuillan (Rissanen & McQuillan 2016).

Similar to the minimal amount of existing research on tessellation, the layering approach is one that has little, if any, research as a ZWD method. When using this method, the designer cuts the fabric cut into multiple strips, without regard to strip width, and the subsequent designs are formed by attaching the cut strips together on the dress form. Since all the strips are used, there is no waste (Cho & Lee, 2015). Both the Tessellation and Layering methods are considered problematic for mass production in regards to grading, since a change of pattern pieces or strips would change the final look of the design.

Subtraction cutting. When using this method, the designer creates the design by placing holes in the fabric where other fabric shapes will plug in or insert into the shaped hole. This method results in zero waste as all fabric is draped and then plugged into the prefabricated holes. Since the fabric could be plugged into the holes in different places on the design, Julian Roberts, an important designer of this method, stated that this approach allows for customization because the garment can be worn multiple ways for more personalized looks (Rissanen & McQuillan, 2016). One example of Robert's ZWD subtraction cut dresses can be worn more than seven separate ways (see Figure 2.5). Subtraction cutting is largely unplanned and mainly relies on draping techniques.

Figure 2.5 ZWD dress designed with subtraction cut by Julian Roberts (2010) (Rissanen & McQuillan, 2016).

Multiple cloth approach. The multiple cloth approach uses different fabrics, simultaneously, to design one or multiple patterns, making it possible for multiple styles in a collection to be combined in one layout (Rissanen & McQuillan, 2016). Yeohlee Teng, one of the original designers of the multiple cloth approach, created three dresses using two fabrics in an exchangeable way (see Figure 2.6), (Rissanen & McQuillan, 2016). According to Carrico and Kim (2014), while the multiple cloth approach to mass garment production is an appropriate means of achieving ZWD in the apparel industry, this method mostly focuses on the fabric use exchangeable in multiple designs, which is not the focus of the current study.

Figure 2.6 Three dresses by Yeohlee Teng (1992) using the Multiple Cloth approach to Zero Waste Design (Rissanen & McQuillan, 2016).

Zero waste design and digital textile design. Integrating digital textile design is an efficient strategy in the process of cutting ZWD patterns (Parsons, 2015; Rissanen & McQuillan, 2016). Parsons (2015) explored the engineered digital prints in the American historic patent. The one piece allowed for creating engineered digital prints for new prototypes, with minimum fabric waste. Adopting the mostly used ZWD process that eliminate sketching as a first step, the researcher aimed to integrate the usage of print design within the initial stage of design development along with pattern cutting. On the other hand, McQuillan and Packer utilized digital textile design to create different patterns and colors from one single ZWD pattern using 100% linen fabric to create a dress, vest and pants (Rissanen & McQuillan 2016) (see Figure 2.7). The designer created the pants using the traditional patterns. Then the negative spaces generated from the pants were utilized for creating the dress and the pants. While digital textile design and engineered prints provides efficiency for printed textiles, this study addresses the challenges from the pattern grading and marker-making aspects rather than textile design.

Figure 2.7 Different textile designs from one digitally printed fabric, a ZWD garment by Holly McQuillan and Genevieve Packer (Rissanen & McQuillan 2016).

Mark Liu is a designer who has influenced the practice of ZWD regarding developing Jigsaw patterns by combining science and art perspectives. Liu's interest in mathematics and 3D printing guided him to innovate fitted designs with geometric shapes as decorative exposed seam allowances (see Figure 2.12). The digitally printed interlocking geometric shapes allow for 100% fabric utilization and serve as cut lines. Thus, Liu utilizes draping techniques using Jigsaw pattern cutting methods to fit pattern pieces together while initiating the design in spherical and Euclidean geometry shaping rather than non-Euclidean (two dimensional based) geometry (UTS, n.d.). Liu adopted this technique in order to solve the problem of eliminating fabric waste along with achieving fitted ZWD garments (UTS, n.d.).

Figure 2.8 A Jigsaw design by Mark Liu (Fashion-Incubator, 2007).

ZWD Jigsaw Pattern Cutting

Jigsaw pattern cutting has been used in the creation of historic dress of multiple cultures. The Japanese kimono is one example of historic dress that utilizes the full length of one piece of fabric in the design. The kimono is created using rectangle pieces of fabric that are cut using the Jigsaw method (see Figure 2.8). Although the Jigsaw method is by far the oldest approach of ZWD use, Rissanen and McQuillan were the first to recreate this approach in the literature, as demonstrated by the Jigsaw pattern hoodie design developed by Rissanen (see Figure 2.9), (Rissanen & McQuillan, 2016).

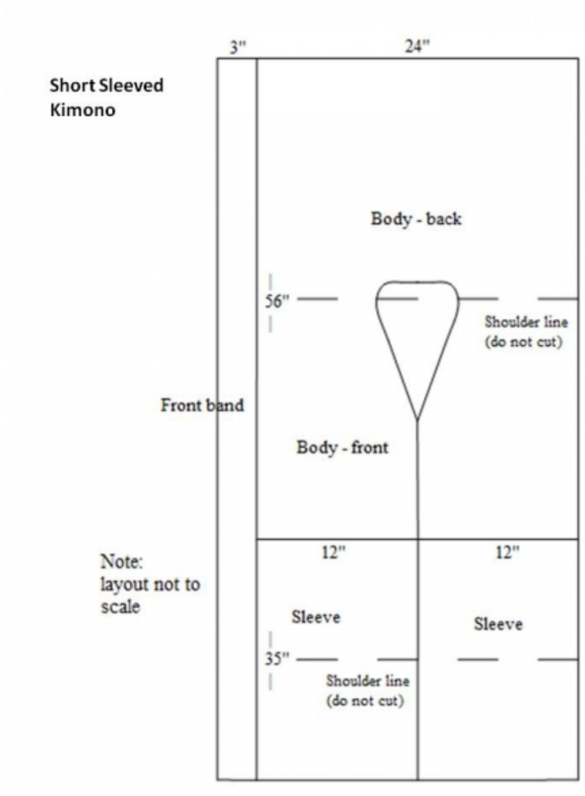


Figure 2.9 Japanese kimono as an example of Jigsaw Zero Waste Design in historic costume (Sallye, 2013).

Figure 2.10 Hoodie generated from Jigsaw Zero Waste Design by Rissanen (2008), (Rissanen & McQuillan, 2016).

The Jigsaw pattern shape resembles an interlocking puzzle, in which all pattern pieces attach to one another, leaving no negative space between pattern pieces (Cho & Lee, 2015; Rissanen & McQuillan, 2016). Jigsaw patterns are also akin to traditional pattern design, which includes varied pattern shapes, unlike the tessellation shape in which repeats of the same pattern is cut (Carrico & Kim, 2014). Jigsaw patterns are shaped to fit the width and length of the fabric, as well as match the straight selvage line. Embedded Jigsaw is another variation of the Jigsaw approach; however, the difference between the two methods is that embedded Jigsaw results in multiple garments being produced in one fabric layout (Carrico and Kim, 2014). Since cut-offs from one garment can be used in another garment, there is no resultant waste, as demonstrated in Figure 2.10. The layout includes jacket and shirt patterns, with no negative space between pattern pieces.

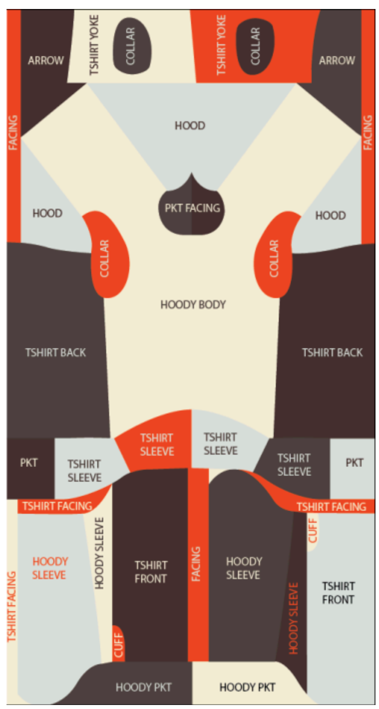


Figure 2.11 Embedded Jigsaw by Holly McQuillan. The layout includes three garments, a hoody and two t-shirts (Rissanen & McQuillan, 2016).

Given that Jigsaw patterns are created using one layout with no gaps between pattern pieces, some major considerations in regards to the adjustments made when creating the patterns within the layout are required, especially for modern styles. The main consideration is the need to take into account how each change of a line or curve of a pattern piece will change the dimension of the adjunct piece or pieces. Another consideration is that any change of a pattern piece will further influence its ability to correspond to any other piece with same measurements. Most importantly, the interlock of Jigsaw patterns would make the current practice of the grading process challenging, because any change of pattern size would influence the marker efficiency and create waste (Carrico & Kim, 2014; James & Kuznia, 2016; Rissanen & McQuillan, 2016). One example of the Jigsaw pattern method is the *Motorbike Jacket* design, by McQuillan. McQuillan modified an existing jacket pattern for zero waste efficiency while maintaining the original visual impacts of the style features. The pattern layout shows the adjustments made to the jacket pattern pieces so they would fit with fabric straight edges and the previously determined dimensions of the fabric layout (see Figure 2.11). Jigsaw pattern shapes are similar to traditional patterns, which makes this method the most appropriate for the investigation of sizing using current grading practice application.

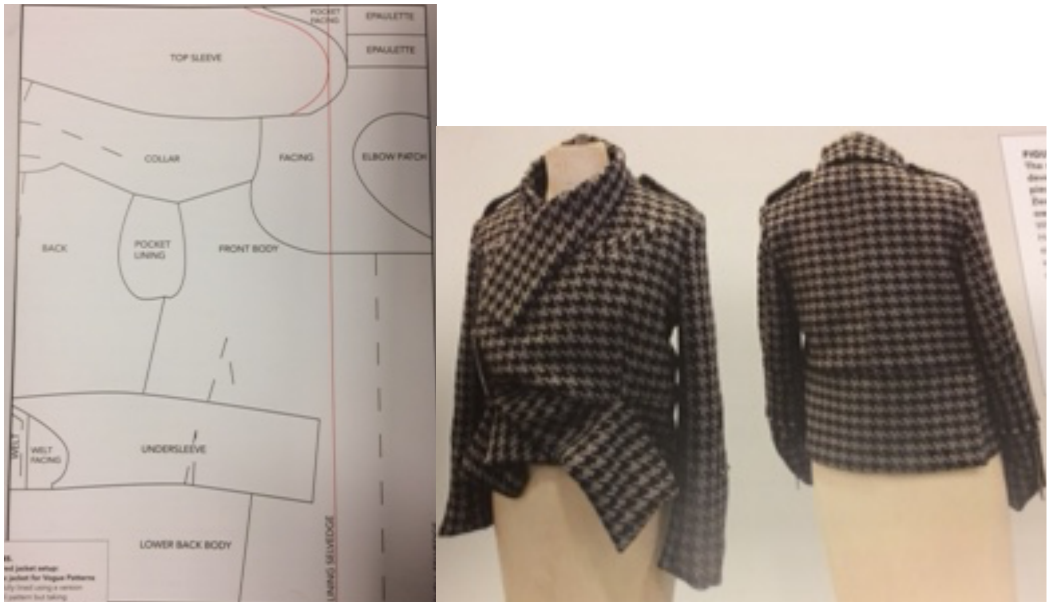


Figure 2.12 Jigsaw layout and garment, *Motorbike Jacket*, by Holly McQuillan (Rissanen & McQuillan, 2016).

Pre-Production Challenges to ZWD

Grading Practice Challenges to Zero Waste Design

The grading methods used by the apparel industry during the early decades of the twentieth century were based on the foundational practices of dressmaking, when pattern making and grading were taught via the apprenticeship system (Bye & DeLong, 1994). According to Bye and DeLong, the traditional procedures of garment grading were dependent upon the graders' ability to memorize the values of grade rules that resulted from multiples of 1/8 inch. Through visual evaluation of the developed patterns, graders checked their grade accuracy in a nested grade. Schofield and LaBat (2005) demonstrated the traditional visual inspection of nested grades, as practiced during the early twentieth century, is not an adequate method to determine whether a graded pattern provided good fit, and they further stressed that fitting a range of sized garments on corresponding models must be implemented to test graded patterns.

Testing graded patterns still occurs in current grading practice; however, the influence of the industrial revolution and fast fashion on apparel production practices have also had a direct influence on current apparel grading systems. New paradigms for sizing systems have sped up grading methods, but also created a challenge regarding the methods of grading mass-produced garments. This shift in the pace of fashion has made grading, from base size to multiple sizes, a challenge of correct fitting when using standard American Society for Testing and Materials (ASTM) sizing charts, including the issue of grade rules and sizing.

Grade Rules and Sizing Issues

The United States apparel industry has been encountering the challenge of meeting consumers' functional needs related to producing apparel with accurate fit. The incremental grade rule method is the one most currently used in apparel grading practice; it is an easy and efficient method to use with a fixed number of grade rules compared to the proportional method that changes the value of the grade rule between sizes (Mullet, 2013; Schofield & LaBat, 2005). However, because of the use of the simplified grading method, fit problems have appeared. These problems occurred because the grade rules in the simplified grading method are parallel between the front and the back of the garments, which is not the way the body shape changes between sizes. In their study of testing the practices used in current apparel grading practice, Schofield and LaBat (2005) emphasized the importance of adjusting pattern shapes during garment grading, to accurately trace the natural growth of body shape to pattern size change.

The American Society for Testing and Materials' (ASTM) standard table of body measurements for adult female has been used by the apparel industry and is another problem relevant to grade rules. The use of the ASTM sizes is not precise in reflecting either accurate body measurements of different sizes or changes in body shape because it does not include the measurement of the armscye. In their study of grading practices, Schofield and LaBat (2005) recommended collecting anthropometric data from apparel companies to derive grade rules for each marker to assure accurate fit. This recommendation would help to customize sizing and decrease fit issues associated with the standard size system through simplified grading.

Creating patterns using the simplified grading method is relatively quick, accurate, and efficient, and, as a result, has been widely adopted by large apparel companies. However, Schofield and LaBat (2005) stressed the accuracy of grading is mostly dependent on the precise input of grade rules to achieve correct fit, especially in computerized grading. On the other hand, even with accurate grade rule input, using the simplified method in grading results in aesthetic fit problems, especially noticeable when grading garment details, such as pockets for large sizes. Bye and DeLong (1994) compared grading methods for details, such as pocket size and placement, and found that grading details should be carefully considered in grading, in order to avoid large details for large garments that negatively impact the appearance of the garment. This consideration is important in order to better meet the goal of the visual effect of graded garments in terms of maintaining the accurate proportion of the garment parts when sizes are increased.

Simplified grading has further influence on visual impacts not only with grading garment details, but also with grading more than two sizes smaller or larger than the base size. Schofield and LaBat (2005) indicated visual effect problems in graded garments using simplified grading rules occurs when grading more than two sizes from the base size, especially for larger sizes. Therefore, it is strongly recommended to grade only two sizes from the base size; if more than two sizes are needed then manufacturers should make a new base size with new fit assurances before another grading is implemented.

ZWD has been mostly implemented with one base size, since the aim of ZWD is to utilize all width and length of the given fabric. Thus, conventional grading is problematic in grading ZWD; following is further information in regards to grading ZWD apparel.

Grading ZWD Patterns

Grading ZWD garments is one of the significant challenges facing the apparel industry regarding current practice. Carrico and Kim (2014), as well as Saeidi (2015) found that it is important to not only investigate approaches of creative ZWD pattern cutting, but to also investigate the feasibility of grading and marker marking in order to infuse ZWD practices throughout the current apparel manufacturing system, while also maintaining the essence of a garment being graded through all sizes. Various challenges to grading zero waste garment patterns across the different ZWD methods have been identified in the literature.

Cho and Lee (2015) mentioned the limitation of their study was applicability of method for mass production. Their research aimed to propose ZWD guidelines and a step-by-step guide for each ZWD method. However, the proposed guide was only appropriate for individual practice rather than small or large scale manufacturing industry practices, since its use results in making prototypes of ZWD garments rather than providing informative guidelines for producing multiple sizes for mass production.

Since the conventional approach of grading patterns results in negative space in marker-making or changes to the essence of pattern shapes, some ZWD designers, such as Yeohlee, have been adopting the one-size-fits-most method (Rissanen & McQuillan, 2016). In this method, garments are adjustable through design features that enable the wearer to tighten or loosen the garment, thereby allowing different sized individuals to wear the garment. Although this method has been used in producing sustainable garments, it has both fit and controversial issues related to different body types and self-esteem as this method limits the boundaries of women's size (Atsavapranee, 2017).

Another method to sizing ZWD garments is the designing-each-size method (Rissanen & McQuillan, 2016), which uses both different fabric widths for the design of each individual size and the original size as a guide. According to Rissanen and McQuillan (2016), due to the trend of sustainable design to design thoughtfully and consume less, this approach would be possible for grading zero waste garments, due to its use of either a narrower or wider width of fabric for each size increment. Designing-each-size has also been seen in historical garments that might work for simple ZWD garments, such as a loose fitting t-shirt. However, this particular method is not suitable for larger scale manufacturing because it is time consuming. In addition, it is also not practical for the current practice of apparel manufacturing because only one fabric width is required for a mixed marker that is usually used in cutting orders with multiple sizes of the same design.

Although sizing ZWD garments is challenging when using conventional methods of grading and marker making, designers have developed different ways for grading ZWD (Rissanen & McQuillan, 2016). Rissanen and McQuillan (2016) suggested an approach of configuring ZWD pattern pieces without completely changing the appearance of the graded sizes from the base size. The method maintains the original marker, thereby preventing the necessity of changing design features for other sizes of the original design in a noticeable way. The authors indicated it is possible in this approach to maintain the outline of each pattern component by managing the amounts of fullness. Furthermore, use of this strategy will enable the marker maker to control fullness across sizes. However, this approach will not maintain the final visual appearance for the graded sizes. Another solution is to consider the utilization of the cross grainline of the fabric, instead of the length grainline, in order to create multiple sizes since the fabric has potential to be widened in particular grading areas, such as the hips. However, this method depends on the fabric type. Following is an example of a two-way stretch knit that represents the needed increased size on the cross grainline (see Figure 2.13).

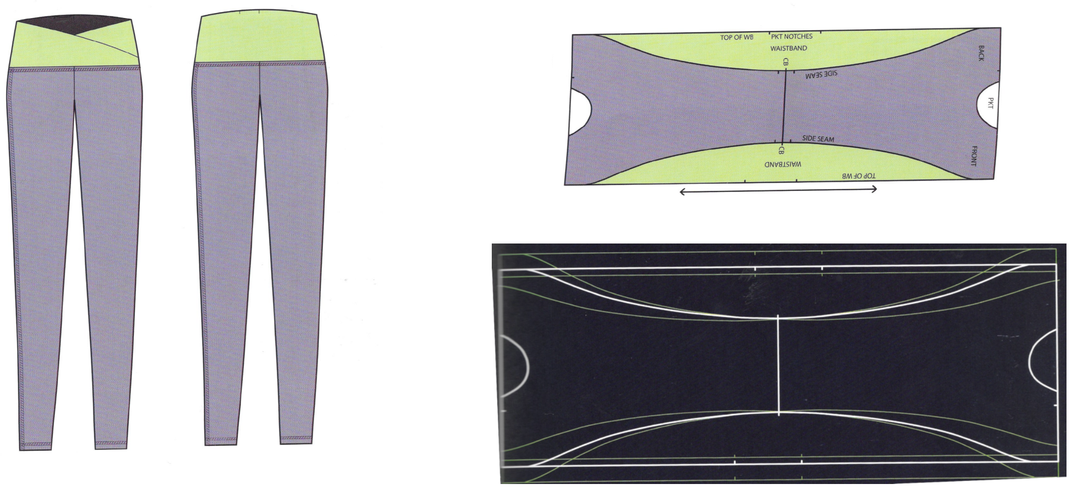


Figure 2.13 Elutheromania is seamless pants in three sizes by Gemma LIoyd (2014) (Rissanen and McQuillan, 2016).

Technical Design Challenges to ZWD

Managing fabric characteristics in marker-making is crucial in order to not lose the features of the original design made by the designers, thus, the collaboration between designers and marker makers is important during the pre-production sectors. However, the arrangement of job roles within the current apparel industry is an obstacle for reducing pre-consumer textile waste during the marker-making process. Rissanen (2013) mentioned that the current system of the design process prevents marker efficiency; Rissanen argued that, in most fashion industry practices, the sketching of garment ideas does not consider the interaction between pattern pieces and fabric width, but consider pattern cutting as a reaction to sketched ideas. The problem with this strategy to reduce waste efficiently is that since garments are generally manufactured in a separate physical location, the fashion designer does not see the amount of waste created during marker cutting; thus, making sizing of ZWD garments a significant challenge.

The aforementioned collaboration is highly recommended, especially when engaging in collaborative decisions between the marker maker and the designer during both the creative and technical design processes of ZWD that impact the grading process, marker layout and final appearance of graded sizes. The following section provides an overview of the influence of materials, color, print, silhouette, and pattern as major elements in garment design (Bubonia, 2017; Glock & Kunz, 2000; Lee & Steen, 2014).

Materials

Fabric has various features that influence pre-production processes and cost for zero waste garments. In addition to fabric monetary investment, material costs are affected by the percentage of utilization (Haque, 2016). Since all fabric must be utilized in designing zero waste garments, cost consideration is mainly focused on labor and time spent for managing waste elimination, while maintaining the most efficient visual appearance of the garments across varying sizes.

The following examples represent some fabric features that require careful consideration during both the creative and technical design processes, in order to either avoid deficiency in visual impact of basic and graded sizes or increasing labor cost through pre-production processes.

Fabric width and weight. Fabric width is one example of the dimensions that are determined by the basic size before grading into multiple sizes. Larger fabric widths have a role in achieving higher efficiency and thus decreasing cost (Dumishllari & Guxho, 2015). Therefore, consideration should be given for the fabric width for the basic design. On the other hand, the fabric weight is a fabric feature usually chosen due to the design and aesthetic of the garment (Bubonia, 2017). When designing zero waste garments, consideration should be given to this feature because a heavy fabric will not hold a lot of gathers or drape as well as a light fabric. That being said, it is important to note that a light fabric cannot achieve the same volume requirements of a heavy fabric. Thus, these differences influence the feasibility of making adjustments, in order to eliminate waste, to the patterns during the marker-making process.

Fabric with raised surface design. Another fabric feature that needs to be considered in order to avoid bulkiness in zero waste garments is the use of dimensional fabrics such as embroidered, beaded, or other means of embellishment. Dimensional surfaces not only increase the cost of the product, but they also require consideration for the feasibility of managing negative spaces in marker-making compared to fabrics with a flat surface by developing thoughtful design solutions.

Quality of Visual Impact

Plain fabrics allow for two-way direction in laying out patterns, however, the unity of color in a design depends on the fabric used, because there are some fabrics which appear a different shade of color if laid out in a different direction (Bubonia, 2017; Lee & Steen, 2014). For example, satin weaves and pile fabrics must be cut in one direction. Thus, there are special considerations that should be given for making decisions related to fabric selection during pre-production processes for zero waste garments. Fabrics that require a one-way direction pattern layout usually consume more yardage than regular plain fabrics (Glock & Kunz, 2000). Further, in zero waste design it also requires extra work when managing negative spaces and increased labor cost if adopting a one-way direction. However, the level of commitment to color unity depends on the companies' standards of quality. Following are some fabric features that influence the visual impact related to color.

Fabrics with nap or pile. Garment patterns meant for nap or pile fabrics, such as velvet, fleece, or corduroy should be laid out in one-way direction for all pattern pieces (Bubonia, 2017, Lee & Steen, 2014). Otherwise, garments or garment parts will not be identical in shade because the color appears darker and deeper when the nap or pile is brushed in an upward direction, while it appears lighter and duller when brushed downward. Two-way direction is efficient for fabrics with not much of a difference in color between the two nap directions. However, a two-way direction marker is adopted with nap or pile for mass production by some companies to reduce cost (Bubonia, 2017).

Fabrics with directional weave. Fabrics such as twill, gabardine or denim, generally require planning when using a one-way layout for marker-making in order to avoid effects on perceived color shade caused by the diagonal weave (Bubonia, 2017; Lee & Steen, 2014). Similar to fabrics with nap or pile, all pattern pieces should be placed on the marker in the same direction. Moreover, there are other fabrics that reflect light, referred to sheen fabric, such as satin. Fabric that reflect light can cause shading when viewed from different angles. Thus, consideration should be given when laying out these fabrics.

Print

There are numerous fabric printed design, and there also fabrics with no prints, which known as plain fabrics. Plain fabric can have a very straightforward layout, in which a pattern can be laid out with the top of the pattern pieces in either direction up or down (Bubonia, 2017; Lee & Steen, 2014). Similarly, most print repeats are designed to allow the pattern pieces to be laid out lengthwise either ways. However, other fabrics with special print features need more consideration, which will be discussed in the following section. Special print features impact the feasibility of grading zero waste garments, or the number of graded sizes able to be generated from the basic size. In addition, special print features require more time when making adjustments to patterns in zero waste garments in order to eliminate waste and avoid the need for using extra fabric, which are considered in conventional fashion design when created with fabrics that have special prints. Following are some special features of fabric prints that impact the visual appearance of the garments.

Fabrics with a one-way print. Prints that require being laid out in a one-way direction are those prints that have images, such as the Eiffel tower, trees, flowers, etc. These fabrics always require they face the same direction in order to maintain a more cohesive and acceptable appearance (Bubonia, 2017; Lee & Steen, 2014). This requirement indicates more fabric usage, which increases cost and waste in conventional pattern cutting process.

Fabrics with print designs needing matching. Matching pattern stripes is an important quality indicator in terms of aesthetic aspects (Bubonia, 2017; Lee & Steen, 2014). A simple shirt or other basic style garments may not need any special consideration. However, additional parts, such as patch pockets, require matching (Bubonia, 2017; Lee & Steen, 2014). In addition, fabrics with large motifs or long spaces between design repeats require planning in order to assure motif matching during and after construction. Similarly, fabrics with mirror images running from left to right are considered to be crosswise symmetric. Asymmetric designs are those with no mirror image from left to right and require a one–way placement of pattern pieces on the fabric in order for them to match in the finished garment (Bubonia, 2017; Lee & Steen, 2014).

Not only prints on fabric, but also woven plaid or tartan matching is an important quality standard in many high-end apparel companies, especially when using a large or dominant plaid (Bubonia, 2017; Lee & Steen, 2014). Plaid would not be easy to handle for zero waste design garments because it requires extra fabric in order to lay the pattern pieces on the marker in a way that allows for maximum matchability for both vertical and horizontal lines. Thus, the adoption of simple styles of zero waste design for garments is preferable over complicated styles because ZWD simple styles require less effort in line matching and managing waste fabric.

Silhouette

Generally, a straight silhouette is more efficient over a curvy silhouette when working with a ZWD that depends on flat cutting, such as in Jigsaw pattern cutting. For example, a cut-off strip resulting from an A-line dress has more potential in being utilized in finishing garment edges than a curved edge cut-off, which decreases both time and cost for labor in pre-production process for manufacturing ZWD.

Grainline

The grainline of garment pattern pieces is designed to align with the lengthwise grain of woven fabrics or the visible rib of knit fabrics. However, it is common practice for marker makers to tilt pattern pieces off-grain to increase fabric efficiency (Glock & Kunz, 2000). The resulting appearance is dependent upon the degree of tilt, fabric type and garment style. Garment designs with a true bias grainline (i.e., aligned at a 45-degree angle to the lengthwise grainline) in the main pattern pieces are more challenging than those utilizing a lengthwise or crosswise grainline due to the difficulty of managing waste. For example, a bias skirt on the true bias utilizes more fabric than one with a lengthwise grainline.

Material, print, color, grainline, and silhouette are all design element factors that influence marker-making efficiency. Thus, since this study aimed to investigate the possibility of making adjustments to graded sizes through the process of marker making, the influential variables related to fabric material, print, or color were eliminated. Therefore, plain fabric with flat plain weave was utilized for developing control and graded sizes of the garments. On the other hand, grainline is one of the influential elements that was considered in this study due to its impact on pattern pieces adjustments (Glock & Kunz, 2000).

The technical design elements are factors that have been considered and evaluated through standard industry practices. Sampling evaluation practices include various means to evaluate accurate appearance and fit related to technical design impacts on prototypes. 3D virtual simulation has been used in most major apparel companies, in order to efficiently manage time, cost and labor (Sayem, 2015). Following is a review of the 3D simulation that has been utilized as an assessment tool for virtual garments in the apparel industry.

Three-Dimensional Simulation as an Assessment Tool

Three-dimensional virtual simulation technology originated in the 1980s and has increased worldwide since the late 1990s (Guan, Yu & Chen, 2009; Lee & Sohn, 2011). According to Sehee (2009), virtual clothing technology is "the process of constructing 3D garments in the virtual space, is used by designers to create clothing in a virtual space through 3D simulation prior to the production of the garment in the physical space to verify features of the garment such as components, materials, fit, pattern layout, and even styling in advance" (p.18). This technology has impacted the progress and efficiency of the apparel industry.

With the current fast pace of apparel production taking place in more than one geographical location, communication between production sections regarding fit sessions is difficult. However, according to Song and Ashdown (2015), as well as Sayem (2015), the emergence, in the last few decades, of 3D simulation of clothed avatars that could be zoomed and rotated have facilitated the process of visualizing the dimensions and folds of a garment. This 3D technology has a significant role in apparel online shopping and pre-production processes because it is considered as an effective tool for large-scale communication in apparel companies (Ainamo, Kulinska, Burniaux, Zeng, & Chen, 2016).

The design interaction between 2D patterns and 3D digital simulation of a clothing model on an avatar, or a scanned body has facilitated the design process to improve the visual impact of the simulated virtual garments Siersema (2015). This is due to the ability for visualizing the design alterations made in 2D or 3D in both the patterns and the simulation. The virtually simulated garment is visible from all sides, which enable the designers to see the design for multiple angles and observe any errors in the design. Correcting errors include fit, prints, proportions, balance, and shaped construction lines.

Even though the advantage of virtual simulation is the facilitation of communicating garment design details, which has contributed to the overall speed and lower cost of prototypes needed to be sent between different locations (Sayem, 2015), from a sustainability perspective, 3D minimizes environmental waste through pre-production processes and is considered as an important contribution to sustainable practice in the apparel industry (Ainamo et al., 2016; Siersima, 2015; Tao & Bruniaux 2012). Since the accuracy of digital evaluation of 3D simulated garments fit has positive effects on sample budgets, this consideration would also influence the number of samples made, which means less physical samples, lower transportation costs, and less use of materials, (Siersema & Kuijpers, 2011).

Optitex

Vendors, manufacturers, and academics use a variety of 3D clothing CAD systems that are currently available on the market. Software solutions include 2D pattern drafting, grading, and visualization techniques (Papahristou & Bilalis, 2017; Sayem, 2015). Several software have been utilized by the apparel industry for fit assessment including Lectra, vStitcher, and Tuka. Optitex (New York, USA) is one of the systems that has been successfully implemented for the 2D to 3D design approach and is being used by various large companies and universities (Gill, 2015; Sayem, 2015). According to the researchers, Optitex also includes 3D garment simulation from 2D pattern pieces using virtual sewing and draping simulation techniques that allow for remote review of the 3D virtual prototypes. In addition, the software provides the opportunity to check garment fit in different fabrics types and fit sizes.

Comparison Assessment

Various studies were conducted to examine both similarities and variations between actual and virtual garments for fit assessment. Little research focused on the pattern alteration for a better fit. Porterfield and Lamar (2017) investigated utilizing 3D virtual simulation impact on the interactive process of garment fitting. The researchers suggested that garment types variation and the expectations by the observers are two factors that influence the evaluation of fitting on 3D virtual simulation. In addition, Porterfield and Lamar (2017) recommended the collaborative comparison of design decisions regarding virtual and actual garment that in order to improve fit accuracy when it comes to design decisions.

On the other hand, most of the studies in the literature have focused on the influence of material or fabrics of the garments on the fit (Joo, Kyoung, & Jun, 2015; Guan, Yu, & Chen, 2011; Mutlu, Popescu & Mocenco,2016). According to Guan, Yu, & Chen (2011), fabric features are one of the main elements that have been investigated in the previous research because of their influence on the fit of the 3D virtual garments. Joo et al. (2015) explored and evaluated the similarities in the appearance of 3D simulation of virtual clothes compared to actual knitted clothes. The purpose was to examine the applicability of the DC system for accurate simulation of the knit garments through performing changes to various poses. The researchers found that the 3D virtual garment presented less fluid drape in the simulation for loose and heavy garments for particular positioning. They also found that the larger and heavier the fabric weight used for the sample, the more appearance variation impact. On the other hand, Guan, Yu, and Chen (2011) investigated the 3D simulation for fur clothing fitting through the experimental exploration of the fabric physical parameters settings. The similarity between the actual and virtual simulation was over 80% identified by the evaluators. Similarly, Mutlu, Popescu and Mocenco (2016) Compared the fit between leather and cotton physical garments to a 3D simulation of 3D scanned models. The researchers used both cotton and leather physical test methods and into the Optitex. The researchers found that 3D simulation was very realistic and that the accuracy of visual impacts depends on the level of accuracy and precision of the fabric parameters measurement data.

Optitex is one of the softwares that provide fabric texting for accurate and pricewise 3D simulation results. Following features should be tested prior to developing 3D simulation (Optitex, n.d.):

- Stretch: is the resistance of the cloth to Stretching forces in the weft or the wrap

- Bend: is the resistance of the cloth to bending forces. This important parameter affects the rigidity versus fluidity of the fabric.
- Shear: is the resistance of the cloth to shearing forces. Shearing forces influence is on the diagonal direction of the fiber/cloth or in other words, the parameter affecting the gliding quality versus stiffness of a fabric that's cut on the bias.
- Weight: refers to the weight of the fabric in grams per square meter.
- Thickness: The thickness of the fabric in centimeter

Both digital and manual methods are used for testing the parameters of the fabrics utilized for 3D virtual simulation. However, each software has a fabric library with specific parameters for commonly used fabrics. (Lee & Park, 2017). Using DC suite software, Vedder and Daane (2015) found that 3D virtual simulation would be an effective assessment tool to examine the visual impact of changing material properties on fit and appearance. They also examined the validity of the simulation by scanning the physical garments on the actual model and comparing the results with 3D simulation in order to achieve precise results.

Some researchers found that further improvements must be conducted regarding the fabric library for higher quality 3D virtual simulation (Mutlu et al., 2016). Mutlu, Popescu and Mocenco (2016) found that further fabric should have proprieties definitions in Optitex, especially leather that the lack of material variations. Similarly, Joo et al. (2015) suggested that specific properties of knit materials are essential. They stated that although many properties are available on DC suite, more realistic representation of different knitted garment requires different knitting patterns to simulate knitting materials. Since an accurate 3D simulation is a good tool for tracing visual impact variation between graded sizes, this study included the use of

3D simulation as an assessment tool using actual fabric parameters professional test for accurate comparisons between virtual and actual garments across graded sizes.

ZWD sizing and fitting is one of the major challenges for the feasibility for mass production. Thus the utilization of current technology to insure accurate and fast examination of fit between sizes would be a crucial effort. On the other hand, ZWD grading practices directly influence and are influenced by traditional production methods because of the use of patterns in grading multiple sizes of ZWD patterns. In addition, grading ZWD is associated with other environmental and economic values. Thus, the following is the discussion of the proposed theoretical framework for this study.

Theoretical Framework

Sustainable Fashion Design Model

Sustainability in fashion design has been encountering various obstacles, including the manufacturing of ZWD garments. The lack of feasibility regarding manufacturing sustainable garments is notable (Aakko & Sivonen, 2013). Aakko and Sivonen described current progress of the industry moving towards sustainable production and consumption of garments as modest. Akko and Sivonen further explained the global use of sustainable development is disappointing and slow. However, they suggested that through various community and local efforts, such as those that apply sustainable practices in apparel design, it is possible to implement those practices globally on a much larger scale. Aakko and Sivonen (2013) observed that the methods of reaching sustainability are not as clear as the aim of sustainability in fashion, which motivated them to provide a model that would help in simplifying the complexity of issues associated with sustainability in small-scale production from the designers' perspective.

The model of sustainable fashion design (Aakko & Sivonene, 2013) is the model used in this study and is based on theoretical data from academic publications, websites, and journal articles that were analyzed to identify and categorize relevant concepts to sustainable fashion design. The reason for using this model in this study is that it involves all three pillars of sustainability addressed in sustainable categories and practices within the apparel industry. The model includes a core category, called 'considered take and return,' which integrates all other categories in the model (see Figure 2.14).

This model addresses the principles and practices involved in the apparel industry and thus how they could grow with regard to sustainable consideration. Even though the categories of these principles and practices are presented separately in the model, the model developer stated that they could occur separated or interacted with other categories in the model. The main category in this mode is "considered take and return," which is the mutual target between the three fundamental fashion design philosophies: C2C, functional design, and slow fashion. On the other hand, since sustainable development does not aim to eliminate fashion in order to mitigate the environmental issues, the author noted that sustainable development interacted with fashion to emphasize the important role of both fashion designer and fashion consumer in developing sustainable fashion design. However, the authors stressed that this model is open-ended and that the model can be further developed with the growth of sustainable fashion.

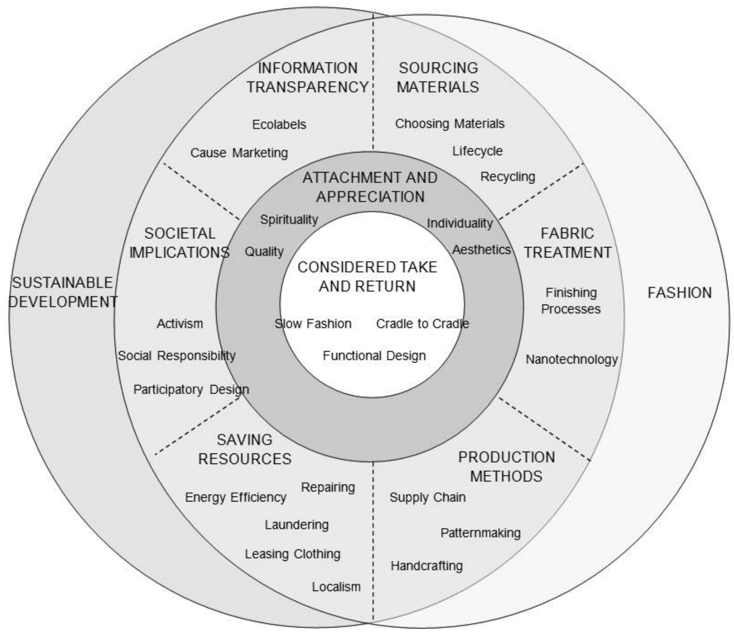


Figure 2.14 Model of Sustainable Fashion Design (Aakko & Sivonen, 2013).

Considered Take and Return

The concept of ‘considered take and return” in relation to sustainable development maintains that people can only take from the existing environmental systems the same amount of resources they put back, in an attempt to reduce environmental pollution and waste generation. In order to make the change toward more sustainable practices feasible and thus realizing “ considered take and return” concept globally, Aakko and Sivonen (2013) emphasized the importance for production sectors and consumers to benefit on a practical level from design philosophies that take sustainability into account regarding fashion design, which includes C2C, Functional Design, and Slow Fashion. Following is a brief description of the three elements of the “take and return” concept.

C2C philosophy developed by Braungart and McDonough (2008. This philosophy promoted paying attention to the lifecycle of materials through the phases of production and consumption. In addition to C2C philosophy, the concept “considered take and return” in the model of sustainable fashion design also includes functional design and slow fashion as central elements, both of which are relevant to the current study. Functional design in this model refers to the idea that design is a means to meeting human needs, culture, and ecology, as well as consideration of the connection between products and time, culture, society and nature (Aakko & Sivonen, 2013). The concept of slow fashion, which is also included in "considered take and return," is not only about the temporality of fashion, but also includes sustainable lifestyle products. Advocates of slow fashion consider the change as a characteristic of the fashion realm and look for procedures to produce sustainable garments that are slow-to-consume and made with carefully planned material cycles, both of which meet individual desires for change, as well as self-expression. These procedures include the redesigning and remaking to save resources while sustaining a sense of attachment to garments. Slow fashion also supports the notion of local economic dependency in regard to resourcing and distribution. In addition, slow fashion maintains transparency in production in terms of the communication between producers and consumers to provide sustainable products with emotional considerations.

Attachment and Appreciation

Based on the core concept of this model "considered take and return," this model addresses the categories of designing sustainable fashion. It is utilized in this study because the sustainable design categories in this model are compatible with the three pillars of sustainability. However, since sustainable fashion design is considered to be a new movement in the apparel industry system, attachment and appreciation of sustainable design is considered a bridge between the core concept of the model and other categories of sustainable practices in the model.

The "attachment and appreciation" concept includes four factors: aesthetics, individuality, quality and spirituality, all of which foster emotional attachment to sustainable garments. The first factor, aesthetics, refers to the notion that the consideration of social and cultural acceptance, along with environmental protection should not be at the expense of a garment's inclusion of beauty and creativity. Individuality, the second factor, is related to the expressive aspect of sustainable garments that allow for the wearer to present the desired look as a means of expressing his/her uniqueness. Quality is the third factor included in the attachment of sustainable garments. The assessment of quality occurs through all the phases of garment manufacturing. It refers to the assessment of fit, style, features, materials and techniques, as well as other aspects of the garment. Spirituality, the final factor, refers to true intentions addressed by ZWD designers to save resources and contribute to people's overall well-being as reflected in the products.

The four factors of attachment and appreciation of sustainable design strengthen the feasibility of adopting the practices of sustainable design that address the core concept of the model "considered take and return." Following is a discussion of the sustainable model's main categories based on the three pillars of sustainability: social sustainability, economic sustainability and environmental sustainability.

Social Sustainability

Social sustainability, in the model of sustainable fashion design, adopts two main categories: societal implications and information transparency. Both categories address the main considerations of social sustainability that lead to human well-being through different practices in sustainable fashion design.

Societal implications. The societal implications category includes social responsibility, activism and participatory design. Social responsibility refers to responsible actions adopted by apparel companies in order to meet fair labor conditions regarding workers' rights, work conditions, wage and work hours including paying overtime. Activism, the next aspect of this category, encourages sending socio-cultural messages through design in order to have an impact on environmental, political or social situations. Finally, participatory design focuses on the role of users in co-designing the products. When users are a part of the process, there is transparency between apparel companies and consumers, which encourages an understanding of connection to the materials used in relation to different cultural, political and ecological levels.

Information transparency. The second category, information transparency, is comprised mainly of two main practices: ecolabels and cause marketing. Ecolables are labels that provide consumers with accurate details about sustainably produced garments. Cause marketing refers to the transparency that producers of sustainable garments should provide when promoting their business; for example, being honest about the environmental or social causes that help increase their business profit.

Economic Sustainability

Similar to social sustainability, economic sustainability contains two categories in the sustainable fashion design model. Saving resources and sourcing materials both have the ultimate goal of maintaining an abundance of resources for the sake of continuous and balanced profit for communities.

Saving resources. Energy efficiency and laundering are the two most important aspects of the saving resources category. During the garment life cycle there are critical sources of environmental impact caused by energy consumption. Therefore, saving resources involves the investigation of alternative energy sources to increase energy efficiency. Laundering, one of the most consistent phases of the garment life cycle, consumes large amounts of energy for washing, drying, and ironing. Thus, saving resources encourages using alternative both natural and synthetic materials. Wool is a natural fabric that require less laundering and utilize both lower water temperature for washing and lower air temperature for drying. More efficiently, polyester is a synthetic fabric that dries naturally in the air fast, which makes the use of clothes dryer not essential for drying polyester garments. Saving resources also includes activities for lengthening the garment life cycle, such as repairing garments, renting garments, and localism, which serves to support the use of local resources and create jobs.

Sourcing materials. The second category, sourcing materials considers the efficiency of energy use, and the management of pollution caused by the processes of fiber manufacturing. Management strategies include the processes of reusing, recycling and reducing waste management strategies, as well as disposal practices. In addition, this concept emphasizes the importance of using the least harmful materials possible to meet both aesthetic and functional market demands. The use of less harmful materials has positive impacts, compared to conventional materials, especially for large-scale production.

Environmental Sustainability

In addition to social and economic sustainability, environmental sustainability is another component of the sustainable fashion design model and includes two different concepts: fabric treatment and production method. Both of these concepts consider how to prevent the harmful components of harsh chemicals used in fabric treatments or in material waste from impacting the environment.

Fabric treatment. During the course of manufacturing, fabric is exposed to a variety of chemicals. Fabric treatments have many environmental impacts due to the energy and water used, in addition to the use of harsh chemicals for fabric treatments in processes such as scouring, bleaching, dyeing, and finishing.

Production methods. Patternmaking, handcrafting, and supply chain are the three subcategories included in production methods. The founders of the sustainable design model suggest that zero waste design is the ideal solution for sustainable garments in order to solve the problem of fabric waste. On the other hand, Aakko and Sivonen (2013) stressed that although handcrafting would not be a contribution to solving sustainability problems regarding mass production demands, the attachment and appreciation of hand-made garments impact the longevity of garments. In terms of environmental sustainability in the supply chain, it is stressed that transparency in production practice is the most important factor to assure environmental protection. All countries participating in garment manufacturing for particular companies must adopt this transparency.

There are some studies that have utilized the sustainable fashion design model to address different solutions for sustainable issues in the apparel industry. Supply chain management is one areas that has utilized this model (Jia, Govindan, Choi, & Rajendran, 2015; Henninger, Alevizou, Oates, & Cheng,2015). One identified study utilizing this model in the supply chain taking design into consideration was conducted by Wang and Shen (2017). They found the use of eco-materials at Patagonia, a sustainable garment company, significantly affected many elements of sustainably designed garments, such as the number of color choices, product weight, pattern design, and product fit. However, the researchers also found that online reviewers of Patagonia's line focus more on functionality of sustainable outdoor garments than on aesthetics. However, little research has addressed the design or production methods utilizing the model of sustainable fashion design.

The Applicability of Sustainable Fashion Design Model in This Study

The ultimate aim of this study is to contribute to sustainable development in the apparel industry; which is the base that the model of sustainable fashion design is built upon. In addition, the concept of ‘considered take and return’ with its association to cradle-to-cradle, slow fashion, and functional design concepts match the objectives of the current study; as zero waste practice considers the best practice of reducing waste caused by apparel production. The elimination of waste will also support creating the equal balance of the take and return concept. The concept of functional design is represented in ZWD when garments are made with environmental considerations, along with considering the functionality of garments for each target market such as active wear versus haute couture gowns. In addition, since the Jigsaw pattern in the current study was a one-of-a-kind design, uniquely patterned for zero waste, it is representative of slow fashion. These designs were created with the intent of maintaining environmental resources as one of the sustainable practices.

Basically, the consideration of production methods through the functional design process makes this model a suitable one for the current study as its base utilizes a design method that simultaneously incorporates both design and production. According to Aakko and Sivonen (2013), ZWD is the ideal solution to pattern making practices when working towards sustainable fashion design; Akko and Sivonen further described ZWD as a process that integrates sketching and patternmaking and requires the consideration of technical and visual elements of design together. The current study would be a good fit for this model and would aim to fill the gap of developing grading ZWD practices.

Attachment and appreciation connect the core concept in this model with the production method and saving resources as two main categories in the model. Since this study is more focused on the elimination of environmental harm caused by pre-consumer textile waste, these categories were mainly considered in this study (see Figure 2.15). In her study, Kirsi Niinimaki (2015) examined the influence of practicing ZWD on material appreciation through experimental design processes through a case study. Niinimaki found that facilitating a new kind of appreciation for fabric utilization could be achieved through fashion design. In addition, Niinimaki found that appreciation of textiles can be fostered through the practice of ZWD approaches. This finding indicates the significant of ZWD evaluation on fit and visual accuracy when comparing the virtual sample to physical across control and graded sizes.

The current study considered two elements related to “attachment and appreciation,” aesthetics and quality. Aesthetics is involved in the design and pattern cutting process developed by the designer of the ZWD style utilized in this study. Quality was considered in the evaluation of grading and marker-making for ZWD garments. Both aesthetics and quality approach the core of the model from different dimensions. Thus, this study examined the interaction between aesthetics and quality on the production method.

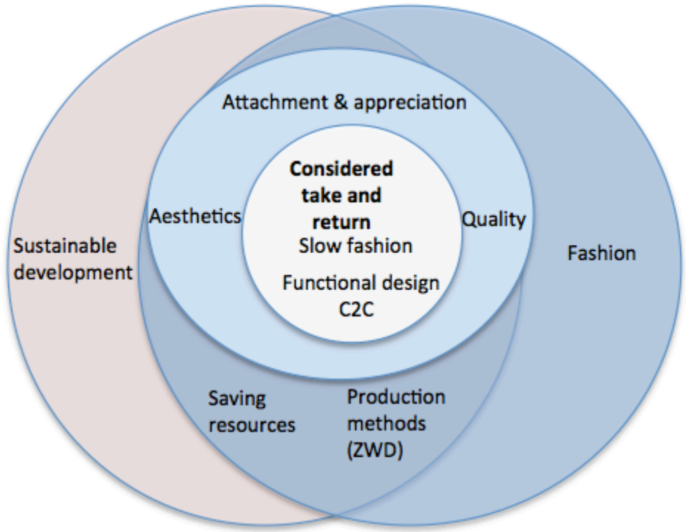


Figure 2.15 The utilized elements from the sustainable fashion design model (Aakko & Sivonene, 2013).

Summary

The review of literature included the key elements needed to address the problem of grading zero waste Jigsaw patterns. The first section reviewed the three pillars of sustainability, followed by the apparel and textile industry's contribution to the problem of climate change, particularly pre-consumer textile waste and its resultant environmental and economic impacts. Further discussion centered on ways in which the strategies to manage waste within the apparel industry have not been efficient, and that ZWD is a strategy for eliminating waste, reducing the consumption of energy, and valuing human resources. The review also included the current practices of grading garments in the apparel industry. With the use of simplified grading and ASTM sizing systems, fit problems developed from this system when grading apparel patterns. However, fit problems can be reduced through use of 3D virtual simulation along with the comparisons between virtual and actual fit. Although there are some suggested procedures to grade ZWD garments, they are still not fully adopted by manufacturers due to conflict with current manufacturing practices. Grading ZWD patterns is not a separate process but directly influences the efficiency of the marker-making process in terms of the correlation between pattern size changes and fabric width. This current study incorporated the model of sustainable fashion design as a framework for the sustainable production method of marker making, along with 3D simulation, which may provide better visual accuracy for a range of sizes in the same design.

CHAPTER III

METHODS

Introduction

The overarching purpose of the study was to improve the sustainability of preproduction methods for sustainable fashion design. The industry software Optitex was used to apply grading techniques to a ZWD Jigsaw design and compare the result across physically and virtually constructed graded garments. Two stages were included in this study to answer the research questions and accomplish the objectives. The first stage involved the production methods; that included three phases to answer the first research question: What pattern piece adjustment methods, for the two graded sizes of the selected ZWD Jigsaw style, result in 100% marker efficiency and accurate virtual visual appearance? The researcher underpinned the functional design component in the Sustainable Fashion Design model through the experimental approach for the production methods. The second stage was the survey stage that ultimately answered the second and third research questions: Can digital 3D simulation be used as an effective and sustainable sizing and fit assessment tool? Does attachment and appreciation of ZWD influence expert judges' evaluation of visual accuracy? The experimental design and the mixed methods approach were the methodologies utilized for this stage.

Table 3.1

An Outline of Stage One Phases

Stage One: Functional design process		
Phase 1: Sample development, grading and marker making	**Phase 2: Digital and virtual testing of Marker adjustments**	**Phase 3: Marker refinement**
1. Developing ZWD princess dress size 8 Control	1. 3D simulation • Virtual testing for utilizing negative spaces in bodice panels	1. Pilot survey feedback
2. Grading, with no sleeves	2. Grading, including sleeves	2. Refinement of patterns and avatars
3. Marker making	3. Marker adjustments for fabric utilization • tilt, and rotation grain for sleeves specifically • increasing skirt width • adjusting non-visible pattern dimensions • create neck facing, pockets and hangers	
4. Marker adjustments for fabric utilization • tilt • decreasing and increasing skirt widths; inclusion of negative spaces in bodice panels • create sleeves from negative space • create neck facing • create hidden support pieces	4. Physical construction and experiment with remaining fall out to create pockets and laundry hangers	
5. Physical construction	5. Finalizing 3D simulation to test the creation of pockets	

6. Analysis	6. Analysis	
Stage Two: Survey		
		1. Development of evaluation statement lists for the comparison sets
		2. Filming the physical dresses and screen taping the virtual dresses before uploading to the survey
		3. Pilot survey
		4. Data collection using online Qualtrics
		5. Data analysis using SPSS for quantitative data and content analysis for qualitative comments

This chapter introduces Stage One design data and analysis methods of each phase of the functional design process. This overview is followed by the in-depth methods, procedures and analyses of each phase of Stage One. The chapter continues by introducing Stage Two survey methodology, including the mixed method utilized for data collection through the use of a survey. Following the discussion of the survey is a presentation of the sampling method for participants, including both purposeful and snowballing methods. Lastly, this chapter includes the approach of data analysis using descriptive statistics.

Stage One: Functional Design Process

The first stage, functional design process, addressed the production methods from the theoretical framework in the Model of Sustainable Fashion Design (Aakko & Sivonen, 2014). In fashion studies, functional design is associated with apparel items that are designed to meet specific needs for the wearer (Lamb & Kallal, 1992). However, in the Model of Sustainable Fashion Design, functional design is considered a major element of the core concept. It refers to complex concepts, including production methods and their use of tools, materials, and processes. Aakko and Sivonen (2014) stressed the necessity of the unity of aesthetics and utility aspects that the designer should consider in developing sustainable garments, instead of utilizing the two aspects exclusively. Thus, this concept of functional design within the Model of Sustainable Fashion Design was appropriate for developing ZWD. In addition, Aakko and Sivonen (2014) stressed the importance of the thoughtful consideration of time, culture, society, and nature when producing sustainable garments.

In the Model of Sustainable Fashion Design (Aakko & Sivonen, 2014), the production methods are considered to form a significant category for practicing sustainable development in the fashion realm. The production methods included in this study were design, grading, and marker making to answer the first research question: What pattern of piece adjustments and marker layouts achieve both 100% marker efficiency and accurate virtual visual appearance? This functional design production stage included three phases: 1) Sample development, grading and marker making, 2) Digital and virtual testing of marker adjustments, and 3) Marker refinement.

Design Data and Analysis

The experimental research design was used to identify the nature of the practice through the phases of the production methods. This study was designed to explore the feasibility of grading ZWD through the marker making process. This included experimenting with ZWD style lines, marker making, and pattern adjustment techniques for better fabric utilization. Regarding the collection of design data, Gray and Malins (2004) stated that researchers in different fields use visuals as a means for multiple purposes. The purposes of using visuals include gathering or generating data, explaining or understanding a situation, and evaluating, analyzing, interpreting, resolving, and communicating findings. In this study, design data was collected through the functional design process stage to document and analyze techniques, procedures, and findings of the experiments. Design data in this study included physical items, such as markers (printed, digital, screen shots), garment part samples and garments (actual, photos, digital, virtual), and other documentation (notes, photos, feedback from faculty) recorded by the researcher. To answer the first research question, design data and practice were analyzed by reflecting on each design technique's efficiency, challenging aspects, and from discussions with the faculty. Designing is not a linear process; rather, it is a process that involves continuous examination of the outcomes and refining (Gray & Malins, 2004). Thus, the design and analysis were ongoing throughout Stage One.

Phase One: Sample Development, Grading, and Marker Making Data and Analysis

Before answering the research questions, a zero waste dress was designed that had "classic" elements of a fitted bodice and a gathered skirt. As seen in Figure 3.1, Phase One included developing a ZWD base size 8 dress and marker, digital grading and mixed marker, digital pattern adjustments, and physical construction. Experimentation was implemented throughout this phase in order to achieve 100% marker efficiency while maintaining visual appearance between graded garments. The design data in this phase included physical samples of designing, grading, marker making, and constructing the control ZWD dress and graded dresses.

Analysis of the design data was ongoing throughout the first stage. The researcher had weekly one-to-one meetings with the advisor, Dr. Sherry Haar, as well as group meetings that included Dr. Wu, a committee member and Optitex instructor. The meetings included a discussion and analysis of the design and/or marker at the time of the meetings. Strengths and weaknesses were identified along with the next steps. The evaluation meetings enriched the design and testing process in terms of broadening the examination of various possibilities to solve problems within the functional design process.

Phase Two: Digital and Virtual Testing of Marker Data and Analysis

Once the ZWD control garment was approved, research question one was addressed:

1. What pattern piece adjustments and marker layouts achieve both 100% marker efficiency and accurate virtual visual appearance? Specifically,

   a. What pattern piece adjustment methods, for the two graded sizes of the selected ZWD Jigsaw style, result in 100% marker efficiency and visual accuracy?

   b. What is the most efficient pattern piece adjustment method and marker layout that maintains visual accuracy as compared between the virtual control garment and the graded virtual garments?

This phase included multiple design steps, including grading and 3D simulation, marker adjustments for fabric utilization, and physical construction. Following the grading process was developing a 3D simulation for the control garment size eight before starting the marker making process and pattern adjustment for the graded sizes. The last step in this phase included the physical construction in addition to finalizing 3D simulation for the virtual graded dresses.

Design data in this phase were similar to the first phase, including physical samples of graded dresses, screenshots, digital files of digital patterns and markers, and photos of applied construction techniques. However, this phase included an additional form of data, which were the digital files of the 3D simulation and screenshots of the applied digital techniques. The addition of three-dimensional simulation enabled the control garment to be utilized as an evaluation tool through the process of simulating the graded sizes.

As in phase one, design data were evaluated through discussions with Dr. Haar and Dr. Wu. In addition, the researcher had many consultation conversations with Optitex technicians. This included phone conversations and remote sessions (when the software technician had access to the researcher's computer screen to examine the problem related to the software). The technical support provided indirect assessment, suggestions, and limitations regarding the use of Optitex, specifically with regard to the 3D simulation.

Phase Three: Marker Refinement Data and Analysis

Phase Three included two main steps: the analysis of the outputs from Phase Two and refinement of graded pattern pieces and avatars. This third phase of the functional design process was the last phase before conducting Stage Two data collection; thus, by the end of Phase Three, videos of the constructed and virtual samples were included in the pilot survey. The feedback from the pilot, regarding the samples, were analyzed at this phase. Design data in this phase included screenshots of virtual samples and digital files of digital patterns. Similar to previous phases, design data were evaluated through discussions with Dr. Haar and Dr. Wu.

Functional Design Process Production Methods and Analysis

Following is the detailed methods and analysis procedures of Stage One, starting with Phase One fabric selection and control sample development, followed by the second and third phases of the production methods. Thus, the below sections provide depth to the previously presented outline and transparency to the functional design process.

Phase One: Sample Development, Grading, and Marker Making

ZWD dress fabric and control design development. A yellow 100% wool crepe fabric, donated from "The Sewing Workshop" in Topeka, KS to the Department of Interior Design and Fashion Studies, was used for the constructed garments. The wool crepe was stable, yet provided a good drape, while the yellow color photographed well compared to dark or pale fabrics, allowing for visual evaluation of the style lines and seams. The fabric width was 56 in., which determined the marker width. Fifty-six inches falls within the typical 54 to 60 in. standard fabric widths for dress manufacturing.

The ZWD jigsaw style, that had been initially selected for this study, was a dress titled *Little Black PARTY Dress*, retrieved from a published resource (Carrico & Kim, 2014) (see Figures 3.1 and 3.2). The style was selected as it included both the upper and lower body, both small and large pattern pieces, and both fitted and loose areas. Additionally, it represented a classic style, the little black dress. However, despite receiving the marker and consultation regarding the size of the dress, the pattern was not replicable due to width differences and a lack of internal markings and construction details. Thus, the *Little Black PARTY Dress* was not used in this study, but rather provided a starting point for the researcher to develop a zero waste princess style dress.

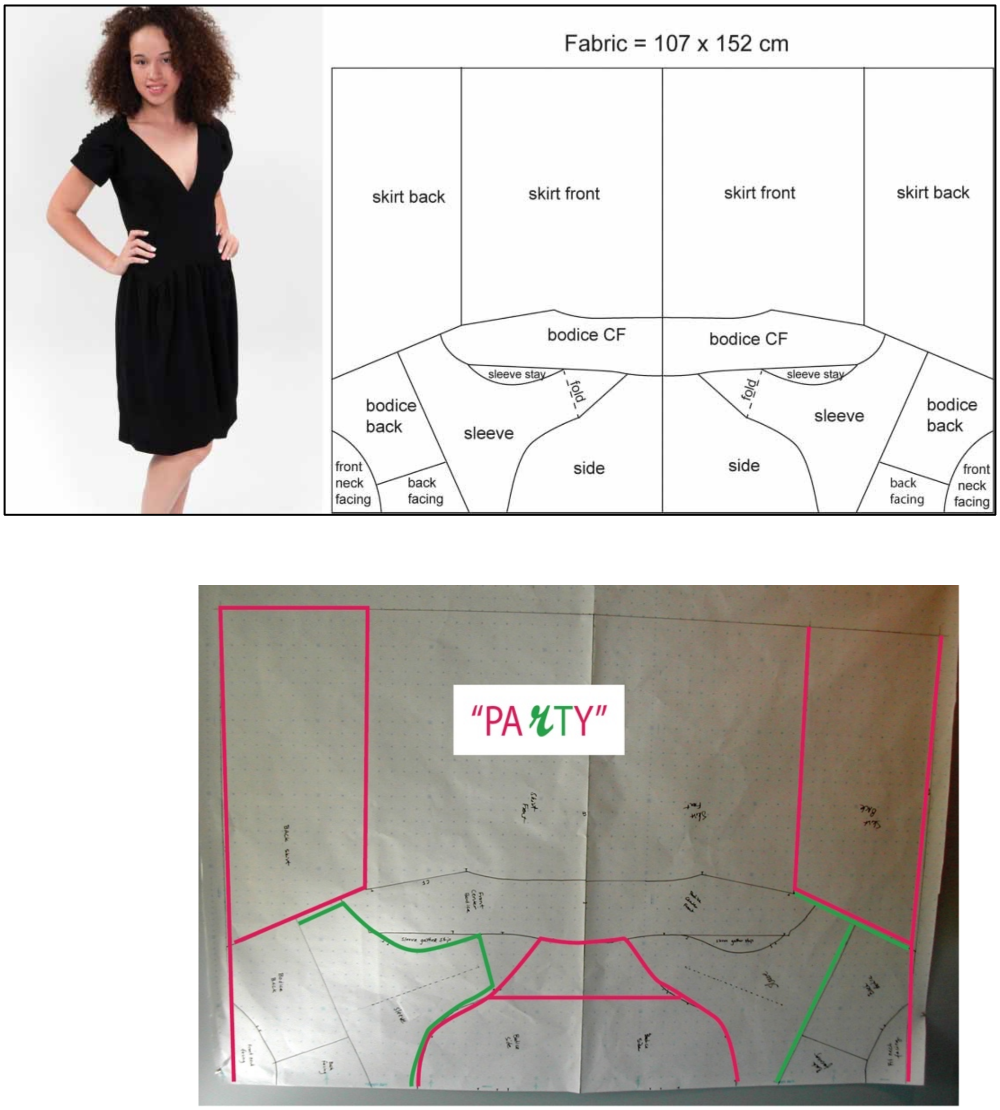


Figure 3.1 Little Black PARTY Dress by Melanie Carrico that served as a point of departure (Carrico & Kim, 2014)

Figure 3.2 Front, back and side views of *Little Black PARTY Dress* by Melanie Carrico. Photos by Melanie Carrico

The first version of the control princess style dress was developed starting with creating the jigsaw marker determined by the fabric width of 56”. The skirt pattern pieces for the front and the back occupied the full width of the fabric; the skirt length was to the knee. Gathers technique was used later to manage skirt fabric width to fit the bodice. The location for the bodice pattern pieces were determined in the marker. The researcher draped the princess style lines for the bodice on a PGM dress form (PGM Dress Form Inc., Baldwin, CA) size 8 and transferred the style line to the marker. Then, the researcher classified the negative space in the marker to be utilized in different areas of the dress. See Figure 3.3. First, the sleeves were the focus for fabric utilization, since they were not draped with the bodice and skirt. Thus, the largest negative space area was utilized for creating the sleeves and other smaller negative spaces were used for finishing the sleeves. The areas that are typically thrown away were used as facings (which refers to finishing a garment part edges, such as neck line opening) or support (which refers to stitching the piece a particular area in the garment to provide support rather than finishing). See Figure 3.3. Larger pieces were used as neck and sleeve facings. Support pieces were stitched to the waistline at side seams of the skirt. The remaining small negative spaces were distributed along the hemline and stitched internally within the fold of the hem.

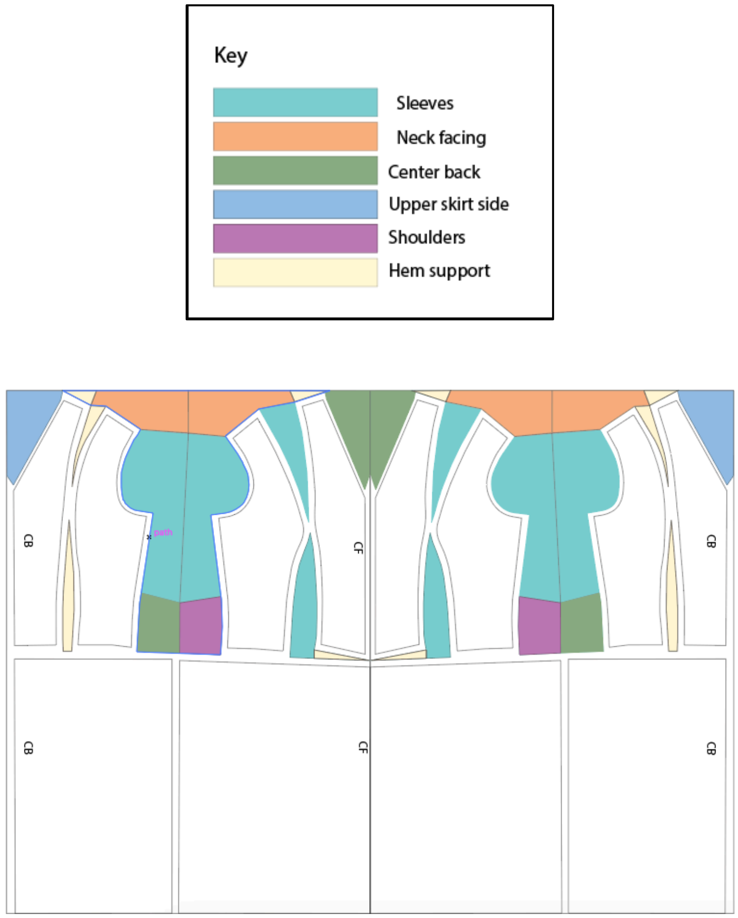


Figure 3.3 Pattern pieces and manual color-coded marker of the ZWD princess control dress

Sleeve design was explored with the assigned fabric waste. Various styles (petal, slit) and techniques (gathers, pleats) were examined. Even though one of the sleeve designs looked aesthetically appealing (see Figure 3.4), a more simplified sleeve design was selected for this study (see Figure 3.5). The selected sleeve design was a modification of the petal sleeve developed from fall out by overlapping two sleeves parts. The first version of the control ZWD dress pattern pieces and marker with 100% efficiency are shown in Figures 3.6 and 3.7. The size 8 control ZWD dress featured a semi-fitted bodice with princess seams, a gathered skirt, and petal sleeves (see Figure 3.6). At this phase, the waste areas were incorporated as facings, support, and hidden in the hem.

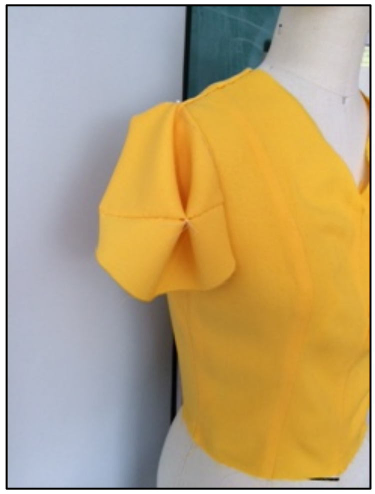


Figure 3.4 ZWD sleeve experimental option

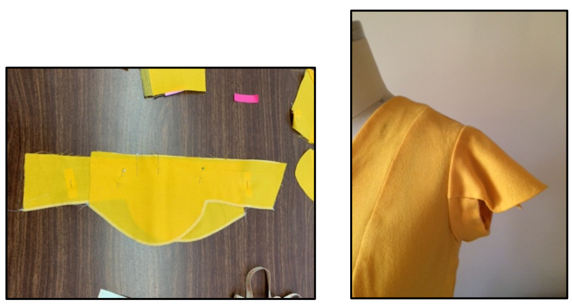


Figure 3.5 Modified petal sleeve

Figure 3.6 The first version of ZWD control princess style dress

Digital procedures. The next step was to prepare the control pattern pieces for the Optitex software (EFI Optitex, New York, NY) by separating individual pattern pieces from the ZW Jigsaw marker. The manual Jigsaw marker was scanned into a PDF format at the actual size using HP DesignJet scanner. After saving the digital copy of the design, the separate pieces were traced in Adobe Illustrator using the pen tool over a template layer and saved in a PDS format for use in Optitex (see Figure 3.7). The seam allowances were included in the pattern pieces and were as suggested by industry: 0.5 in. for all seams, except the seams with a facing were 0.25in. Cleaning the patterns in PDS was the last step before grading the patterns. This step included the elimination of unnecessary points on each pattern piece, and the adjusting of the grading points.

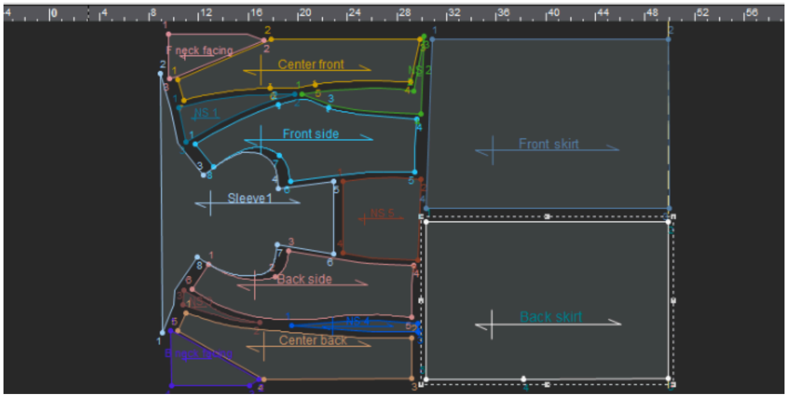


Figure 3.7 ZWD princess style dress in PDS (Optitex file).

Grading. Once the separation of the control block patterns was complete, they were graded into two sizes; one larger (Misses' size 12 as XL) and one smaller (Misses' size 4 as XS). The control size (Misses' size 8 as M) of the Jigsaw pattern was graded using the simplified grading system. According to Mullet (2015), simplified grading includes an even distribution of grade rules between front and back, all at the same identified grade points. Since the simplified grading method is problematic to use with the full range of garment sizes, researchers stated that it is not recommended to size ZWD garments for more than a maximum of five sizes (McQuillan & Rissanen, 2016). They further argued that grading more than five smaller or larger sizes results in changes to the style lines of the final garments or eliminates some parts of the pattern pieces. Thus, this study included graded sizes within the range of five sizes from the control size.

The grading process started by creating a grade rules table for each pattern piece of the style; a 2" grade rule was distributed for grading size M to size XS, and a 2.5" grade rule was distributed for grading size M to size XL through the use of relative grade rules per size (see Appendix 2). In this first phase of sizing, grading was applied to the bodice pattern pieces, but not to the sleeves or skirt width. The reason was to continue sleeve experimentation from the negative spaces of the marker. In terms of the skirt, the grading included the length of the skirt only. The width of the skirt was fixed because gathering was the adjustment method being used to manage width variation between sizes. The graded nest, that included the three sizes (control 8, and graded 4 and 12) stacked together, was developed after finishing the distribution of the grade rule for each pattern piece (see Figure 3.8).

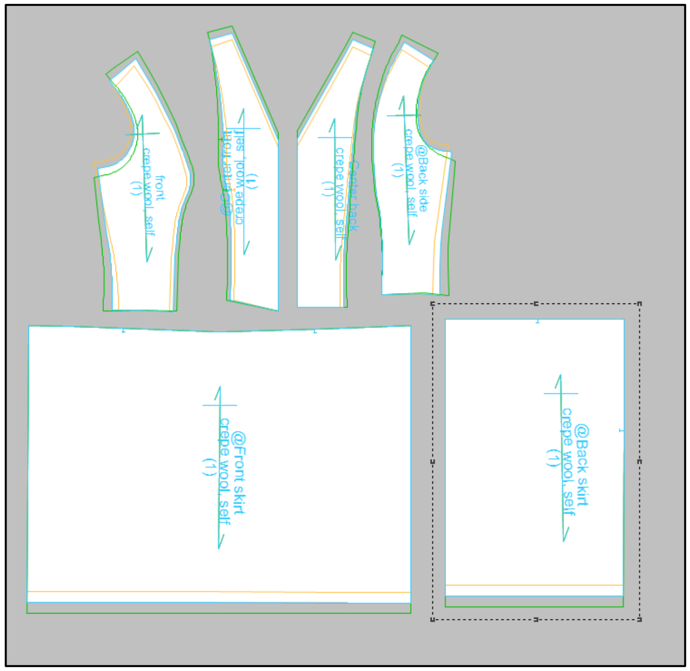


Figure 3.8 The graded nest of the ZWD princess control in PDS (Optitex file), including center front and back, side front and back, and skirt front and back

Marker making. Establishing a cutting order was the first step of the Optitex marker making process. Cutting orders include the record of style, size, quantity, and other information. This information includes order number and date, style and fabric to be cut, quantities of each size, special requirements, and date of completion. The "special requirements" part in the cutting order would be the location to add instructions related to the marker making and cutting for ZWD.

The Optitex software does not allow for separating graded sizes from the base size nest. Thus, the researcher copied the original file twice in order to work on each graded size separately in PDS files (in the drafting module) to allow for independent pattern adjustments for each graded size later on. Then, the graded pattern pieces were uploaded to the marker module in Optitex in order to plan the layout, where the software calculated the value of the marker efficiency.

Pattern pieces could be placed on the marker according to bundle (which includes all pattern pieces for a particular size), which is defined as the blocked marker, or regardless of bundle which refers to the mixed marker. Prievous research suggests that, in most cases, the blocked marker did not provide high marker efficiency compared to the mixed marker. Thus, multiple marker making configurations with different layouts were tested to reach the maximum efficiency with the mixed marker for the graded sizes, which was 83.77%. Moreover, two digital pattern adjustment techniques were considered during the marker making process before plotting the marker. First, 10 degrees of tilting the pattern pieces was applied through the marker attributes. Marker attributes is a section in the PDS files where some layout characteristics of the pattern pieces in the marker could be determined automatically. This adjustment resulted in improving the marker to reach 84.65% efficiency (see Figure 3.9). In addition, pattern division was experimented on the front skirt piece for size 4. However, this technique did not improve efficiency.

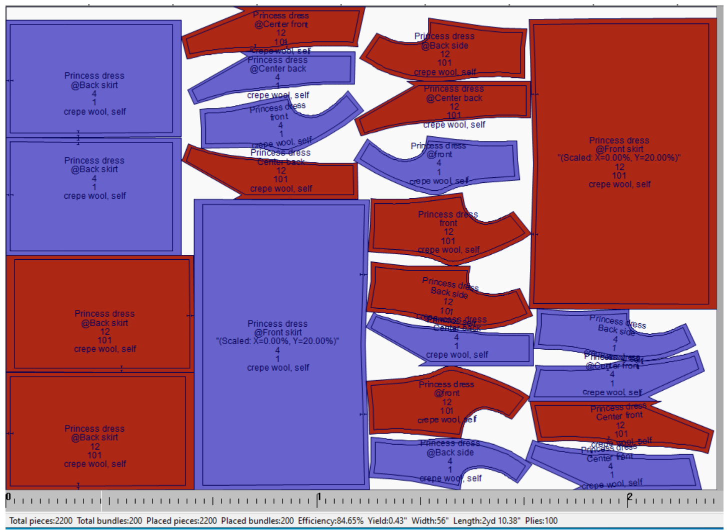


Figure 3.9 Graded marker in phase two with sizes 4 and 12

Manual marker adjustments for fabric utilization. After establishing the digital marker making configuration, the marker pattern file was transferred from Optitex to an Adobe Illustrator file in order to be printed as a PDF format using a wide format plotter. This procedure was important as the Marker in Optitex does not allow for edits to the pattern pieces or negative space. It was also beneficial to work with the negative pieces in actual size, manually, instead of on a computer screen. Thus, marker experimentation continued manually. Figure 3.10 shows a digital version of the manual marker with color coding by size and initial classification of fabric utilization. According to Gray and Malins (2014), "color coding is a simple but helpful strategy for quickly identifying different types/sections of information" (p. 46). Most front and back bodice pattern pieces show the seamline of the original pattern with extended areas, that could be utilized or managed as darts. The yellow color represents the pieces for creating the sleeves. The turquoise color represents the pieces that would be used for neck facings. Whereas the green areas represent hem supportive pieces.

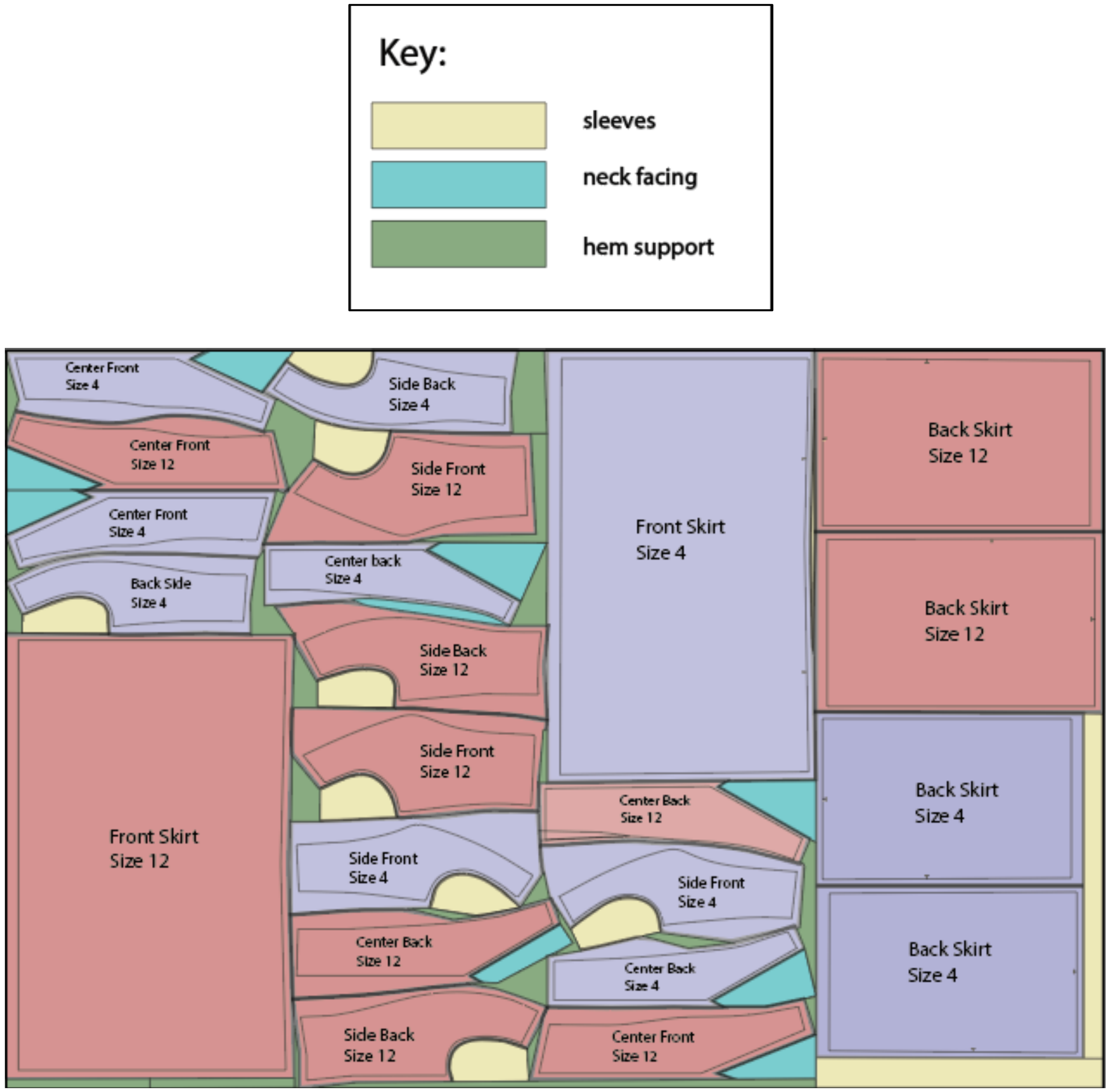
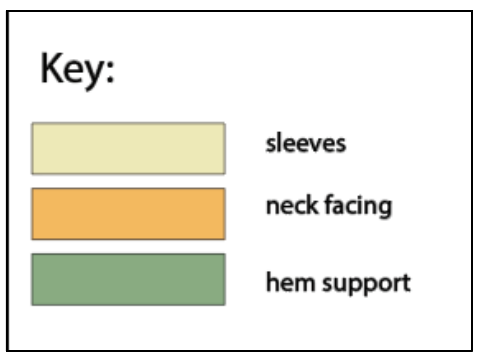


Figure 3.10 First mixed marker for graded sizes (4 and 12) with fabric utilization areas color coded

After determining the negative spaces with color coding, the following techniques were applied for fabric utilization: adjusting visible pattern dimensions, adjusting non-visible pattern dimensions, and creating garment parts. Figure 3.11 is a digital version of the adjustments made manually. Adjusting visible pattern dimensions was the first technique considered in this phase. Size 12 skirt front and back pattern pieces were increased to utilize negative space of the marker (see Figure 3.11). In addition, the size 4 skirt front piece was decreased; this adjustment created additional space for the sleeves (lower yellow areas in Figure 3.11), as the sleeves were generated from the negative spaces. On the other hand, darts were created inside most of the bodice pattern pieces to utilize the negative space between each panel of the bodice as well as the extended areas seen in the prior marker (see Figure 3.10 and 3.11 side and center pieces).

Adjusting non-visible pattern dimensions was another technique to utilize marker negative spaces. This included creating facing for the necklines (see orange areas in Figure 3.11) and support pieces in the hem (see light green areas in Figure 3.11). Creating garment parts was another technique used to utilize fabric. Even though sleeves are considered a fundamental garment part, in this phase, sleeves continued to be explored using the negative spaces that are adjacent to the armholes and using the strips from the fall out as extensions for the sleeves (see yellow areas in Figure 3.11).



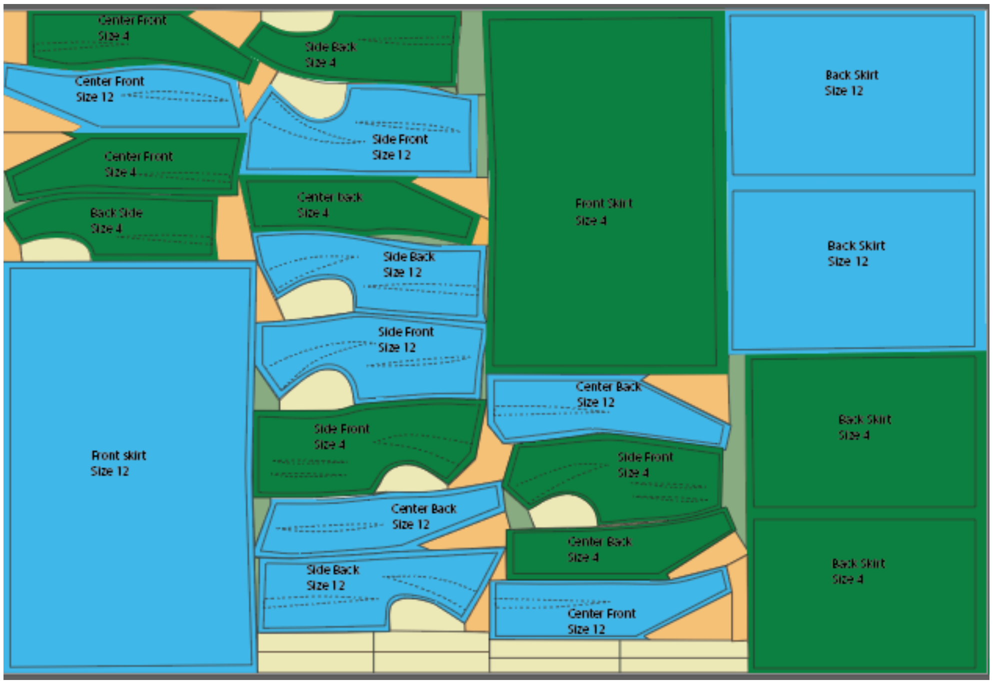
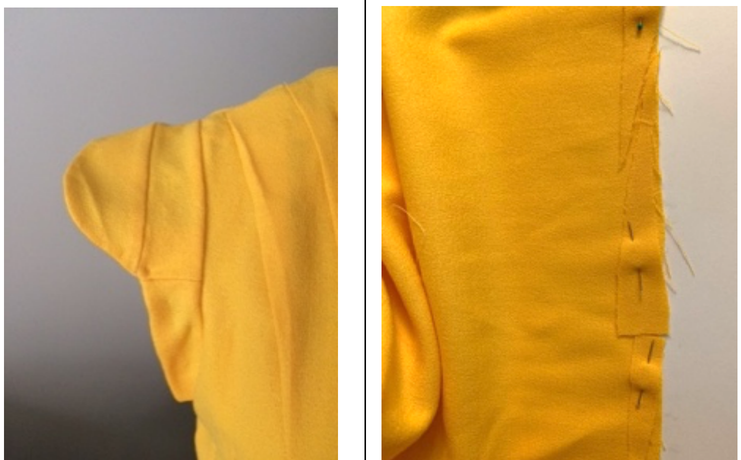


Figure 3.11 Manual marker after pattern pieces modifications

Physical Construction. The researcher cut the marker pattern pieces in yellow wool crepe fabric and constructed the graded physical dresses. In order to make the sleeves in the graded dresses look similar to the sleeves in the control, sleeves were sewn with strip extensions (see Figure 3.12 A); the figure shows the front view of the sleeve for size 4. On the other hand, given that the pieces used for facing did not fit the measurements of the neckline, piecing was utilized to connect some extensions. Lastly, the remaining negative space were distributed around the hem and stitched internally before folding the hem (see Figure 3.12 B); the figure shows the small pieces aligned to the edge of the skirt hem.



A	**B**

Figure 3.12 Sleeve construction detail (A) and fabric utilization in hem (B)

Analysis

The adjustments made during design development, grading, and marker making improved marker efficiency, while the physically constructed control and graded dresses served as forms of data for analyzing visual similarity between the control and graded sizes. The analysis was conducted by the researcher, Dr. Haar, and Dr. Wu, according to the evaluation criteria that would be used by participants during the survey stage to determine visual similarity between the control and graded sizes. The evaluation criteria included silhouette, drape or hang, fit or ease, garment part dimension, internal seamlines, and gathers. See Appendix for the survey.

The silhouette of the graded dresses looked similar to the control. See Figure 3.13 for the control and graded garments. The drape or hang of the hem was imbalanced from using fall out in the hem as support. Regarding the fit and ease, size 4 was more closely shaped to the body compared to the control; however, size 12 had closer shape to the bust and more ease on the waist. When comparing dress part dimensions, the bodice dimensions and the skirt dimensions of the graded looked similar to the control. The sleeves of the graded sizes had obvious differences from the sleeves in the control dresses. Because the sleeves were created from the negative space, the negative space pieces did not provide enough length to create the petal of the sleeves, which influenced the visual accuracy of the dimension, especially for size 12 as the sleeves looked shorter in length compared to the control. Regarding the internal seam lines, an area of concern was difference between the princess seam lines of the control, compared to the visually different darts of the graded samples. In addition, the shoulder seam lines looked proportionally small, as they looked similar to control size shoulders seam lines. In addition, there were differences in the scoop shape at the lower bodice front. Compared to the control, the large size had less curve, whereas the small size had more. While the neckline shape appeared similar, there were differences in how they laid on the form. In terms of gather distribution, size 12 lacked the visual accuracy by being unevenly distributed, as they did not drape evenly on the form due to the changes of bodice fit from adding darts. Overall, the appearance of the phase one ZWD graded dresses did not meet the expectation for visual accuracy when compared to the control (see Figure 3.13).

Figure 3.13 ZWD dresses in the first phase (control size in the middle, large in the left, and small in the right)

Based on the analysis, the dresses were adjusted to address the discussed issues. Regarding the drape of the skirt, the hem depth was increased (where the tiny and thin pieces were stitched within the fold); this improved the hang of the hemline. In terms of the fit and ease, center front and back darts were eliminated for bodice size 4. Also, the amount of dart intake decreased for side back and side front shoulder darts. For bodice size 12, the amount of dart intake was decreased for center front darts and the side front shoulder dart. The side front shoulder dart was also shortened to allow more ease for the bust. These adjustments improved the fit and improved the similarity of bodice dimensions between graded and control. In addition, it improved the internal shoulder seam proportional dimensions for size 12. With the improvement of bodice fit, the reconstruction of neck facings added to the improvement of the appearance and visual accuracy of the necklines with relatively better lay on the dress form. Moreover, the improvement of the bodice fit improved the distribution of the gathers for size 12 and the shaping of the waistline scoop after reconstructing the skirt to the bodice for both graded sizes.

Another meeting with Dr. Haar and Dr. Wu was conducted to review the adjustments of the samples. See Figure 3.14. According to the analysis, even though the overall look was improved, major visual accuracy issues remained. For both graded sizes, eliminating some darts and improving the fit were not sufficient to correct the visual accuracy related to the internal seam lines, as the remaining darts differed from princess seamlines of the control bodice. Besides, it was not feasible to adjust sleeves of the graded sizes to look more similar to the control, as the sleeves were created from the negative spaces. Overall, the appearance of the

ZWD graded dresses did not meet the expectation for visual accuracy to the control. Thus, the process moved to Phase Two to continue improving the visual accuracy between the control and graded samples.

Figure 3.14 Second version of ZWD dresses in the first phase after some adjustments (control size in the middle, large in the left, and small in the right)

Phase Two: Digital and Virtual Testing of Marker

In the previous phase, the first phase of the functional design process, adjustment methods were explored on the marker and physical samples. The final analysis of the first phase provided information regarding the methods that had potential for fabric utilization and the methods that did not, or which needed further exploration. In this second phase of the functional design process, the adjustment methods that were acceptable in the first phase moved to virtual application. On the other hand, for the adjustments that were not successful in the first phase, new adjustment methods were experimented, using 3D simulation as a tool for efficient assessment through the functional design process. Before presenting the marker adjustments for this phase, a description of the 3D simulation procedure used in this phase is presented.

3D Simulation

The 3D simulation module in Optitex was used to compare the visual accuracy of both the fit and appearance of the graded sizes and control size. The construction of the physical dresses informed the potential adjustment techniques to be applied in 3D simulation. 3D simulation of the control dress in size 8 was initially implemented to establish the procedure prior to simulating the graded sizes. In 3D simulation, stitch lines were determined on each 2D pattern piece. Then the drape was automatically simulated on the 3D avatar. The default avatar main measurements in Optitex were adjusted to be compatible to the PGM dress forms used for draping the physical dresses. Not all of the dress form measurements were adjustable in the Optitex avatar.

Utilization of the 3D simulation started at this phase throughout the process of applying additional adjustment techniques to the patterns. This provided visual assessment that helped with refining the pattern adjustments based on software feasibility. In addition, simulation use addressed the possibility of reducing fabric waste by reducing the overall number of physical sample garments.

Marker Making Virtual Testing

The fabric utilization process at this second phase was informed by the analysis of the first phase to improve the visual accuracy between the control and the graded dresses. Fit and ease issues were the main concern from the first phase; thus, this phase started with testing a couple of digital techniques to evaluate the results virtually. Following are the virtual testing procedures to address the inconsistent ease and visual dissimilarity concerns generated by having darts in the graded sizes.

Based upon the results of the first phase, developing the darts as a technique for managing fabric excess in the bodices did not result in similar appearance between the graded sizes and the control. Developing the darts in Optitex was specifically functioned for managing bust shaping; thus, there is a particular shape of the dart. However, the current study required more flexible techniques for shaping the bodice while managing fabric excess. Thus, moving the darts toward the seam lines, as folds, was proposed. Folds differs from the darts in Optitex as fold lines need to be drafted, whereas there is a specific function for adding the darts to the pattern by locating two points on the edge of the pattern that extend as one tip point to a specific location inside the pattern. Selecting "add dart" in Optitex would automatically make the dart fabric intake show internally (it was seen not on the outside of the dress) when stitched and simulated on the avatar.

The researcher aimed to experiment with folds in Optitex; however, the fold function in Optitex controls the fold of the fabric, to be directed in or out, only if the fold was located in the edge of the garment, such as the fold of the collar; which was not the case with the fold in the current ZWD dress. Thus, the researcher tried to resolve this issue by stitching the two lines of the fold. However, the software considered the fold as a style technique and did not allow for directing the fabric intake internally, because only seam allowances could be stitched internally (see Figure 3.15). In other words, the fold was seen on the outside of the dress.

As the fold technique did not work, fish-eye darts, which are diamond shaped darts with two points, were experimented with near the seam allowance. Even though they looked acceptable, they required cutting the internal part of the dart, and thus would need managing of the fall out. In addition, the use of fish-eye darts did not allow the researcher to utilize the desired uneven area of the negative space in the dart (see Figure 3.16).

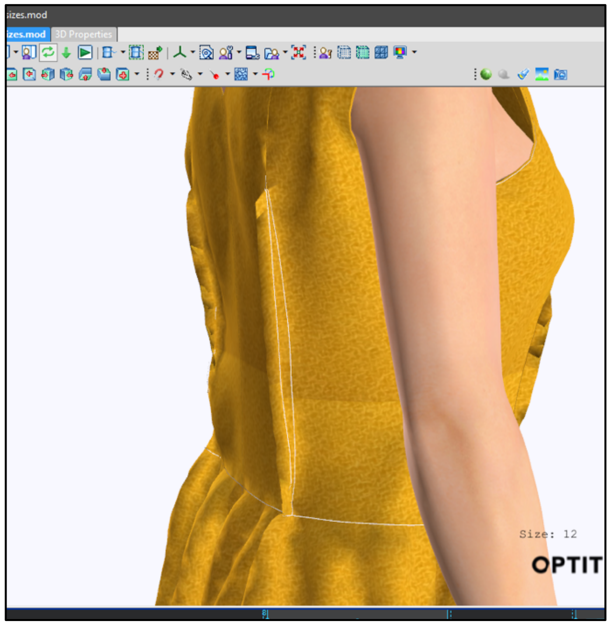


Figure 3.15 Stitching a fold in Optitex 3D showing the result as an external fold.

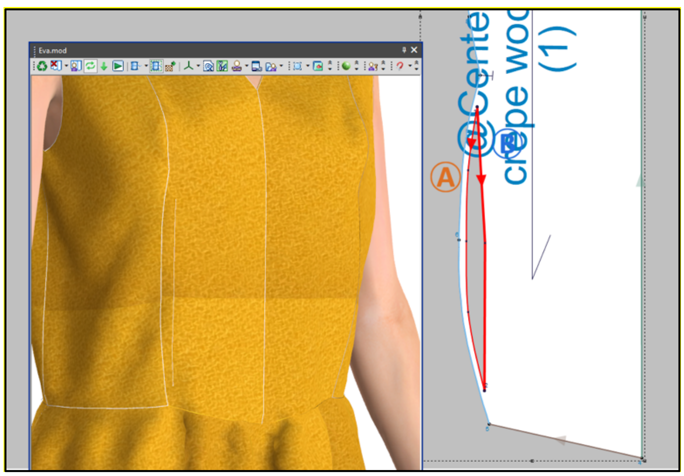


Figure 3.16 Stitching a fish-eye dart in Optitex 3D with the creation of an internal cutout (red outlines)

Analysis

A meeting with Dr. Haar and Dr. Wu was conducted to report the issues with the 3D simulation regarding managing negative spaces related to the bodice. It was recommended to utilize the negative space around the bodice pieces as wide seam allowances, even though this option had been avoided in phase one as having potential impact on seam shaping. However, the software did not consider the internal lines (the line around the original pattern piece) as seam lines, and thus did not allow the wide seam allowance to be kept internally. In other words, the seam allowances appeared on the outside of the 3D dress. The resolution was to separate the extra width from bodice seamline and stitching the negative space as a separate piece to the bodice. The process moved forward starting with making a new mixed marker after including the graded sleeves.

Grading

In this second phase, grading was applied to sleeves. Sleeves in the first phase were developed out of the negative spaces of the marker; however, in this phase, the sleeve widths were graded while keeping the length of each sleeve piece. Sleeves were graded during this phase in order to improve the similarity of sleeve dimensions across sizes. Thus, a new mixed marker was developed to include the sleeves using the same grading attributes as the final version of the marker in phase one. The marker included two adjustment techniques to increase the efficiency. First, 10 degrees tilting was applied to the marker. In addition, rotating the sleeve pieces was applied.

Marker Making Digital Procedures

The marker file for this phase was saved as a pdf format (from the print setting) of the Marker module; then it was opened in Adobe Illustrator to trace the negative spaces. In order to apply marker adjustments digitally and to evaluate the outcomes virtually, the negative spaces were traced digitally using the pen tool in Adobe Illustrator and color-coded. See Figure 3.17.

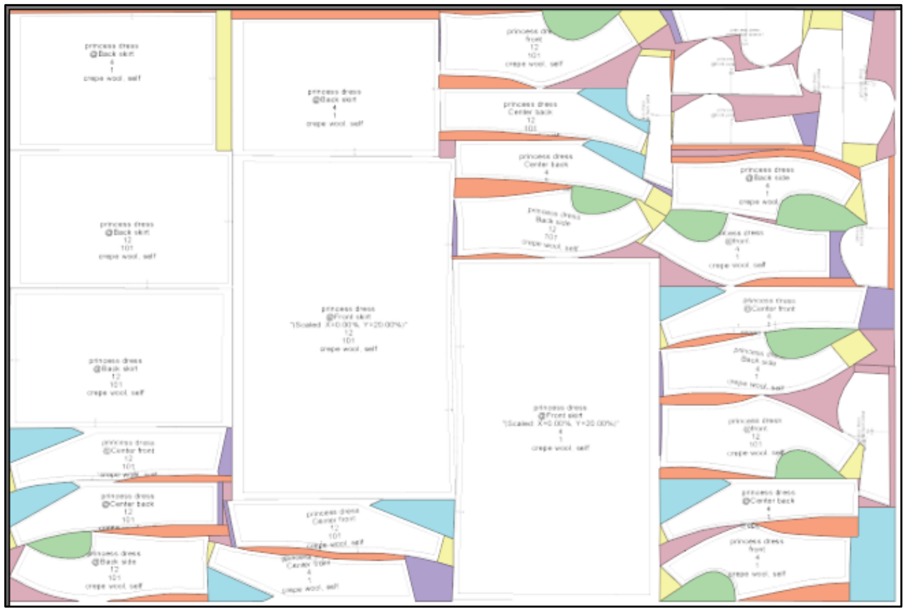


Figure 3.17 First digital color-coded marker, with the sleeves, for phase two

The marker was transferred to the PDS module file (2D pattern design system) (see Figure 3.18); the gray pieces are the negative spaces that were color-coded in Figure 3.17. Then, the negative spaces were distributed to each dress size in a separate PDS file in order to be stitched in a particular area of the dress, whether as a neckline facing or seam allowance, etc. (see gray areas within the blue outlines in Figure 3.18).

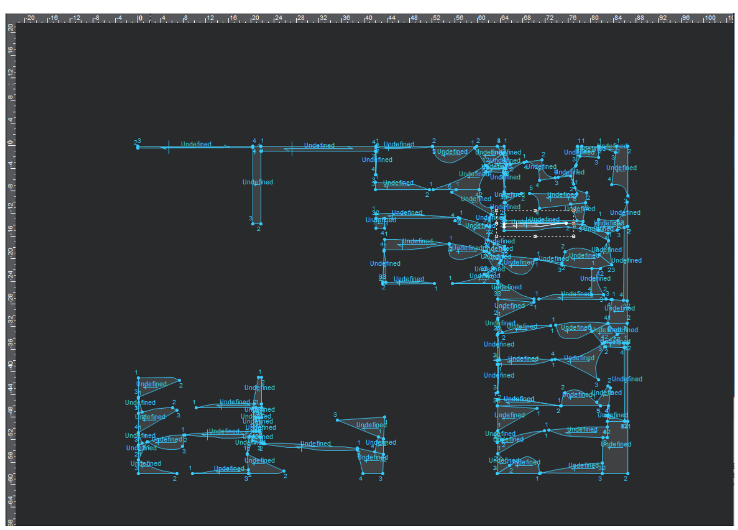


Figure 3.18 Negative spaces (gray areas) of the marker in PDS module of Optitex.

The first step of utilizing the fall out was virtually stitching the negative spaces beyond the bodice seam lines to the bodice so the 3D appearance would imitate the typical physical construction (see long white separate strips in Figure 3.19). This was a complex process in Optitex. Even though the separate pieces (negative space) were stitched to the bodice internally, they did not stay internal, but rather, they once again tended to appear externally (see Figure 3.20). To solve this problem, the researcher experimented with layer order and different stitching locations of the separate pieces with bodice parts in order to keep the internal pieces in place. Stitching the separate seam allowance to the bodice worked better on the vertical lines, such as princess lines under the bust level, compared to the horizontal lines such as the shoulders and waistline. The narrow width of the shoulder, compared to the princess style line on the bodice, also made stitching the seam allowance difficult to manage; thus, some pieces were eliminated from the simulation.

Moreover, the software applied the stitching and adding points mainly to the control size, as the graded sizes were dependent to the control. This negatively influenced the accuracy of stitching the fall out pieces, as they were not graded. For example, the fall out pieces that were stitched to size 12, were too small as they were from the control grade. Thus, trimming was used with some pieces.

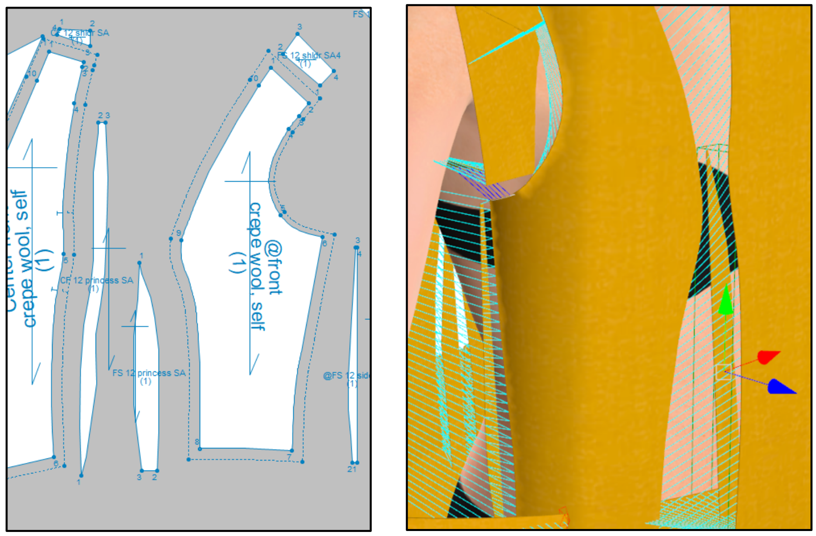


Figure 3.19 Excess width managed as separate seam allowance strips in the bodice

Figure 3.20 Separate seam allowance shows externally at the shoulder

This process of stitching the seam allowance to the bodice took the longest time through the experimental procedure but was not successful for all the parts. Thus, not all the separate seam allowances were included in the virtual simulation; trimming and removal of some pieces were applied, especially in the shoulders.

Another step of 3D simulation was attaching the sleeves to the armhole. Overlapping the petal sleeves was considered as a practical approach for manipulating the size of the sleeves by moving the two parts of the petals until they fit the armhole. However, this overlapping was not feasible in the software, even with the use of the layering functions. So, division of the sleeves was the solution to achieve the desired look of the overlapping (see Figure 3.21). This made the stitching and positioning of the sleeves more complex, which also influenced the accurate set of the shoulder on the avatar as the sleeves tended to slip down (see Figure 3.22). The solution for this issue was to reposition the bodice pattern pieces closer the center, even though this improved the set of the shoulders, the appearance was still not perfectly accurate.

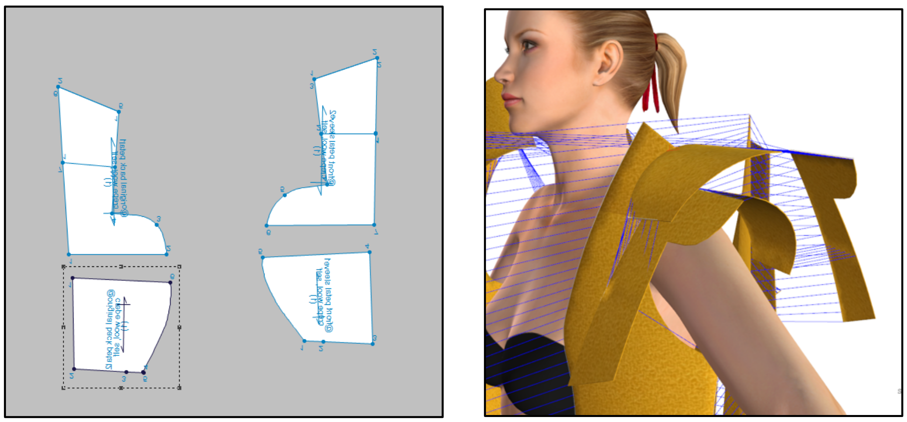


Figure 3.21 Divided sleeve in 2D pattern and in 3D simulation

Figure 3. 22 shoulders inaccurate simulation due to complex structure

On the other hand, similar strategies used in phase one included the use of some negative space for neck facings and change of pattern piece dimensions for the skirt. Similar to the first phase was the fabric utilization for the neck facing including the use of extensions for the neck facing around the front and back neck lines. A similar issue of seam allowance showing externally, was the case with most of the neckline facings (see Figure 3.23), even with arranging the order of layering the pieces for simulation. One solution was to add stitches to attach the facings from different locations; however, parts of the facings tended to show externally, which led to removal of a few facing pieces as well.

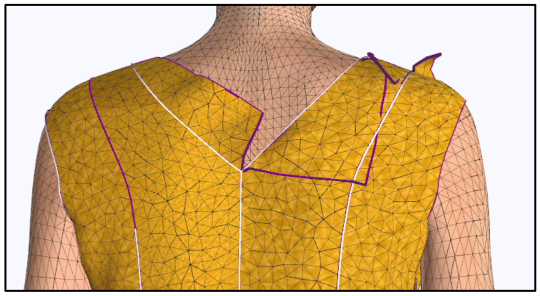


Figure 3.23 neck facing simulation issue of showing externally

Adjusting the dimensions of pattern pieces in this phase was similar to the first phase. The front skirt for size 12 was increased to utilize fabric; this technique was lastly considered after cutting the marker which slightly shifted the pattern pieces around (see the upper left pattern pieces in Figure 3.17 compared to Figure 3.25). Figure 3.25 shows the utilization of the negative space (removal of a yellow and orange negative space from Figure 3.17), but due to time limitation, adjusting the entire marker was not possible; thus, a proposed marker with colored areas after making this adjustment was documented (see Figure 3.25). Using the gather technique to manage fabric width for size 12 increased the similarity to the control in terms of the amount of gathering in the front skirt. The gathering technique in the virtual phase two was modified to improve the distribution of gathers for more similarity across sizes. This was applied by increasing the resolution of the simulation that made the folds of the gather look finer and deeper. However, the increased 3D gather simulation caused the Optitex file to crash, thus the maximum resolution was not applied (see Figure 3.24). Instead a partial resolution increase was applied which improved the gather appearance but did not have the most realistic appearance.

Figure 3.24 gathers before and after smoothing compared to the physical version

Figure 3.25 Second color-coded marker in phase two

At this point, most of the negative space areas were utilized; however, it was challenging to incorporate the remaining small pieces. For example, the software was not able to experiment with folding and joining the folded small pieces to develop a pocket. Thus, the researcher returned to experimenting with the feasibility of the fabric utilization techniques on the physical fabric. The third color-coded marker for this phase was developed before finalizing the modifications of the pattern pieces (see Figure 3.26). Figure 3.27 is the Optitex marker after removing two negative pieces from the upper left side of the marker. The final marker with modified pattern pieces ready for printing is seen in Figure 3.28.

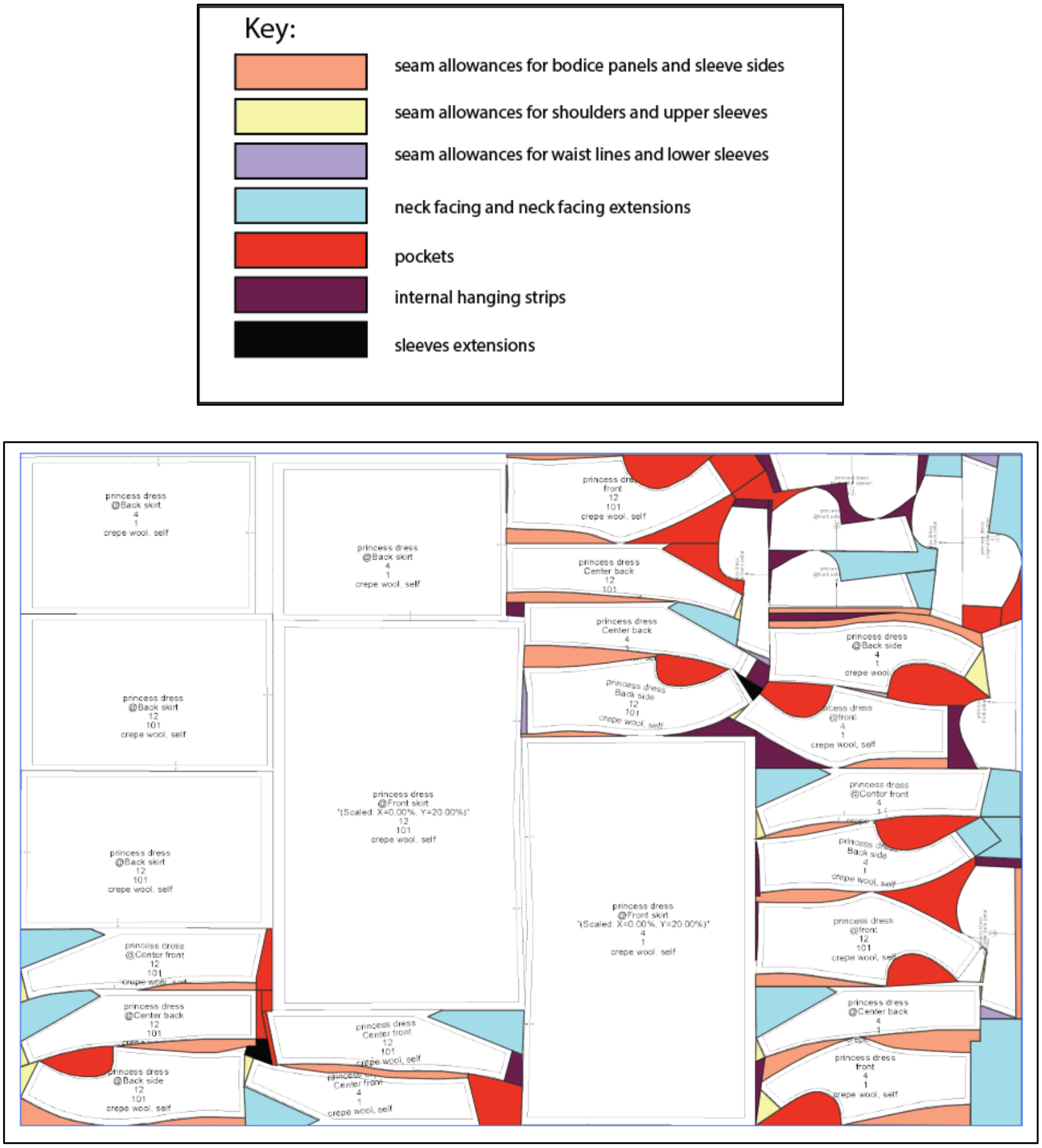


Figure 3.26 Third color-coded marker for phase two

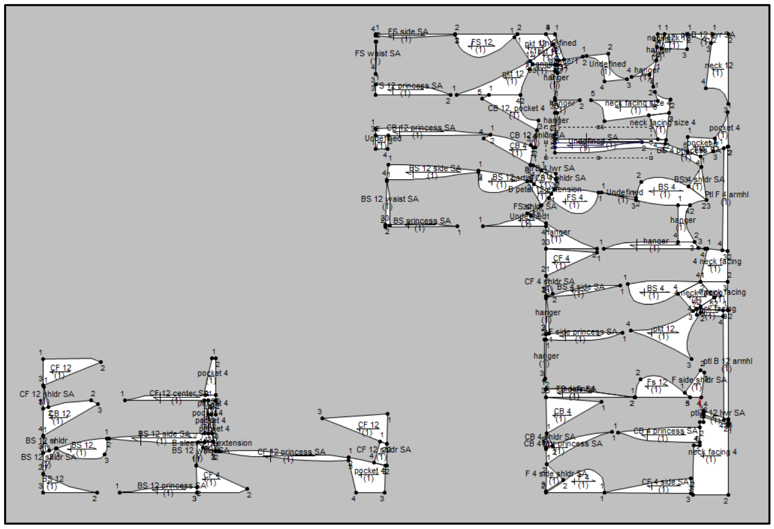


Figure 3.27 Labeled negative space in PDS for the third and final marker for phase two

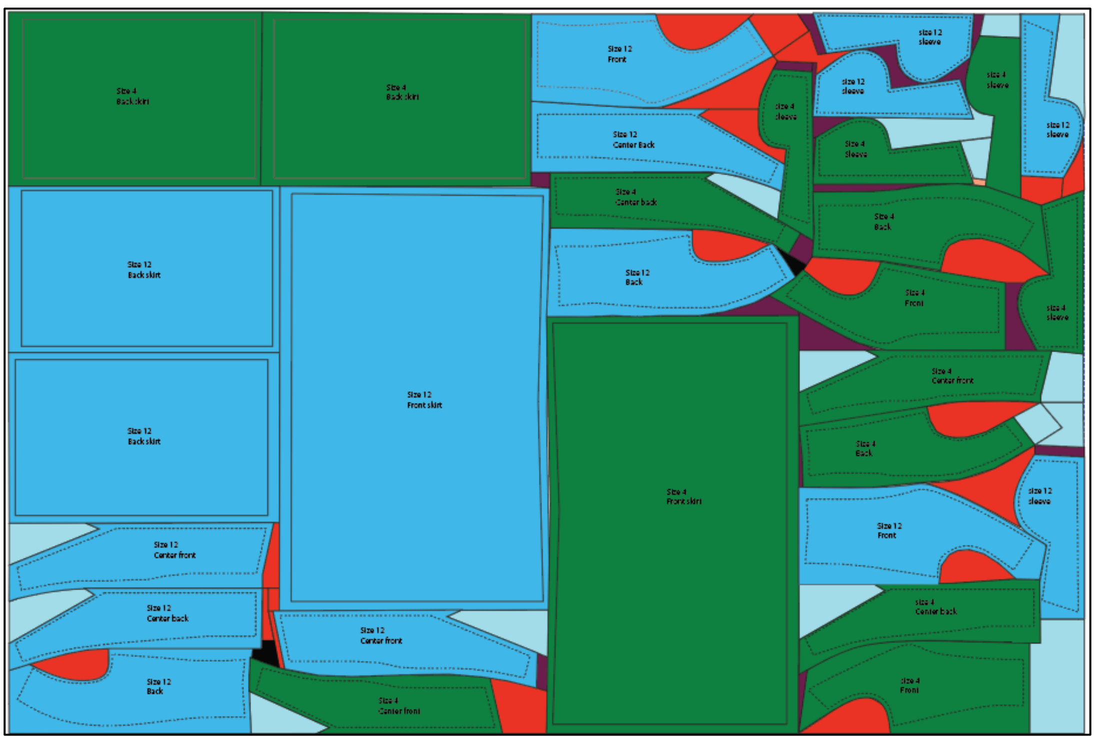


Figure 3.28 Final marker after pattern modification

Physical Construction

The next step was to physically construct the garments following the modifications made in Optitex. The outcomes of the physical construction guided the utilization of the remaining fall out for the virtual simulation. The printed marker (figure 3.25) was laid out on the fabric and cut; each size bundled with its cuts off. The physical construction process was more straightforward and less time consuming for the researcher than the virtual stitching. This was especially true for stitching the bodice parts. However, overlapping between wide seam allowances of the princess style lines (after the inclusion of the negative space to the seam allowance) and the wide shoulder seam allowance needed consideration to avoid bulkiness. On the other hand, seam allowances in the dresses were finished (via overlock machine with no cutting) separately to maintain zero waste. The separate finishing included shoulder seamlines, bodice pieces seam, and skirt bodice joining seam lines for both graded sizes. An example of the separate seam allowance finishing that occurred in the waistline of a graded dress is shown in Figure 3.29.

Figure 3.29 Separate overlock finishing of seam allowances of the bodice and skirt

Since the sleeves were graded on the width dimension only, overlapping was the technique applied to control the construction of the two petals portions of the sleeve, so they fit with the armhole measurements for the graded sizes. This process was also straightforward in the physical construction compared to 3D simulation. An additional extension (see two black areas in Figure 3.25) was needed for the sleeve strip for size 12 due to the relatively large armhole measurement compared to the control and small size (see Figure 3.27).

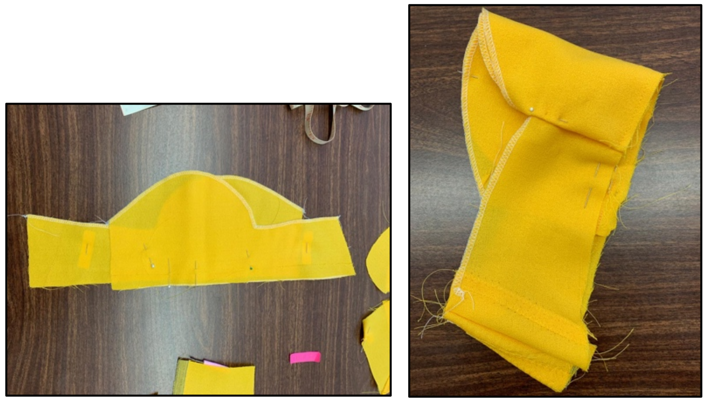


Figure 3.30 Sleeve size 12 with extension to the lower edge

The first phase analysis informed that the drape of the dresses was influenced by the small pieces stitched in along the hem internally; this technique was avoided in this phase. Instead, the small pieces were joined (i.e., stitched) to create larger areas. Thus, allowing for the exploration of new garment parts, such as pockets.

The remaining fall out underwent experimentation for use functionally inside the garment as pockets and hanger loops. One internal pocket for each graded size was developed by piecing fall out in the shape of a pocket pattern. See Figure 3.28. The fall out were stitched using the zigzag stitch. There was only enough fall out for one pocket per graded garment.

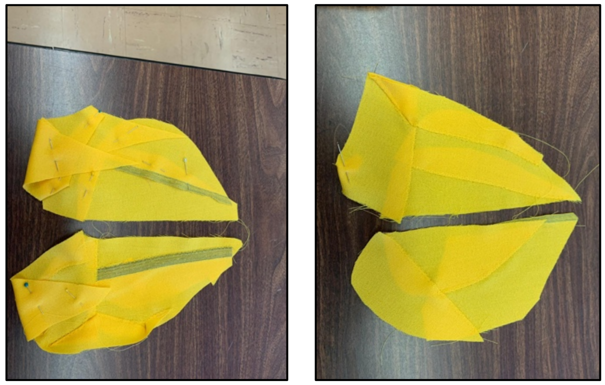


Figure 3.31 Fall out stitched to create pocket pieces

The remaining small pieces were joined through stitching and utilized functionally as hanger loops (see Figure 3.29). Hanger loops are used to distribute and support the weight of a garment by looping around the hanger. Loops are typically attached at the underarm or waistline. Not being fundamental parts of the garment, the dress hangers were not included in the 3D simulation. In addition, the software would not have easily 'understood' the joining process.

Figure 3.32 Dress hangers constructed out of the remaining fall out pieces

Finalizing 3D Simulation

After the waste resolutions were determined in the physical garments, the changes were applied in Optitex except for the hanger loops as noted. The process of creating the pockets was feasible with no challenges in physical construction, but it was not possible in the 3D simulation following the same piecing technique. Maintaining the same pattern pieces made the pockets show externally and influenced the drape with obvious bulkiness. In addition, stitching the small pieces internally was not feasible in the software. Thus, the researcher divided the pocket pieces (that were folded in the physical version) and merged the pieces in the PDS file. See Figure 3.30. This increased the size of the pockets and resulted in awkward and asymmetric shapes of the pockets. Thus, the researcher trimmed the pattern pieces until they aligned and were not showing externally, and to mimic the shape of the physical pockets in this study, as much as the virtual simulation feasibility allowed (see Figure 3.30).

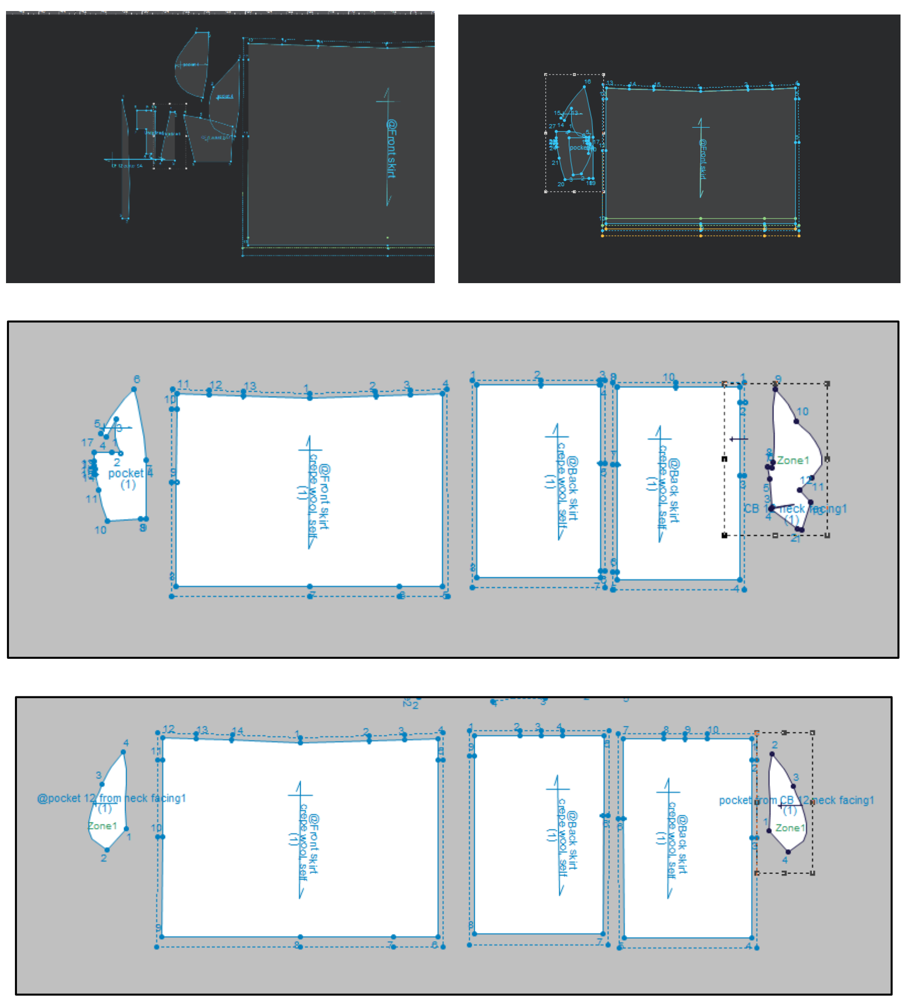


Figure 3.33 Digital pocket development

Analysis

In order to respond to the recommendation from the analysis of the first phase, the adjustments at this phase started with grading the sleeves. Then, a marker was developed to test new fabric utilization techniques for improving the efficiency while maintaining the virtual accuracy between the control and the graded. The 3D simulation of the control and the graded dresses served as forms of data to inform the researcher about the visual similarity between the control and graded sizes. Similar to the first phase, there were regular meetings for the analysis regarding the 3D simulation followed by the analysis for the constructed dresses; these meetings were conducted by the researcher, Dr. Haar, and Dr. Wu, with the consideration of the assessment criteria included in the survey.

Regarding the visual accuracy of the silhouette or overall shape, it was acceptable for the constructed dresses; however, due to the software deficiency for simulating the skirt smoothly and an appropriate distance from the avatar, in virtual graded size 4, the silhouette was not very similar between sizes of virtual dresses. Also, the dress slipped down the shoulder slightly which influenced the overall silhouette when comparing the virtual to the constructed.

In terms of the drape of the dresses, which was related to the falls and folds of dresses on the forms, the visual accuracy of the constructed dress drape was acceptable. However, as mentioned earlier, the drape of the virtual dresses was not as comparable, due to the tendency of the fabric to drape closer to the body that might be caused by the internal layers of the pocket located at the upper side seam of the skirt.

A noticeable improvement of the constructed dresses was the fit and ease of the bodice; the increased amount of the seam allowance to occupy the negative space allowed for better fit and accurate amounts of ease. However, noticeable fit issues appeared in the virtual dresses, even after the removal of some fall out pieces. The virtual fit issues were also caused by the difference in avatar measurements compared to the corresponding dress form.

The improvement of the dimensions of the garment parts was noticeable in the constructed dress parts, especially in the sleeves, compared to the first phase. The sleeves in this phase were graded, thus they had proportionally more appropriate dimensions. The overall visual accuracy of the dimensions of the virtual garment parts was acceptable.

The improvement of the visual accuracy and similarity of the internal seam lines in the constructed dresses was also noticeable, due to applying wider seam allowances instead of folds or darts for managing negative spaces around the bodice pieces. On the other hand, some internal seam lines appeared inaccurate in the virtual dresses, due to the avatar measurements issue.

The distribution of gathers was acceptable in the constructed dresses; the difference in gathers between front and back, as the front included more gathers, of size 12 was acceptable. However, the gathers in the virtual dresses were not acceptable, but were kept due to the software capacity and management of file size for simulating the gathers.

Even though there were some fit issues in the virtual dresses, the researchers accepted the overall look of the dresses based on the software capacity for handling ZWD strategies and the inability to create the exact avatar size. However, adjustments to the avatar and refining stitching and simulating virtual internal pattern pieces continued in order to improve the accuracy and appearance of the virtual dresses. Some issues were feasible to solve, such as the tendency for the shoulders to drop off the avatar. This was resolved by repositioning the pieces closer to the avatar.

After finishing the construction of the physical dresses for this phase, taking photos of the physical dresses and details, and screenshots of the digital work were captured to document the results of the applied techniques, including challenging techniques and different adopted techniques. Constructed garments were placed on the correspondingly sized dress form and filmed in anticipation for the survey stage. The Clt. files (the digital files that display the 3D cloth with or without an avatar), of the 3D simulation were screen taped to view similarly to the videos of the physically constructed dresses (see Figure 3.32). Videos and 3D screen taping then underwent analysis by three of the design faculty at the department of Interior Design and Fashion Studies. The analysis is discussed in Phase Three, Marker Refinement.

Figure 3.34 Physical and virtual dress results of phase two

Phase Three: Marker Refinement

Three faculty members provided feedback regarding the constructed and virtual dresses included in the pilot survey. Overall, the physical dresses were acceptable, which fits with the analysis by the researchers in the second phase. However, there were some comments regarding the virtual dresses. The feedback indicated that there were some issues with the avatars that impacted the fit of the dresses especially in size 12. As seen in Figure 3.32 there are folds at neckline and upper bust. In addition, the shoulder drop for the avatars was high, and the torso for size 12 was proportionally short. These issues influenced the comparability between the virtual and the constructed dresses as noted by one of the pilot reviewers. As noted before, this problem was due to the avatar measurement system in Optitex; it did not allow for precise compatible measurements to the physical dress forms. However, adjustments continued by lifting the bust height to both size 4 and 12. In addition, adjustments on the bodice patterns were applied specifically for the size 12 bodice to fit the avatar. Moreover, shoulder slopes were lowered for size 4 and 12. However, refining the measurements to exactly reflect the actual physical form was not feasible. With the changes to the dresses to improve the fit, minor marker adjustments would be applied to the marker after the refinement of the patterns. But due to time limitations, redoing the marker was not implemented immediately. The refined virtual dresses were re-uploaded in videos to be embedded in the Qualtrics survey (see Figure 3.33).

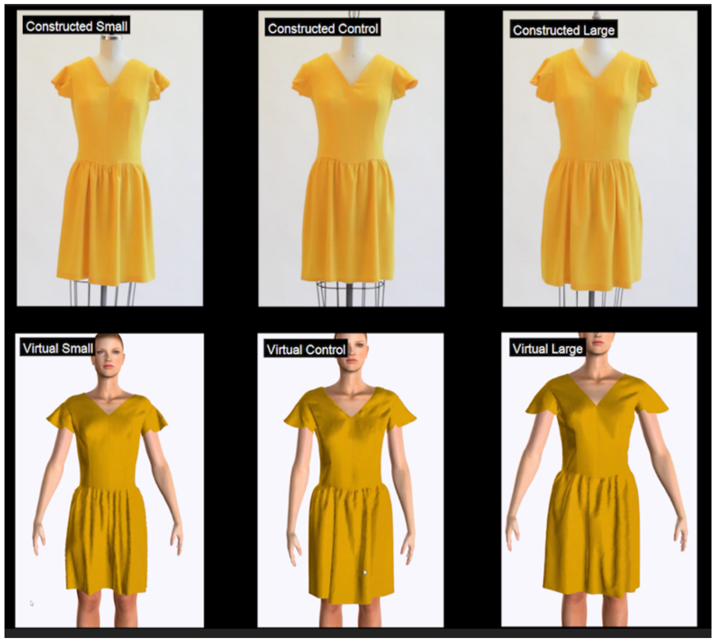


Figure 3.35 Final physical and virtual dresses

Stage Two: Survey and Data Analysis Methods

Experimental Design

In addition to the experimental practice in the first stage, the experimental research design was used to identify the nature of the investigation in stage two. Spector (1981) defined experimental research as a design that includes one or more independent (experimental) variables manipulated by the researcher in a specific set of experiments. In this research design, the independent variables, the physical control and at times the virtual control, were observed to evaluate the effect after making a change or manipulation of the pattern pieces of the graded garments. These changed variables in size (smaller and larger from the control size) and patterns (physical and virtual) are called dependent variables. Kumar (2014) described experimental research as a design that involves the researcher making or creating a "cause" in the independent variable and then evaluating the effect on the outcome. Regardless of the number of independent variables, both definitions emphasized the significance of the inclusion of manipulation on the independent variable and the measure of the change or effect after making the cause. This manipulation was applied to the size of the control in the grading process, and to the graded pattern pieces of the through pattern adjustments. Thus, the experimental design approach was the most appropriate research design for this study to evaluate specific criteria related to the visual accuracy of the virtual and physical dresses after making changes to zero-waste graded sizes compared to the control size.

Experiential design researchers adopt various approaches to evaluate the results of their studies. Researchers use multiple tools, including questionnaires, photos and drawings for assessing the independent variable in experimental research, to measure the efficiency of the effect of the treatments or changes applied to the independent experimental group. In this study, an online survey was used as the tool to collect both quantitative and qualitative data regarding the assessment of multiple comparison sets across the control dresses and graded dresses.

Mixed Methods Approach

Experimental design studies, which are described by Given (2008) as the "systematic empirical investigation of observable phenomena via statistical techniques," usually include a quantitative approach as empirical methods of investigation. Lee & Park (2017) evaluated the suitability of 3D virtual fit simulation as an assessment tool utilizing quantitative methods. The quantitative results were considered as empirical statistics that contributed to the improvement of increased industry adoption of virtual simulation. Due to the technical nature of this study, which may lead to developments in industry practice, a quantitative approach was the primary method in this stage.

However, this stage of data collection included both quantitative and qualitative approaches. The quantitative approach using the Likert scale (Kumar, 2014) refers to numeric data that are collected through a scale of specific values and stands for a rate or level of agreement when the participants are requested to select one option to rate their assessment of something. In this study, respondents selected one assessment rating and then were asked to provide written comments to clarify their Likert scale ratings. The use of mixed methods is common when using "attitudinal scales" (Kumar, 2014), as the textual data would provide a diversity of the attitudes rather than just representing the intensity of the opinions. Bye, LaBat, McKinney, and Eun Kim (2007) evaluated current apparel industry grading practices using mixed methods for data collection. To assess fit, Bye et al. (2007) compared between traditionally-graded patterns and fit-to-shape patterns on participants using the total number of pattern adjustments as quantitative data; on the other hand, the analysis of the visual assessment of the garments in the 3D scan was considered as qualitative data. In this study, the actual assessment was received through the quantitative Likert scale approach, whereas qualitative comments were provided for clarification of the assessment. Thus, the use of mixed methods was the ideal approach for this study to answer the second and third research questions.

Question two: Can digital 3D simulation be used as an effective and sustainable sizing and fit assessment tool? Specifically,

a. what is the visual accuracy between the physically constructed control garment and the virtual control garment?

b. what is the visual accuracy between the physically constructed control garment and the two graded physically constructed garments?

c. what is the visual accuracy between the virtual control garment and the two graded virtual garments?

d. what is the visual accuracy between the two graded physically constructed garments and their corresponding virtual simulation?

Question three: Does attachment and appreciation of ZWD influence expert judges' evaluation of visual accuracy? Specifically,

a. Are evaluations by ZWD designers similar or different from technical designers regarding the visual accuracy between the control garment and the sized garments for both constructed and virtual garments?

Sampling Method

The participants for this study included two groups: zero-waste design judges and technical design judges. Two sampling methods were used for recruiting the two groups: the purposive method and the snowballing method. In the purposive sampling method, the participants are chosen based on characteristics in a non-random way (Kumar, 2014). On the other hand, the snowball sampling method is the process of selecting individuals who recommend other individuals to participate in the study (Kumar, 2014). The purposive sampling method was used to select zero waste experts who are key knowledge builders and academics in ZWD. In addition, the purposive sampling method was efficient in recruiting technical designers who work in the apparel and textile industry in various apparel companies. The snowball method, on the other hand, was best used for recruiting more judges in this study because it is useful when the researcher intends to communicate with few individuals who are not personally known members of the research team (Kumar, 2014).

Survey Instrument

The purpose of using the survey was to answer the second and third research questions in this study. The second question related to the efficiency of digital 3D simulation as an effective and sustainable sizing and fit assessment tool. This included the comparison of the visual accuracy between the physically constructed control garment and the virtual control garment, the physically constructed control garment and the two graded physically constructed garments, the virtual control garment and the two graded virtual garments, and the two graded physically constructed garments and their corresponding virtual simulation.

The third research question was related to the "attachment and appreciation" perceptions in sustainable fashion. These perceptions are involved in the sustainable fashion design model underpinned by this study. Thus, the survey was utilized to find the answer, whether attachment and appreciation of ZWD influenced expert judges' evaluation of visual accuracy between ZW designers and technical designers.

Surveys are one of the most critical measurement tools in experimental and quantitative research (Kumar, 2014). Even though the use of the questionnaire does not provide the researcher with an opportunity to clarify participants' responses, it does offer participants more anonymity (Kumar, 2014). Therefore, the participants had an opportunity to answer the questions with no situational influence, providing the study with an increase in the accuracy of collected information. Moreover, the questionnaire included spaces for qualitative comments that allowed judges to emphasize and/or elaborate on their individual ratings, which provides more reliable data since the judges were not limited to numerical ratings.

The online survey was developed using Qualtrics Survey Software (Provo, UT). The survey link was included in an invitation email letter that also served as the consent form to complete the survey (see Appendix 1). The survey was comprised of two parts. The first part included demographic information regarding the participants' education, employment, duration of occupation, and experience with ZWD and digital grading and 3D simulation systems. The second part included statements referring to the evaluation of five comparison sets (see Table 3.2), which were viewed as videos of the physically constructed and virtual dresses. Appendix 3 includes a link to access the survey so the committee members can also see the videos and Qualtrics format. In addition, the appendix includes the survey questions outside of the Qualtrics format.

Judges completed the second part of the questionnaire using a five-point Likert scale with options from strongly disagree to strongly agree. Space for qualitative comments was provided after each comparison set for participants to explain their evaluation. Utilizing the comments as qualitative data allowed the participants to emphasize their rating with substantiating commentary.

Each comparison set included videos to view the dresses while rotating 360° simultaneously in order to compare the dresses from all sides. The videos were labeled with "control" for the base size 8 and "large" or "small" for the graded sizes for both constructed and virtual models. By incorporating the video feature in the questionnaire, the results were more reliable since 2D photos would not allow the judges to see the garments in three-dimensions from all sides.

Table 3.2

Questionnaire Comparison Sets of the Physical and Virtual ZWD Control and Graded Dresses

Comparison Category	Sets	Comparison Elements		
1. Control dresses	1	Control virtual	Control physical	
2. Physical dresses	1	Control physical	Graded physical size 4	
	2	Control physical	Graded physical size 12	
3. Virtual dresses	1	Control virtual	Graded virtual size 4	
	2	Control virtual	Graded virtual size 12	
4. Graded dresses	1	Graded physical size 4	Graded virtual size 4	
	2	Graded physical size 12	Graded physical size 12	
5. Overall virtual vs. physical	1	Physical size 4	Physical control	Physical size 12
	2	Virtual size 4	Virtual control	Virtual size 12

Data Collection Pilot

After completing the functional design process and receiving IRB approval for the survey of human subjects, the survey was pilot tested by three faculty members from the Department of Interior Design and Fashion Studies at Kansas State University. The data collection pilot was implemented before performing final data collection in order to meet the research objectives with a maximum potential of reliability and validity of outcomes. The aim of the pilot was to assess the clarity and wording of the questions and the quality of the videos before collecting the actual data using the proposed methods in this chapter to evaluate the feasibility, time, and potential pitfalls regarding conducting the actual experiment. Upon the feedback from the pilot, refinements were implemented in the questionnaire. These refinements included improvements in video labeling, adjusting some of the avatar measurements (as discussed in Phase Three: Marker Refinement of Stage One) in order to improve virtual fit and visual clarity of the 3D simulated dresses.

Data Analysis

The data analysis process in the survey stage was composed of two parts. The first part utilized statistical analysis, using the Statistical Package of Social Sciences (SPSS) (see Table 3.3), to analyze the data from the online survey completed by the judges. The values resulting from the participants' rating of the graded Jigsaw designs were analyzed using descriptive statistics. Descriptive statistics is a quantitative analysis method that describes features (means) of the collected numerical data (Geoffrey & Wickens, 1991). Dispersion is a measure in descriptive statistics that was utilized to provide more descriptive details relevant to the resulting data, using the minimum and maximum rating values in relation to the mean. This analysis informed the study with outcomes regarding each criterion in the survey related to the visual similarity of the ZWD graded dresses compared to the control.

Table 3.3

Independent and Dependent Variables in the Questionnaire

Research Question	Comparison Set	Independent Variables	Manipulated Variables	Dependent Variable Manipulation
2	1	Physical control	Virtual control	3D simulation to assess appearance and fit
2	2	Physical control	Physical graded	Adjustment methods to grade ZWD
2	3	Virtual control	Virtual graded	Adjustment methods to grade ZWD 3D simulation to assess appearance and fit

2	4	Graded physical	Graded virtual	3D simulation to assess appearance and fit
3	5	Physical control and graded	Virtual control and graded	Adjustment methods to grade ZWD 3D simulation to assess appearance and fit

The other part of analysis included the content analysis (Julien, 2008). This method was used for analyzing data from the judges' written comments. The responses to the open-ended questions, at the end of each comparison set, included deeper and comprehensive assessment and/or suggestions related to the overall assessment of the presented samples. These responses contributed to answering the second and third questions of the study. The analysis also represented the difference between the ZWD judges and the technical design judges towards grading ZWD. The interpreting of data was organized based upon the criteria order in the survey.

The comment spaces were available to the judges in the first and second parts following demographic information and the comparison sets. A comment space was below the demographic data to clarify or add any information. Also, a comment space was below the Likert scale statements for the first comparison set between the constructed control and the virtual control. For the second, third and fourth comparison sets, there were comment spaces below the Likert scale statements for each pair of the comparison sets. Thus, for the second comparison set, there was a comment space below the comparison between the constructed control and size small and another comment space between the constructed control and constructed large. For the third comparison set, there was a comment space below the comparison between virtual control and virtual small and another comment space below the virtual control and virtual large. In terms of the fourth comparison set, there was a comment space below the comparison between constructed large and virtual large and another comment space below the comparison between the constructed small and virtual small. Moreover, there was a comment space below the Likert scale statement for the final or fifth comparison set between the two groups of physical and virtual samples. Finally, there was one comment area at the end of the survey for any final comments.

Qualitative data have been utilized by researchers in quantitative surveys in different approaches using the text form. On the other hand, multiple analysis approaches have been utilized for this type of data; content analysis is the most common approach for comment and open-ended qualitative responses in surveys (Julien, 2008). Contextualizing quantitative data is significant in surveys as it ensures more depth to the numeric data by providing details, opinions, or personal experiences. The content analysis method was utilized to analyze qualitative comments and responses in this study by coding the responses based on the pre-determined evaluation criteria to clarify the selected rating. For example, grouping comments related to the fit of the dresses, whereas another group of responses were related to the visual fabric accuracy between virtual and constructed dresses. For the last question, the responses were categorized based on the judges' profession. See Appendix for categorized comments. Then, similarities and differences between the responses were noted to support or clarify the ratings of the statements. In addition, extreme assessments with strong agreement versus strong disagreement were noted to contribute to the overall evaluation and to support the relationship between the judges' profession and their evaluation. Moreover, the comparison between the responses was utilized to show the difference between the two groups' evaluations.

Validity and Reliability

This study included the production methods through the functional design process including creating a ZWD, manual grading, marker making, and construction, as well as use of modules in Optitex software including grading, marker making, and 3D simulation. The researcher had experience in ZWD and manual methods with average skills using the Optitex software, which provided validity to the functional design process. In addition, the documentation of the functional design process involved researcher notes, photos, screenshots, and videos. These tools provided transferability and replicability to the study. Moreover, the analysis of each phase during the design process provided further validity to the study. On the other hand, the inclusion of the textual comments in the survey added to the instrument validity. Lastly, the triangulation of the collected data including garment samples and videos as outcomes of the functional design process and quantitative and qualitative data via the survey provided reliability to the overall findings of the study.

Summary

This chapter included two stages: the production methods stage and the survey stage. The functional design process in the Model of Sustainable Fashion Design guided the first stage of the methods in this study. The first stage included three phases: sample development, grading and marker making; digital and virtual testing of the marker; and marker refinement. The constructed and virtual outputs from stage one were used in stage two survey. The experimental research design was adopted to guide the mixed method approach of data collection in stage two. Data was gathered through an online Qualtrics survey, using both purposive and snowballing sampling methods to invite ZWD judges and technical designer judges to participate in the study.

Lastly, descriptive statistics was used for data analysis. In addition, the content analysis approach was used for analyzing the qualitative comments by the judges.

CHAPTER IV

RESULTS

The purpose of this study was to explore the feasibility of grading ZWD for industry production using digital and virtual methods, to ultimately improve the production methods of sustainable fashion design. This purpose was achieved through production methods of developing a ZWD, exploring grading, marker, and sizing garments manually, digitally and virtually through three phases of the experimental functional design process. To analyze the garment outcomes an online survey was completed by expert judges. This chapter first presents the results of the production methods phases to answer the first research questions. Then, the statistical results are presented to answer the second and third research questions in this study.

Question One Results

The first question in this study was:

1. What pattern piece adjustments and marker layouts achieve both 100% marker efficiency and accurate virtual visual appearance? This first question included two specific sub-questions:

   a. What pattern piece adjustment methods, for the two graded sizes of the selected ZWD Jigsaw style, result in 100% marker efficiency and visual accuracy?

   b. What is the most efficient pattern piece adjustment method and marker layout that maintain visual accuracy as compared to the virtual control garment and the graded virtual garments?

Pattern Piece Adjustments

The findings from the first phase of the functional design process provided the pattern pieces adjustments and marker layouts for 100% efficiency that answered the first research sub-question: What pattern piece adjustment methods, for the two graded sizes of the selected ZWD Jigsaw style, result in 100% marker efficiency and visual accuracy? After the size 8 control ZWD was developed, the pattern pieces were transferred to Optitex for grading sizes 4 and 12, and for generating the marker. Then, five pattern piece adjustment methods were applied to the graded patterns for increasing marker efficiency: a) modifying grainline of pattern pieces, b) adjusting visible pattern dimensions, c) utilization of negative space (fabric fall-out) to create visible garment parts, d) utilization of negative space to create non-visible garment parts, and e) utilizing negative space to create hidden parts. The strengths and weaknesses of each method are discussed as they related to marker making as well as visually accuracy.

Modifying specified grainline. This first pattern adjustment method included tilting pattern pieces up to 10 degrees in the marker. This process was selected to be automatically allowed for all pattern pieces to increase the marker efficiency.

Adjusting visible pattern dimensions. Visible pattern adjustments included dividing pattern pieces and extending and decreasing pattern pieces. The skirt pattern pieces were extended to increase the width of the size 12 skirt (see Figure 3.11). On the other hand, front pattern pieces were decreased in width for skirt size 4. Changes to the skirt length could be applied to the small dress, however, this did not increase the efficiency of the marker, thus it was not applied in this study. Extending pattern pieces is a common practice for sizing skirt widths as it maintains proportions between garment parts as the size increases. The extending technique for size 12 and the decreasing technique for size 4 allowed the gathered skirts of the graded sizes to appear more similar to the control. However, this technique is dependent on the marker; if the marker has different layout, extending the pattern pieces might not be possible.

In addition to extending the widths of the skirts, inclusion of negative space areas around bodice pattern pieces was also the technique applied to most of the bodice panels. Even though this technique is not a common industry practice, it was explored to utilize fall-out. The negative spaces areas around the bodice pattern pieces included areas adjacent to princess seamlines, center front and center back, side seams, shoulders, waistline, sleeve lower edges, and armhole edges.

To manage pattern change dimensions, gathering and darts were the two techniques explored. The gathering technique is a common industry technique that was used successfully in the skirt waistlines. In order to maintain visual similarity across the three sizes, the amount of gathering varied by size with fewer gathers for size 4 and more for size 12. However, the drape of the gathers was negatively impacted by the unresolved fit issues in the bodice in the first phase (see Figure 3.14).

Darts were experimented with in the first phase to manage fabric excess in the sides of bodice panels. Even though it is a common practice to use this technique to manage fabric to shape curves in the bodice area, it is not a common practice to manage added amounts of fabric in the marker phase. The darts did not provide successful results as the visual accuracy differed between the control and graded sizes with darts. The addition of darts may not have been as noticeable in a complex garment; however, the simplicity of the style made the additional darts obvious. In addition to the visual accuracy, reaching accurate fit was time consuming with the darts as the darts influenced the ease around bust and waist areas (see Figure 3.14).

Pattern division is a common industry practice to increase the marker efficiency as it allows for increased options of placing smaller pattern pieces. The division technique was initially applied to the skirt front size 4 pattern piece, as it was one of the largest pattern pieces in the marker which had potential to increase marker efficiency. In the end the skirt division did not increase marker efficiency and thus did not move forward as an adjustment method.

Utilizing negative space to create visible garment parts. A third pattern adjustment was to create garment parts out of the negative spaces. Such spaces were used for the sleeves, neck facings, and support pieces. This technique is not common in industry practice, rather sleeves and neck facing are typically cut from pattern pieces rather than being created from the fall out. The use of support pieces from fall out is not an industry practice.

The control dress sleeves were created as a modified petal style. Four of the adjacent pieces to the armhole of the bodice pattern pieces were used to create the petal portions for size 4, and the other four adjacent pieces were used for size 12 petals (see yellow areas in Figure 3.11). These curved negative pieces influenced the use of a petal style sleeve. The sleeve under portion and ability to size came from narrow rectangles (see yellow strips in Figure 3.11). The petals and strips were overlapped around the armhole of each graded dress to create the graded sleeves. Even though this was a good technique to utilize fabric it negatively impacted visual accuracy due to obvious seamlines that were needed for accurate widths (see sleeves in Figure 3.13). In addition, it was challenging to maintain the larger proportion for size 12, that appeared a bit smaller than it was supposed to be (see Figure 3.11).

Utilizing negative space to create non-visible garment parts. This adjustment method included the creation of neck facings. Neck facings were created in this phase out of the negative spaces that were adjacent to the front and back neckline openings of the two graded dresses (see orange areas in Figure 3.11). The pieces were stitched along the neckline to finish the neckline opening. Extensions were pieced to the main neck facing pieces to fit the measurements of the neckline (see orange areas not adjacent to the neckline in Figure 3.11). Overall, this technique was successful; however, it needed revision in the construction process, as the approach to piecing the facing influenced the accurate fit and lay of the neckline (see the improvement of the neckline facing in phase one, Figures 3.13 and 3.14).

Utilizing negative space to create hidden parts. The last adjustment method in the first phase included the creation of support pieces for the hem. Support pieces were also created in this phase out of the remaining small negative spaces located throughout the marker (see light green areas in Figure 3.11). The supportive pieces were attached around the hem for both graded dresses. This technique was useful for managing the tiny pieces of the fall out, however, with the fabric type used in the current study, this technique negatively influenced the hang and balance of the hemline.

The findings from the first phase of the functional design process led to answering the sub question two: What is the most efficient pattern piece adjustment method and marker layout that maintain visual accuracy as compared to the virtual control garment and the graded virtual garments? To answer this question, a number of marker adjustment methods, that were tested from the first and second phases were integrated in a system. The reason for combining the results for sub-question two is that the process went through trial and error moving between the digital maker, the avatar, and constructed versions.

Most Efficient Pattern Adjustments and Marker for Visual Accuracy

Following are the most efficient pattern piece adjustment methods that were tested through the functional design process to increase marker efficiency: a) modifying grainline of pattern pieces, b) adjusting visible pattern dimensions, c) adjusting non-visible pattern dimensions, and d) utilization of negative space (fabric fall-out) to create non-visible garment parts.

Modifying specified grainline. The first pattern adjustment method related to the grainline. It included tilting patterns in the marker and rotating the sleeve pattern pieces in the marker. Tilting the patterns to improve the marker efficiency was a useful and efficient approach that was applied successfully in both phases by tilting the patterns 10 degrees while in the PDS file. Rotating the sleeves worked efficiently in the second phase. Five sleeve petals were laid on the crosswise direction in the marker, while three petals were laid with the length grain (see Figure 4.1). Even though this technique was efficient for fabric utilization for ZWD, it might not work with longer and/or larger sleeve styles as it would influence the drape or hang of the sleeves.

Adjusting visible pattern dimensions. This second adjustment method included increasing and decreasing pattern dimensions. This method worked efficiently in both first and second phases. In the second phase pattern adjustments included extending a pattern piece; this technique was applied successfully to the front skirt of size 12. In addition, use of gathers aided in the visual accuracy between the control and larger size skirt dimensions in both constructed and virtual dresses. However, visual accuracy of gather appearance in Optitex was not as successful as it was in the constructed garments. Multiple resolution adjustments, in addition to applying the shrinkage function, were experimented to improve the visual accuracy of the skirt gathering but did not result in the desired appearance compared to the physical dresses. The techniques of adjusting pattern dimensions are dependent on the marker; if the marker has a different layout, extending the pattern pieces might not be possible.

Another adjustment method from the first phase was creating darts from the negative space around bodice pattern pieces. Since this method negatively influenced the fit, ease and visual similarity to the control, darts did not move forward. Thus, managing negative spaces around the bodice parts was applied using the following adjustment method.

Adjusting non-visible pattern dimensions. This method included increasing seam allowances for bodice and sleeves pattern pieces (see negative spaces around bodice and sleeve patterns in Figure 4.1). One issue regarding the increased seam allowance was that the negative spaces around two identical pattern pieces were not the same and did not have even edges for both sides which required overlock stitching each edge individually for all seam lines to avoid trimming the fabrics (see Figure 3. 29).

Even though the increase of seam allowances was successfully applied in the physical dresses it was not feasible in Optitex. The relatively wide irregular-shaped seam allowances for most of the bodice panels was difficult for the 3D stitching. The applied digital technique was made by stitching negative spaces (as separate pieces) to the seam allowance to mimic the physical procedure. This solution was challenging as it required removing some negative spaces (seam allowances) in order to keep the virtual dresses comparable to the physical dresses (see Figure 3.23). The removed pieces from the virtual dresses included most of the shoulder seam allowance (added amounts of negative spaces), upper princess line seam allowances, and most of waistline seam allowances. Thus, the virtually stitched garment did not include all of the waste fabric as Optitex was not able to stitch such unusual applications.

Utilizing negative space by creating non-visible garment parts. This last adjustment method that utilized negative space in the marker to create garment parts included creating neck facings, pockets, and dress hangers. Neck facings were created with relative efficiency in the first phase but did contribute to bodice and neckline fit and appearance issues. However, in the second phase, there were more negative spaces that worked efficiently as extensions to the neck facing in the constructed dresses (see blue areas in Figure 4.1). The consideration of physically stitching the pieced parts skillfully was required to avoid increasing thickness and bulkiness of the pieced fabrics. On the other hand, digitally joining the internal pieces while keeping the stitching internal toward the body did not work for all the neck facings in Optitex.

Side pockets in the skirts were also created successfully in the second phase. One pocket was attached to the right side of the dress skirt (right side for the wearer) for each graded size. The reason for only one pocket was due to the limited amount of remaining fabric. The pockets were created by piecing, using a zigzag stitch, the small negative spaces and folding the edges of the pieces to reach the regular shape of the pocket that was then stitched to the side seam of the skirt (see Figure 3. 31). This technique worked very efficiently in the physical garments and did not impact the skirt drape or hang.

On the other hand, the 3D simulation did not handle the number of stitches to join the pocket pieces. The software 'froze' through the 3D draping process while joining the stitches. When the pieces were joined to be shaped as a regular pocket, the researcher had to decrease the size of the pocket, as it was challenging to stitch the large pocket to the skirt while keeping the pieced pockets inside (without seeing them externally). The 3D simulation did not reflect the physical process accurately due to the software's limited capacity to handle this technique smoothly (see Figure 3. 33). Thus, the virtually stitched garment did not include all of the waste fabric as Optitex was not able to stitch such unusual applications.

Key:

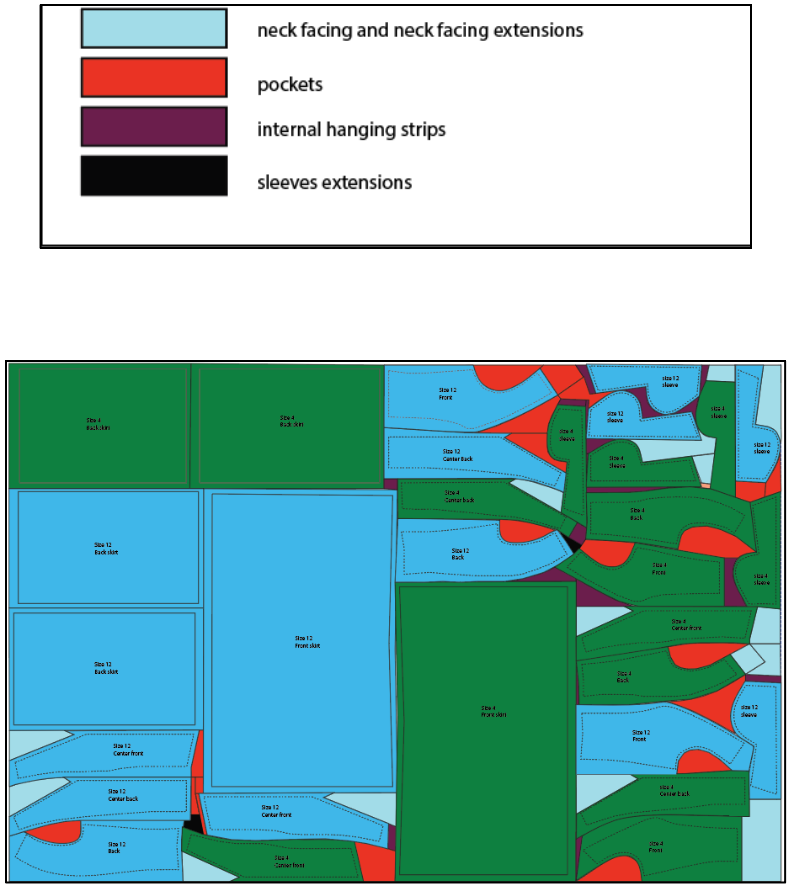


Figure 4.1 Final marker for ZWD princess style graded dresses

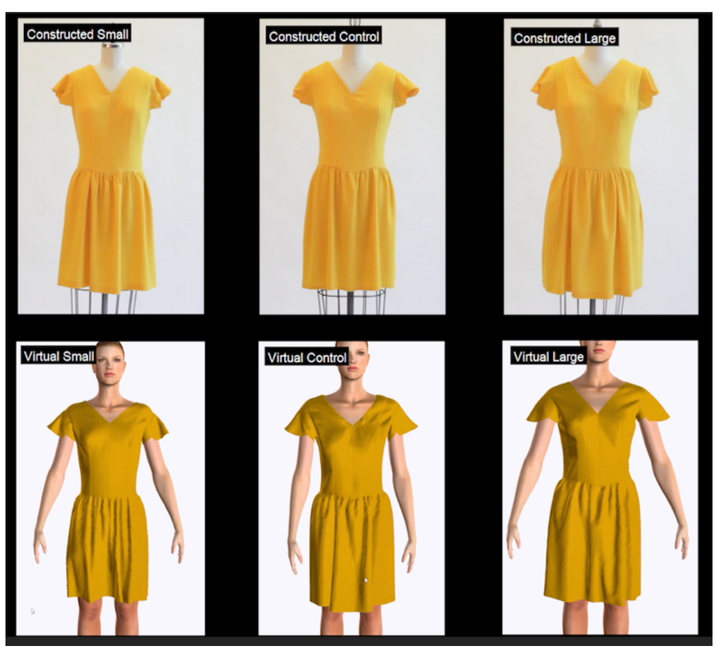


Figure 4.2 Final physical and virtual ZWD princess style dresses

Survey Participant Results

The survey descriptive statistics, including mean and standard deviation of the responses, are first reported, followed by the qualitative comments supporting or clarifying the statistical results. Following the results of each question is a summary of the findings. The presentation of the findings is arranged by sample description and the two remaining research questions. Participants assessed the design elements of the graded dresses and the efficacy of the 3D virtual simulation of the virtual dresses compared to actual garments. This process was implemented via an online survey, completed by expert judges to answer the second and third research questions: Can digital 3D simulation be used as an effective and sustainable sizing and fit assessment tool? Does the attachment and appreciation of ZWD influence expert judges' evaluation of visual accuracy?

Sample Population

Demographic information is a relevant data source related to the type of judges who assessed the physical and virtual dresses across the graded sizes of ZWD in the survey. These data include the demographic variables relating to highest degree or level of school completed, current job titles, working years, in addition to knowledge and experience the judges have in grading, zero-waste design, and 3D simulation.

Six ZWD designers and six technical designers participated in this study. The six ZWD judges are assistant professors, associate professors and a full professor in apparel and textile design and sustainability who are the world's most notable academic researchers in ZWD. The number of working years for professors were between 6-years and 30-years. On the other hand, the technical-design judges currently or previously worked for apparel companies including Walmart, Nike, Anfcorp, North Face, Adidas, Hanes, and Under Armour. The technical designers occupied positions of apparel patternmaker, technical designer, and technical design manager, with working experience between 1-year to 29-years. Participants were first recruited using the purposive sampling method, and then snowball participants from the initial contacts. Thus, ZWD key researchers, alumni, and industry partners in technical design were contacted first, and then other participants recruited from the initial participants assistance. Overall, ZWD judges have higher level of experience and knowledge in ZWD than the technical design judges; whereas ZWD judges have less experience and knowledge in digital pattern grading and 3D simulation. However, participants have various levels of experience with ZWD, except for one technical designer, who has no experience at all. Most participants have at least some knowledge of digital pattern grading and 3D simulation (see Table 4.1).

Table 4.1

Demographic variables of participants.

	ZWD judges					Technical design judges				
	N	M	SD	Max	Min	N	M	SD	Max	Min
Knowledge and experience with ZWD	6	4.67	0.52	5	4	6	2.83	1.47	5	1
Knowledge and experience with digital pattern grading	6	3.5	1.05	5	2	6	4.17	0.75	5	3
Knowledge and experience with 3D simulation	6	3.17	0.98	4	2	6	3.83	.75	5	3

Judges combined					
	N	M	SD	Max	Min
Knowledge and experience with ZWD	12	3.75	1.4	5	1
Knowledge and experience with digital pattern grading	12	3.83	.94	5	2
Knowledge and experience with 3D simulation	12	3.50	.91	5	2

Note. 1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree.

Question Two Results

The results of question two were obtained through the analysis of data collected through the online survey completed by two groups of judges: ZWD judges and technical design judges. The judges completed the survey by rating the statements to assess fit and appearance criteria regarding four comparison sets. The findings for this question also represent the open-ended comments to support the evaluator ratings.

The second research question in this study was: Can digital 3D simulation be used as an effective and sustainable sizing and fit assessment tool? This question had four sub-questions to determine visual accuracy between the: a) constructed control and virtual garments, b) constructed control and graded constructed garments, c) virtual control and virtual graded garments, and d) graded constructed and graded virtual garments. The results of this question are averaged across the ZWD and technical designers. Question 3 provides a comparison across the two expert groups.

What is the visual accuracy between the physically constructed control garment and the virtual control garment?

The expert judges compared the two control garments (see Fig. 4.3) by watching a video of the garments simultaneously rotating 360 degrees. They then responded to the degree of similarity using a Likert scale with options of strongly disagree, disagree, neutral, agree, and strongly agree.

Figure 4.3 Images of constructed control vs. virtual control

Table 4.2
The descriptive statistics for the visual accuracy between the physically constructed control garment and the virtual control garment.

Assessment criteria	Mean	SD	Min	Max
Overall similarity	3.67	.78	2	4
Fabric visual similarity	3.25	.87	2	4
Sufficient visual information	3.33	1.07	1	5

Note. 1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree.

Responses indicated that the overall visual similarity between the physically constructed control garment and the virtual control garment is mostly acceptable (M =3.67, SD=0.78). See Table 4.2. One participant commented that there is a difference in the location of the waistline and back neckline depth. This participant also commented that there is a difference in postures of the dress form versus the avatar. The participant explained that the difference is seen in the angles of shoulders in relation to the hips, and is also seen between the body and the dress form proportion.

On the other hand, the responses regarding the similarity of fabric appearance (structure and thickness) and response to the form (drape and ease) mostly indicated a neutral assessment (M=3.25, SD=0.87). One participant commented that fabric in the virtual appears to have thicker yarn and a lower thread count.

Similarly, responses regarding the provision of enough visual information in the virtual simulation that sampling in the actual fabric is not a necessity also indicate a neutral assessment (M=3.33, SD=1.07). When asked to clarify their assessment, the judges provided different opinions regarding the similarity between the constructed and virtual control dresses. Three participants commented that, even though the virtual and physical dresses look very similar, the virtual sample could replace the physical one for style assessment, but the physical sample is still needed for the fit assessment.

Other participants provided more specific comments regarding the exclusive use of virtual sampling. One participant commented that the virtual dress has more gapping and looseness and that unnecessary corrections would be made if the fit were based on the virtual model, which would ruin the physical dress. Another participant commented that virtual simulation would eliminate all muslin samples but would not be considered as a final sample when using new fabric. A third participant stated that the physical sample would be needed to ensure fit for different body types and fabric drapes. This participant showed an understanding of the difficulty of laying the virtual garment as cleanly as one can a physical garment; this participant also added that Optitex tends to simulate gathers projecting outwards instead of lying flat against the body of the avatar. On the other hand, one participant commented that the experience in the garment styles with particular fabric types would allow the designer, due to the familiarity with visualizing the accurate drape, to assess the virtual samples and eliminate physical sampling. Another participant said that even though the gather looks bulkier on the virtual and the back neckline is higher than the virtual, a physical sample would be unnecessary.

Summary. Overall, the responses showed that there was neutral assessment with tendency to agreement on the visual accuracy between the physically constructed control garment and the virtual control garment. These findings showed that the visual fabric similarity had the lowest rating, even though the overall similarity between the two control dresses had a relatively positive assessment. Interestingly, a ZWD judge with seventeen years of experience strongly disagreed that the virtual simulation provided enough visual information to render sampling in the actual fabric unnecessary, whereas a technical design judge with twenty-nine years' experience strongly agreed with the statement. Further discussion between judges' groups regarding the efficiency of the visual information provided by the virtual samples that could replace the physical sample is in the results for question three.

What is the visual accuracy between the physically constructed control garment and the two graded physically constructed garments?

The expert judges compared the constructed control to the two graded samples (see Fig. 4.4) by watching a video of the garments simultaneously rotating in a circle. They then responded to the degree of similarity using a Likert scale from strongly disagree to strongly agree.

Figure 4.4 Images of physically constructed control compared to constructed size 4 (small) and size 12 (large)

Table 4.3
The descriptive statistics for the visual accuracy between the physically constructed control garment and graded physically constructed garments.

	Control vs. size 4				Control vs. size 12			
Assessment criteria	M	SD	Max	Min	M	SD	Max	Min
Silhouette	4.5	0.52	5.0	4.0	4.33	0.50	5.0	4.0
Drape	4.33	0.89	5.0	2.0	4.42	0.52	5.0	4.0
Fit and ease	4.25	0.87	5.0	2.0	4.17	0.84	5.0	2.0
Dimensions of dress parts	4.25	0.62	5.0	3.0	3.83	0.84	5.0	2.0
Internal seams location	4.42	0.52	5.0	4.0	4.42	0.52	5.0	4.0
Distribution of gathers	3.75	1.06	5.0	2.0	3.67	0.99	5.0	2.0
Overall acceptability	4.08	0.10	5.0	2.0	4.09	0.70	5.0	3.0

Note. 1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree.

The results for the second sub-question of the first research question indicate the visual accuracy between the physically constructed control garment and the two graded physically constructed garments. The judges first evaluated the silhouette or the overall shape with direction to compare the outline of the two dresses. Results for size 4 compared to the control indicated mostly strong agreement with visual accuracy (M=4.5, SD=0.52). The statistical results of size 4 were similar to those for size 12 compared to the control regarding silhouette visual accuracy (M=4.33, SD=0.50).

The second criterion was drape or hang by comparing the folds and falls over the form of the graded samples compared to the control. The responses indicated agreement in visual accuracy between the constructed control and size 4 (M=4.33, SD=0.52). There was even more agreement for size 12 compared to the control regarding drape or hang (M=4.42, SD=0.55). When asked to clarify their opinion, three judges commented that the control waistline appeared to slope more to the back compared to size 4.

Participants' responses regarding the ease and fit for the proportional distribution (by comparing looseness or tightness at waist and bust levels) of size 4 compared to the control indicated agreement (M=4.25, SD=0.87). The statistical results of size 4 were similar to those for size 12 compared to the control regarding the fit and ease of visual accuracy (M=4.17, SD=0.84). Two judges noted bust ease difference between size 4 and the control.

The fourth criteria judges evaluated were the proportional dimensions of dress parts or pieces by comparing the similarity between sleeve dimensions, bodice dimensions, and skirt dimensions. The participants' responses indicated agreement in visual accuracy between the constructed control and size 4 (M=4.25, SD=0.62). In contrast, the responses for size 12 compared to the control indicated slightly less agreement (M=3.83, SD=0.84). Three judges commented that the neckline in size 4 and size 12 look proportionally smaller than the control. In addition, one judge commented that the sleeve hang and proportion of size 12 looked different than the control. For the hem, one judge commented that the hem was wider on size 4 than the control, whereas another judge commented that the hem looked longer on size 4 than on the control.

In terms of evaluating the location of internal seam lines (comparing the center, princess, side, and armhole seams) of size 4 compared to the control, the responses indicated agreement in visual accuracy between size 4 and the control (M=4.42, SD=0.52). Also, the statistical results for size 4 were similar to those for size 12 compared to the control regarding the location of internal seam lines (M=4.42, SD=0.55). One judge commented that the graded dress has an uneven waistline with a different slope for size 4 compared to the control, whereas two judges commented on this difference in size 12 compared to the control. Another judge commented that the scoop of the waistline in the front seemed more pronounced in the control than in size 12.

The sixth evaluation criterion was visual accuracy of the distribution of gathers between the physically constructed control and graded skirts. Judges were asked to compare the fullness of the skirts. Between size 4 and the control, responses indicated that most agree (M=3.75, SD=1.06). There was slightly less agreement for size 12 compared to the control regarding the visual accuracy of the distribution of gathers in the skirts with (M=3.67, SD=0.99). Of the six evaluation criteria, distribution of gathers was viewed as less similar than the other criteria (see Table 4.3). Two judges commented that gathers in the skirt were different between the control and size 4 dresses. For size 12, six judges commented that there were fewer gathers in the large skirt's back, and one judge commented that size 12 had tighter and more numerous gathers than the control.

The final evaluation of the comparison set sought judges' overall level of agreement to the acceptable appearance between the control and graded for grading a ZWD. Overall, judges' responses regarding the visual accuracy acceptability between size 4 constructed dress compared to the constructed control indicate agreement (M=4.08, SD=0.10). There was similar statistical results of agreement on the overall acceptability between size 12 and control (M=4.09, SD=0.70). Lastly, one judge thought that the overall proportion of size 12 and the control dresses was not the same.

Summary. The overall assessment regarding the visual accuracy between the physically constructed control garment and the two graded physically constructed garments showed agreement. This finding aligns with the assessment from the Stage One, the functional design process, as the development of the constructed dresses was straightforward in terms of applying the adjustment methods while maintaining the visual accuracy between the control and graded sizes.

Even though it is common for larger graded sizes to be more problematic with fit assurance when grading regular clothing (Schofield & LaBat, 2005), the findings in this study show that grading ZWD results in fit and appearance issues for both smaller and larger sizes. Judges commented on issues related to the bust ease, waistline appearance, skirt gather distribution, neckline, sleeves, and skirt proportional dimensions. These issues were caused by the need to utilize all of the fabric. The added amount of fabric to the seam allowance in the front and back bodice panel pieces influenced the different appearance of the waistline scoop between the control size and size 12. The differences in the skirt gathers were due to the fact that size 4 had proportionally more gathers than the control. In addition, size 12 had more gathers in the front than in the back. Lastly, because the widths of the skirt were not graded, the dimensions of size 4 skirt appeared proportionally larger than the control, and the waistline included more gathers, which made it appear to have looser silhouette and difference in gather distribution appearance, compared to the control. Even though the researcher attempted to maintain appearance between the physically constructed ZWD control and graded dresses the results were not perfect. And while the expert judges certainly noticed the visual differences between the control and the graded constructed dresses, the overall visual comparisons were acceptable.

What is the visual accuracy between the virtual control garment and the two graded virtual garments?

The expert judges compared the virtual control to the two graded virtual dresses (see Fig. 4.5) by watching a video of the garments simultaneously rotating in a circle. They then responded to the degree of similarity using a Likert scale of 1 strongly disagree, 2 disagree, 3 neutral, 4 agree, and 5 strongly agree.

Figure 4.5 Images of virtual control compared to virtual size 4 (small) and size 12 (large)

Table 4.4
The descriptive statistics for the visual accuracy between the virtual control garment and graded virtual dresses.

	Control vs. size 4				Control vs. size 12			
Assessment criteria	M	SD	Max	Min	M	SD	Max	Min
Silhouette	3.92	0.10	5.0	2.0	4.25	0.62	5.0	3.0
Drape	3.25	1.22	5.0	1.0	3.33	1.30	5.0	2.0
Fit and ease	3.0	1.21	5.0	1.0	3.17	1.27	5.0	2.0
Dimensions of dress parts	3.83	1.03	5.0	2.0	4.08	0.90	5.0	2.0
Internal seams location	4.33	0.50	5.0	4.0	4.25	0.62	5.0	3.0
Distribution of gathers	3.25	1.06	5.0	2.0	3.25	1.36	5.0	1.0
Overall acceptability	3.33	1.07	5.0	2.0	3.5	1.17	5.0	2.0

Note. 1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree.

The results for the third sub-question of the first research question represents the findings regarding the visual accuracy between the virtual control garment and graded virtual dresses. The visual accuracy of silhouette or overall shape was the first criteria for the judges to evaluate; the judges were directed to compare the outline of the two dresses. Results indicated mostly agreement that the silhouette or overall shape of size 4 appeared the same as the control (M=3.92, SD=0.97). The statistical results for size 12 indicated even more agreement on the visual accuracy (M=4.25, SD=1.62). When asked to clarify their evaluation, one judge commented that the skirt silhouette was closer in size 4 compared to the control. Another judge commented that the only difference was the fullness of the skirt between size 4 and the control; otherwise, the virtual would replace the physical sample.

The visual accuracy of drape or hang was the second criteria for evaluation by comparing the folds and falls over the body of the virtual graded dresses compared to the virtual control. Results indicated neutral agreement of size 4 visual accuracy (M=3.25, SD=1.30). Similar statistical results were found for size 12 (M=3.33, SD=1.30). One judge commented that the drape was different between size 4 and the control, and another judge commented that the skirt side seam of size 4 did not fall smoothly.

Fit and ease, with similar proportional distribution between virtual graded and virtual control was the third criteria of the evaluation. Results indicated neutral agreement of visual accuracy for size 4 compared to the control (M=3.00, SD=1.21). Neutral agreement was also reported for size 12 (M=3.17, SD=1.27). The statistics for fit and ease visual accuracy indicated the least agreement among the other evaluation criteria. Two judges commented regarding the fit of the backside bodice of size 4 looking larger than the control, whereas three judges commented that size 12 has looser fit compared to the control. Similarly, one judge commented that size 4 had more ease around the bust, while the control had more ease on the chest. On the other hand, one judge commented that the dress size 4 was sitting lower on the shoulders. A difference between the two judge groups' evaluation was distinguished in this comparison set for the virtual size 4 compared to the virtual control. For both criteria of drape and fit and ease, one ZWD judge strongly disagreed that these aspects of size 4 looked similar to the control, while another ZWD judge strongly agreed that they did.

Another criterion for analysis was the visual accuracy of the dimensions of dress parts or pieces. Results indicated mostly agreement of visual accuracy for size 4 (M=3.83, SD=1.03), whereas the results indicated more agreement for visual accuracy for size 12 compared to the control (M=4.08, SD=0.90). One judge commented that the armhole of size 12 looked smaller than the control.

The visual accuracy of the location of internal seam lines was the fifth criterion for comparing virtual graded dresses to the virtual control dress. Results indicated agreement on the similarity between size 4 compared to the control (M=4.33, SD=0.50). Similarly, size 12 was found similar when comparing the location of internal seam lines (M=4.25, SD=0.62). One judge commented that the side seam looks proportionally longer on size 12 than the control. Another judge commented that the side seam on the size 12 skirt kicks forward.

The following evaluation criteria was regarding the visual accuracy of the distribution of gathers in the skirt between the virtual graded and the virtual control. Results indicated neutral agreement for size 4 (M=3.25, SD=1.06) and size 12 (M=3. 25, SD=1.36). Interestingly, one of the ZWD judges strongly disagreed that the distribution of gather in the skirt of size 12 was similar to the control, whereas, another ZWD judge and a technical designer judge strongly agreed with the statement. When asked to clarify their rating, two judges commented that the distribution of gathers in size 4 was difficult to assess with the quality of rendering. Another judge noted that the gather distribution in size 4 was shifted from the front across to the side front. On the other hand, three judges commented that size 12 had fewer gathers compared to the control, whereas another judge commented that size 12 had uneven gathers.

The final evaluation criteria of the comparison set was the overall level of agreement to the acceptable visual accuracy between the virtual control and the virtual graded dresses. Overall, the responses for size 4 indicated neutral agreement (M=3.33, SD=1.07). However, results indicated slightly more agreement for size 12 compared to the control (M=3.50, SD=1.17). Only one judge commented that size 12 compared to the control looks the best. Another judge commented that it was difficult to assess the two dresses as the simulated fabric in both skirts seems unlike fabric.

Summary. The overall evaluation regarding the visual accuracy between the virtual control garment and the two graded showed neutral level of agreement. This level of accuracy fits with the findings from the second phase of the functional design process, as the constructed dresses showed more similarity between control and graded dresses, due to the originality of the construction techniques compared to the complex virtual process for stitching the virtual dresses.

All fit and ease issues along with issues related to the accuracy of the location of internal seam lines were caused by two main reasons. First, the stitched separate seam allowances to the bodice panels and second, the difference of measurements between the dress forms and the avatars.

In terms of the issues related to differences in the distribution of the skirt's gathers, they were caused by the difference between the amounts of gathers between the control and the graded which impacted appearance and visual accuracy. Other gathers issues were related to the issue found in the functional design process which was the quality of rendering gathers with the software.

The accurate drape of the skirts in Optitex was challenging with the tendency to drape close to the body, which influenced the silhouette of the garment. This may be due to the stitched pocket in only one side. The pocket did contribute to the side seam of skirt size 4 not being draped smoothly.

What is the visual accuracy between the two graded, physically constructed garments and their corresponding virtual simulation?

The results for the fourth sub-question of the first research question indicated the visual accuracy and compatibility between the two graded physically constructed garments and their corresponding virtual dresses sizes (Figure 4.6). The procedure was the same as reported for the pior comparison sets.

Figure 4.6 Images of graded virtual compared to their corresponding sizes of constructed graded.

Table 4.5

The descriptive statistics for the visual accuracy between the two graded physically constructed garments and their corresponding virtual simulation sizes 4 and 12.

	Control vs. size 4				Control vs. size 12			
Assessment criteria	M	SD	Max	Min	M	SD	Max	Min
Silhouette	3.67	1.16	5.0	2.0	3.92	0.10	5.0	2.0
Drape	3.0	1.48	5.0	1.0	2.92	1.24	5.0	2.0
Fit and ease	3.85	1.17	5.0	20	3.33	1.30	5.0	1.0
Dimensions of dress parts	4.08	0.90	5.0	2.0	3.92	0.10	5.0	2.0
Internal seams location	4.33	0.65	5.0	3.0	4.17	0.72	5.0	3.0
Distribution of gathers	3.42	1.17	5.0	2.0	3.0	1.13	5.0	2.0
Overall acceptability	3.40	1.35	5.0	1.0	3.25	1.22	5.0	2.0

Note. 1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree.

When evaluating the silhouette, results indicated almost agreement of visual accuracy for size 4 (M=3.67, SD=1.16). There was similar level of agreement indicated by the statistical results for size 12 (M=3.92, SD=0.10). One judge commented that there is a difference in the silhouette of a skirt for size 4. Another judge noted that the virtual size 4 and the physical size 4 look very similar, but the virtual needs some manipulation regarding its set on the shoulder. On the other hand, two judges commented that the sleeve in size 12 stood out more on the virtual sample than on the physical.

The drape or hang of the virtual graded compared to the constructed graded was the second evaluation criteria for this comparison set, between virtual graded and constructed graded, where the judges compared the folds and falls over the forms. The results indicated neutral assessment regarding the visual accuracy for sizes 4 (M=3.00, SD=1.48) and sizes 12 (M=2.92, SD=1.24). The drape and hang criterion had the least agreement out of the six assessment criteria. Interestingly, one of the ZWD judges strongly disagreed that the drape or hang of the virtual size 4 and the constructed size 4 look similar, whereas another ZWD judge and a technical design judge strongly agreed with the statement. When asked to clarify their ratings, judges commented that in size 12, the sit of the shoulder and hip was different from the physical sample and that the drape of the virtual sample looks frumpy. Another judge noted that there were drag lines in the virtual sample for size 4. On the other hand, one judge commented that the virtual skirt did not hang like physical in size 12. While another one commented that the sweep does not lay right along the hem for size 4.

Regarding the fit and ease evaluation between virtual graded and constructed graded, the results indicated a low level of agreement between size 4, (M=3.58, SD=1.17), whereas the statistical results for size 12 tended toward a neutral level of agreement, (M=3.33, SD=1.30). Interestingly, one ZWD judge strongly disagreed that the fit and ease of virtual size 12 has the same proportional distribution as constructed size 12, whereas a ZWD judge and a technical design judge strongly agreed with the statement. When asked to clarify their responses, two judges commented that there was a difference in the fit of the bodice for size 4.

The fourth evaluation criterion was regarding the visual accuracy of the dimension of virtual graded dress parts compared to the constructed graded; in this evaluation, the judges compared the similarity between sleeve dimensions, bodice dimensions, and skirt dimensions. The results indicated agreement for size 4, (M=4.08, SD=0.90). Whereas the statistical results for the size 12 indicated relatively less agreement, (M=3.92, SD=0.10). One judge commented that the neckline shapes did not match between size 4 and the control; two other judges noted that there was a difference between the virtual and physical neckline angels for size 12. On the other hand, another judge commented that the sleeve length in the 3D looked longer than the physical in size 12.

The evaluation regarding the visual accuracy of the location of internal seam lines between virtual graded and constructed graded was the fifth criteria for this comparison set, where the judges compared the center, princess, side and armhole seams. The results indicated agreement of visual accuracy for size 4 (M=4.33, SD=0.65) and for the size 12 (M=4.17, SD=0.72). One judge noted that the side seam looked disproportionate,

In terms of the visual accuracy of the distribution of gathers in the skirt in virtual size 4 compared to constructed size 4, responses indicated low to neutral agreement (M=3.42, SD=1.17). Whereas the results for size 12 indicated a neutral level of agreement (M=3.00, SD=1.13). Three judges commented regarding the difference in the distribution of gathers for size 4. One judge commented about the difference in size 12. On the other hand, one judge commented that for checking the grade, the virtual size 4 and 12 were acceptable, but not good enough to replace samples for sales due to the difficulty to asses gathers virtually. Another judge noted that the gathering looks good in size 4 and 12, but its rendering makes it different from the physical; one more judge firmly commented that physical gathers in size 12 looked better than the virtual as the later looked large and billowy.

The purpose of the final evaluation of the comparison set was to obtain judges' overall level of agreement to the acceptable appearance between the virtual graded and the constructed graded. The responses indicated neutral level of agreement for size 4 (M=3.40, SD=1.35) and somewhat more neutral level of agreement for size 12 (M=3.25, SD=1.22). Interestingly, one of the ZWD judges strongly disagreed that, overall, virtual size 4 is acceptable in appearance compared to constructed size 4 for grading a ZWD design, whereas another ZWD judge and a technical design judge strongly agreed with the overall visual accuracy for size 4.

Summary. The adjustments made on the pattern pieces and avatar measurements in the third phase of the functional design process in Stage One positively influenced the appearance and visual accuracy between virtual graded and constructed graded. This resulted in the highest rating for the visual accuracy between virtual graded compared to constructed graded regarding the similarity of the internal seam location. However, fit issues existed in both graded sizes across the constructed and virtual dresses, especially with the drape of falls and folds on the avatars. The drape of the skirt for the virtual dresses was not as smooth as the constructed; this was mostly due to the internal pockets in one side of each graded dress.

The findings from the results of this comparison set also showed that the similarity between the constructed dress size 4 and its corresponding virtual dress was slightly higher than in size 12. This may support that the issue for lacking the precise compatibility of the avatar measurement and the dress forms (that was encountered in this study) shows fewer fit issues in smaller sizes.

Question Three Results

The fifth and final comparison set included all six constructed and virtual dresses. The same evaluation statements for comparison set one (comparing constructed and virtual control) were used. Data were analyzed to answer the third research question in this study by comparing the means between the two judge groups, ZWD judges and technical design judges. The judges completed the survey by rating the level of agreement when comparing all three virtual dresses to constructed dresses.

The third question in this study was: Does attachment and appreciation of ZWD influence expert judges' evaluation of visual accuracy? This question had subquestions to determine the difference between ZWD judges' responses from technical design judges regarding the following: a) the overall similarity between virtual and constructed, b) the fabric similarity between the virtual and constructed regarding appearance (structure and thickness) and response to the form (drape and ease), and c) the virtual simulations provision of enough visual information that sampling in actual fabric is not a necessity.

Are evaluations by ZWD designers similar or different from technical designers regarding the visual accuracy between the control garment and the sized garments for both constructed and virtual garments?

The two groups of the expert judges compared the constructed and virtual garments (see Fig. 4.7) by watching a video of the garments all rotating in a circle. They then responded to the degree of similarity using a Likert scale of strongly disagree, disagree, neutral, agree, and strongly agree.

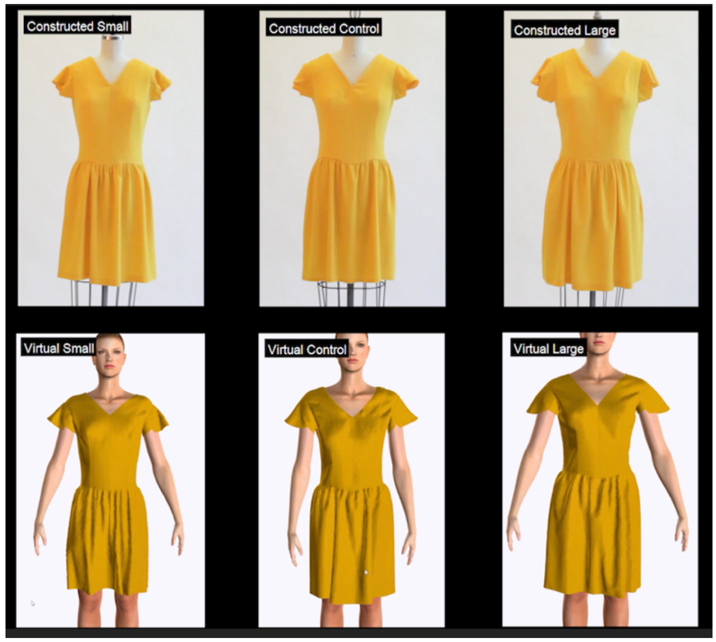


Figure 4. 7 Images of the virtual dresses compared to the constructed dresses.

Table 4.6

Evaluations by ZWD designers and technical designers regarding the visual accuracy between the constructed and virtual garments.

	ZWD judges				Technical design judges			
Assessment criteria	M	SD	Max	Min	M	SD	Max	Min
Overall Similarity between physical and virtual dresses	3.17	1.72	5	1	3.83	0.41	4	3
Fabric visual similarity	2.67	1.51	5	1	3.50	0.84	4	2
Sufficient visual information	2.00	0.90	3	1	3.33	0.82	4	2

Note. 1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree.

The results for the third research question represented the evaluations by ZWD designers and technical designers regarding the visual accuracy between control and virtual garments. The statistics regarding the overall similarity between the physical and virtual dresses indicated that ZWD judges represented less agreement (M=3.17, SD=1.72) than the technical design judges' assessment (M=3.83, SD=0.41). One ZWD judge stated that there are multiple differences in proportions and fit.

Similarly, regarding the fabric (drape and ease) similarity between the physical and virtual dresses, statistical results indicated that ZWD judges' responses indicate less agreement (M=2.67, SD=1.51) than the technical design judge's assessment (M=3.5, SD=0.84). One ZWD judge commented that there was considerable color difference between the physical and virtual samples and that the texture of the virtual fabric appears to have a slight sheen. And one ZWD judge commented that the fabric of the virtual sample appears thicker and drapes less smoothly than the actual fabric.

Similar to the previous findings, the results regarding the sufficient visual information between physical and virtual dresses indicate that ZWD judges had less agreement (M=2.00, SD=0.90) than technical design judge's assessment (M=3.33, SD=0.82). One technical design judge stated that the drape of the virtual fabric and the positioning of the shoulder makes the virtual as good as style sampling, not fit confirmation for the style. Another technical design judge commented that the virtual samples and the constructed samples share enough similarities that constructed samples would not be needed, especially for a size run.

Summary. The overall assessment regarding the visual accuracy between the virtual garments and the constructed garments showed neutral to disagreement levels. Most of judges' comments, regardless of expertise area, indicated the deficiency of 3D simulation to mimic the significant design aspects of the physical dresses. One of the technical design judges commented about virtual sampling: "I think this shows the distinct shortcomings of Optitex virtual draping. It is difficult to position the garment correctly on the body, and therefore difficult to use Optitex as a Fit confirming software. Another technical design judge noted: "Style confirming yes, but not as accurate for Fit or production readiness." Likewise, a ZWD judge commented about the necessity for physical samples: "Even if these were a closer match, fitting in fabric for at least the control size will be necessary. A trained live fit model can identify small fit issues that are not apparent in an image. It is certainly possible to reduce the number of fittings with a live model using virtual technology, but the way the garment fits and moves with the body in different fabrics cannot be assessed with current technology. This may never be possible, unless the technology begins to actually model fabric behavior instead of mimicking it."

Even though the yellow wool crepe fabric used in this study was sent to Optitex to test actual fabric parameters for 3D simulation, some judges commented that the virtual fabric did not accurately represent drape similar to the physical dress. A technical design judge commented: "I believe that 3D rendering is a great way to reduce sampling and to visualize details/fit across a range of sizes that may not always be accessible in dress forms/fit models. Rendering the fabric seems to be one of the bigger challenges and leads to most of the discrepancies between 3D and constructed." A final comment regarding virtual fabric simulation was given by a key ZWD researcher judge: "I suggest giving feedback to the software developer as there is an opportunity to better simulate the hang of the fabric."

The findings from the results of the third research question conclude that there is a relative difference between the overall level of agreement regarding assessment by technical design and ZWD judges. The findings indicate that ZWD judges have lower levels of agreement on the overall appearance and fit of virtual dresses compared to technical designer judges. However, both ZWD judges and technical design judges suggested that with some improvement in the software, less physical samples to evaluate fit would be possible and that virtual sampling could even replace physical samples to evaluate style of ZWD. On the other hand, the level of disagreement by the ZWD judges regarding the overall similarity between physical and virtual dresses, virtual fabric similarity and efficiency of the virtual dresses to replace physical dresses compared to technical designer judges represent ZWD judges' aspiration for actual improvement of the software that would impact the progress of ZWD manufacturing.

CHAPTER V

SUMMARY, DISCUSSION, AND CONCLUSIONS

Introduction

Results of the Functional Design Process and survey were reported in the previous chapter. This chapter consists of five parts. First, this chapter starts with a summary of the study. The summary of the study is followed by a discussion of the findings for each of the three main research questions. Third is the recommendations for software practice followed by the recommendations for further research. The purpose of these recommendations are to expand the practice by providing further variables and suggestions for experimentation. The fifth section, conclusions, describes how this study could be considered as an endeavor to contribute to the improvement of the current sustainable production methods in the apparel industry.

Summary of the Study

Traditional practices of pattern cutting within the apparel industry result in a considerable portion of fabric waste that negatively impacts the environment. Currently, garment manufacturers make responding to fashion trends, at the lowest possible cost, the main priority, regardless of fabric waste, to ensure economic profit. In addition, marker efficiency, where textile waste is calculated, is traditionally a technical procedure during the pre-production process that is a reaction to pre-determined designs. On the other hand, one of the sustainable challenges when working with ZWD is the feasibility of pattern grading under the current apparel production system. However, since the Jigsaw ZWD approach is similar to the traditional two-dimensional pattern cutting method, it has the most potential for use in large scale manufacturing of varied sizes, using current grading and marker making practices. As an endeavor to overcome the fitting issues that are associated with current grading practices, even with the use of 3D simulation, this study included both 3D simulation technology and physical sample garments for grading ZWD.

Thus, the purpose of this experimental study was to explore the feasibility of grading zero waste garments for industry production using digital and virtual methods. This study was guided by the Model of Sustainable Fashion Design (Aakko & Sivanon, 2014) as its main aim is to improve the development of sustainable fashion design practices, including the production methods through functional design. This model also proposed the relationship between attachment and appreciation of sustainable fashion design and the development of sustainable practices in the apparel industry. The theoretical framework in this study guided the methods for answering the three main research questions: What pattern piece adjustments and marker layouts achieve both 100% marker efficiency and accurate virtual visual appearance? Can digital 3D simulation be used as an effective and sustainable sizing and fit assessment tool? Does attachment and appreciation of ZWD influence expert judges' evaluation of visual accuracy?

The first research question was answered through a functional design process that included three phases: sample development, grading, and marker making; digital and virtual testing of marker adjustments; and marker refinement. The application of typical and novel marker making and design tactics for functional utilization of the cuts offs resulting in no fabric waste of the mixed marker of the graded sizes was explored. To answer the second and third research questions, an online questionnaire was utilized to collect data through numeric rating using a Likert scale, qualitative comments to support the rating, and responses to open-ended questions to provide validity to the findings. The purpose of the data collection through the questionnaire was the judges' evaluation related to the efficiency of the graded virtual samples compared to the physical based on six design criteria. The purposive and snowball sampling methods were utilized to select the participants for the two groups in this study, six zero waste design academic researchers and six industry technical designers. The judges compared the samples via video, between and across groups. Descriptive statistics methods were used to analyze the quantitative data, whereas the content analysis approach was used to categorize the qualitative responses.

Discussion of Findings

Question One Discussion

The first research question was: What pattern piece adjustments and marker layouts achieve both 100% marker efficiency and accurate virtual visual appearance? The findings from the first research question indicated that four pattern piece adjustments provided 100% marker efficiency and accurate visual appearance across the constructed dresses. However, this adjustment system did not provide accurate visual appearance between the physical and virtual dresses. The adjustment methods in this study were adapted from the methods suggested by Glock and Kunz (2005). These methods are commonly used in marker making to increase fabric efficiency by making changes to the pattern pieces and placement of pieces in the marker. In the current study, some of these adjustment methods by Glock and Kunz (2005) were used, and others were explicitly developed for ZWD to reach 100% marker efficiency.

The combination of adjustment methods used in this study developed a system. These methods included modifying grainline, adjusting visible pattern dimensions, adjusting non-visible pattern dimensions, and utilizing negative space by creating non-visible garment parts.

This system was used sequentially in this study. However, this system may be adapted and or select from based on the marker style.

This system started with two methods that were identified by Glock and Kunz (2005) that included modifying of specified grainline before adjusting visible pattern dimensions. The modification of grainline included tilting and rotating of pattern pieces to improve efficiency. Tilting was a straightforward marker procedure that could be set automatically to modify the grainline in the marker. On the other hand, rotating pieces was effectively applied only to the sleeves in Phase Two. Rotating could be experimented further to include more pattern pieces with a different fabric type and marker style as the drape of the current style would be negatively impacted if the large pattern pieces were laid on the bias or cross grain.

Another technique that was identified by Glock and Kunz (2005) and applied in this study was adjusting pattern dimensions without noticeable change to fit and style. This technique was applied to the skirt dimensions in Phases One and Two by decreasing and increasing skirt width, and it worked to improve the efficiency and relatively maintain the visual accuracy between the control and graded sizes using gathers to manage fabric excess. Adjusting the visible pattern was a method in the system that would be beneficial as one of the initial approaches as it determines the remaining areas of the negative space in the marker. While this method worked with the skirt in this study, it did not work with the panel pieces of the bodice as it influenced the fit and ease when managing fabric waste using darts.

Two more adjustment methods worked efficiently for the internal parts of the constructed dresses. These two methods were developed specifically for ZWD in the current study. One method was adjusting non-visible garment parts. This was primarily accomplished by utilizing negative space as increased seam allowances. However, it is essential to acknowledge the possible impact on fit and drape from the additional bulk. The last adjustment method used in this system was creating non-visible garment parts by utilizing the fabric of the remaining negative spaces in the marker to create neck facings, pockets, and dress hangers. As the neck facings were considered as important garment parts to finish the necklines edges, fall out were first utilized to create both front and back neck facings for both sizes before utilizing the remaining fall out to create the pockets and the dress hangers. Overall, the ZWD style, number of garment parts, and pattern piece shapes would determine the ideal order of the adjustment methods.

One pattern adjustment recommended by Glock and Kunz (2005) was splitting pattern pieces by creating a seam. This technique of splitting the pieces was experimented on the skirt but did not improve the efficiency. However, creating a seam was included in the sleeves in Phase One, but it negatively influenced the visual accuracy between physical control and physical graded dresses. Splitting pattern pieces method could be applied with different fabrics types and different Jigsaw marker styles.

On the other hand, two methods were developed specifically for ZWD in the current study but did not result in visual accuracy between control and graded. One method was developing the sleeves from the negative space. This method was not efficient when applied in the first phase as the difference between the sleeve control and graded dimensions and internal seamlines were obvious. However, this method could work better with other sleeve styles. Another method that was not efficient was creating non-visible hidden parts, such as hem support, as it influenced the drape of the skirt. However, it would work efficiently with different types of fabrics and/or a more fitted silhouette.

The use of Optitex throughout the functional design process was efficient with the regular practice of grading, marker making, and drafting. However, the software did not allow for efficient nor accurate visual representation as a 3D simulation when faced with atypical seam allowances and layering. According to Meng, Mok, and Jin (2012), the interactive style edits in both 2D and 3D garments are efficient when altering patterns; however, in the current study, the application of the adjustments to the pattern pieces were relatively challenging, due to the non-typical approach of ZWD construction.

The challenges stemmed from the unusual combining and layering of pieces that were required in order to maintain zero waste. The software is familiar with joining two pieces with the same seam allowance, but required novel applications to accurately depict varying seam allowances and multiples layers. Another challenge was the amount of time and ripple effect from making a pattern piece adjustment. Each change required the researcher to edit the other pattern pieces onto the avatar. In addition, it was not feasible to overlap the petals of the sleeves when joining the sleeves to armhole. Thus, division of each petal into two pieces was necessary to achieve visual accuracy. Similarly, this overlapping challenge also occurred when joining pocket pieces. Moreover, the gathers simulation did not have accurate drape; the gather line and the resulting drape appeared bulky. A final challenge was the inability to accurately adjust the avatars to the dimensions of the brand of dress forms used in the study. Thus, the grading result was not accurately represented on the avatars.

The findings from this question provide evidence for the importance of the production methods in the Model of Sustainable Fashion Design (Aakko & Sivonene, 2014). Zero waste design must address sizing challenges during the pre-production methods in the functional design process to support industry methods for sustainable development in fashion design.

Question Two Discussion

The second research question was, can digital 3D simulation be used as an effective and sustainable sizing and fit assessment tool? The results of the survey questions indicated various levels of agreement regarding the visual accuracy of fit and appearance between the dresses included in the comparison sets one through four. When comparing the physically constructed control garment to the virtual control garment, the evaluation was neutral with a slight tendency to agree that 3D simulation could be an effective sizing and fit tool. When comparing the controls to their graded sizes, the physically constructed graded dresses had the highest ratings of visual similarity to their control. In contrast, the virtual graded dresses had the lowest ratings for similar appearance to their virtual control. When comparing the constructed graded dresses to their virtual graded dress, the similarity was neutral with size 4 having a slightly higher rating of similarity. Criteria that consistently scored lower for the virtual garments were drape, fit and ease, and distribution of gathers. Song and Ashdown (2015) also reported ease and drape differences between 3D simulation and physical prototypes, and like this study noted needed improvement in the software. Judges' in the study made similar comments regarding the software's capacity to represent the accuracy of gathers. Criteria that were consistently evaluated higher were the location of internal seam lines and dress part dimensions. The location of internal seam lines, including center seamline, princess seamlines, side seams and armhole seamlines were highly rated due to the adjustments made on the measurements and proportion of the virtual avatars to look similar to the physical dress forms.

The expert judges reported more visual similarity across the constructed dresses when compared to the virtual dresses, which was especially true when evaluating the fit and ease. This finding supports prior research findings by Vedder and Daane (2015) that stressed the importance of the actual garments to ensure accurate fit and ease. In terms of grading ZWD, the similarity across the graded constructed dresses does provide support for grading ZWD that has elements of fit and fullness.

Interestingly, the similarity between the virtual control and size 12 compared to the virtual control and size 4 was slightly higher. Noticeable differences were the silhouette, fit and ease, dimensions of dress parts, and overall acceptability. This finding is in contrast to prior research indicating that there are more grading issues when increasing sizes of garments (Schofield & LaBat, 2005). This finding in the current study is likely due to the avatar sizing deficiency to be compatible with the dress form that made visual inaccuracy more evident in the smaller virtual size.

Overall, the results from the second research question indicate that even with the fit issues that influenced the similarity between constructed and virtual ZWD graded dresses, the 3D simulation can reduce the number of physical samples needed to grade ZWD. But the physical samples are still necessary for evaluating fit and appearance for visual accuracy mainly due to the deficiency of 3D simulation to mimic the virtual fabric of the physical garments and the deficiency of current software capacity to simulate the garments with precise, accurate fit. This supports the findings of previous studies that virtual simulation of the sample would be a useful tool to check for major fit issues of different design aspects of the garments (Lee & Park, 2017). Even though virtual samples can not fully replace physical samples, the use of 3D simulation in virtual samples would still be considered as a fit and sustainable tool for grading ZWD. As noted in prior research (Papahristou & Bilalis, 2017; Salmon, 2014), 3D simulation would decrease the number of physical samples through pre-production, thus reducing waste and saving time and cost. Even though these findings may speed up production, the aim of this study emphasized the efficiency of using 3D simulation to reduce the number of physical samples which answered the second research question in this study.

Question Three Discussion

Does attachment and appreciation of ZWD influence expert judges' evaluation of visual accuracy? This question was answered by comparing the judge groups' responses to similarity between the constructed and virtual dresses. The technical design judges had a neutral to slightly agree assessment, while the ZWD judges had a neutral to disagree assessment. The Model of Sustainable Fashion (Aakko & Sivonen, 2014) indicates that the appreciation and attachment to sustainable fashion would necessarily support sustainable production methods. However, when considering both the quantitative data and qualitative comments, appreciation and attachment to sustainable fashion may be seen in the ZWD judges' higher expectations and thus lower evaluations of similarity across constructed and virtual garments.

ZWD judges' were more apt to recommend software capacity improvements for better simulation of 3D virtual samples for ZWD grading. This finding supports research by Kirsi Niinimaki (2015), who found that experimenting with ZWD changes fashion designer's attitude toward textile value in addition to increased appreciation from practicing ZWD approaches. In this study, the appreciation of ZWD may be represented in the higher expectations from the ZWD judges. In order for ZWD to be integrated into the current apparel industry system the software capacity must advance beyond typical preproduction methods to address the unique methods used by zero waste designers.

On the other hand, the technical design judges were more understanding of the software's limitations to accurately visualize the physical samples virtually. This finding supports prior research by Song and Ashdown (2015) who stressed the importance of having expert fit-judges when assessing the fit of 3D simulation compared to physical samples due to their knowledge and expertise in this technology in addition to understanding the nature of the software. Even though technical judges were more understanding of the software's shortcomings, neither group of expert judges found the 3D simulations sufficient enough to replace the ZWD physical samples. Thus, there is a need for improving 3D simulation capacity to minimize the number of physical samples needed for grading ZWD.

Recommendations for Software Improvement

The improvement of the Optitex marker making module and 3D simulation module would be most beneficial for ZWD. A more manageable marker making module that allows for pattern adjustments for each size on the marker platform would be useful to avoid multiple processes of transferring the pattern pieces between Optitex and Adobe files for adjusting the patterns. In addition, more improvements regarding the software's capacity for handling irregular seam allowances and more feasibility for layering patterns with irregular stitching for internal pieces would be beneficial. A challenge of this study was discrepancy between the PGM brand of physical dress forms and the avatar measurements. Thus, the software could include further options to manipulate the avatars. Moreover, the improvement of 3D simulation regarding the texture rendering for gathering is necessary for more realistic views of the gathers. These recommendations for Optitex are based on the researcher's average experience in using Optitex, along with the feedback from the participants in this study, who are researcher academics and expert apparel industry technical designers.

Recommendation for Future Research

Future research could assess the visual impact of fit and appearance of different ZWD styles and different garment categories. In addition, future studies could assess graded ZWD garments in a variety of size ranges. This study included twelve designers as judges, including ZWD academics and technical designers, to evaluate the final actual garments; future studies could include a larger number of judges or different groups of judges, such as apparel consumers. It is also recommended to examine grading of different fabric types, widths, designs or prints, as well as spreading modes, such as face-to-face or single.

Future research could also explore grading ZWD with different pattern piece numbers and pattern shapes, whether with more simple products that have a low number of pattern pieces or with complex products that have a high number. Another valuable exploration would be to examine bias designs. Moreover, this study could be replicated to investigate how ZWD interacts with different body types.

Lastly, this study utilized technology that was available at a particular time of the research process. A noted challenge was the discrepancy between the PGM brand of physical dress forms and the avatar measurements. A recent addition to Optitex software was compatibility with the Alvanon brand dress form measurements. Thus, the use of Alvanon dress forms in future research is highly recommended.

Conclusions

This study focused on grading ZWD patterns as one of the main challenges to produce ZWD in large scales. Due to the similarity between the Jigsaw marker and the marker created for typical pattern cutting, this study represented some findings that would contribute to improving sustainable practices for producing ZWD within the apparel manufacturing current systems.

The findings in this study showed that achieving 100% marker efficiency is feasible in apparel production with the use of the suggested marker adjustment system in this study. The consideration of both visual accuracy and fit through the utilization of all fall out through the suggested pattern adjustment system was achieved. The adjustment methods in the system could be used entirely or partially in the same order used in this study, or they could be used selectively based on the style of the marker.

On the other hand, with the current capacity and functioning of technology, the implementation of 3D simulation to grade ZWD would not be feasible for the apparel manufacturing system to eliminate the physical samples. However, the potential for reducing sample numbers for producing ZWD in large scales would have an enormous positive impact toward sustainable development in the apparel industry. This impact is associated with decreasing the solid waste caused via pre-consumer processes, especially with the increasing pace of production and consumption with the fast fashion phenomenon. The decrease in the number of physical samples would contribute to the three pillars of sustainability by decreasing the impact of soil and air pollution, decreasing the waste of energy consumption, natural resources, and embedded labor and knowledge.

Attachment and appreciation for sustainability may have an influence on developing production methods in the apparel industry. Through the consideration for aesthetics and quality in ZWD garments, sustainable fashion designers may realize the interaction between slow design and functional design through the production methods of ZWD; even though ZWD is considered as a slow fashion principle, the utilization of the functional design process in this study guided the exploration to examine grading ZWD as one major challenge to produce ZWD in a larger scale.

In contrast to post-consumer waste, managing the pre-consumer textile waste is the industry's responsibility to manage by adapting current practices to mitigate the negative influence that is mainly affecting the environment. Even though the total amount of solid waste resulting from the cutting process is little, 10-20%, preventing this waste would be significant. However, since the application of the adjustment methods system that was applied in this study did not succeed virtually, the findings of this study may support that the appreciation and attachment for ZWD would improve the communication within the apparel manufacturing sections by the collaboration between designers, technical design, and construction in terms of managing fabric utilization through the initial stages of design instead of responding to design aesthetics regardless of the utilization of materials. This consideration of unity for both aesthetics and utility would ultimately reduce waste, decrease energy consumption and maximize the utilization of the labor while ensuring the production of ZWD with regard to current aesthetics.

Despite the difficulty of prompt implementation of the findings from this study to the current practices in the apparel production system and/or experimenting with new approaches for grading ZWD, addressing the attachment and appreciation for sustainable apparel design in academia and industry is significant. Attachment and appreciation attitudes toward ZWD may foster efficient collaboration and communication to decrease, if not eliminate, the fall out in marker making processes for typical garment production. In addition, sustainability consideration attitudes would foster designers valuing materials through the initial stages of fashion design with material utility in mind.

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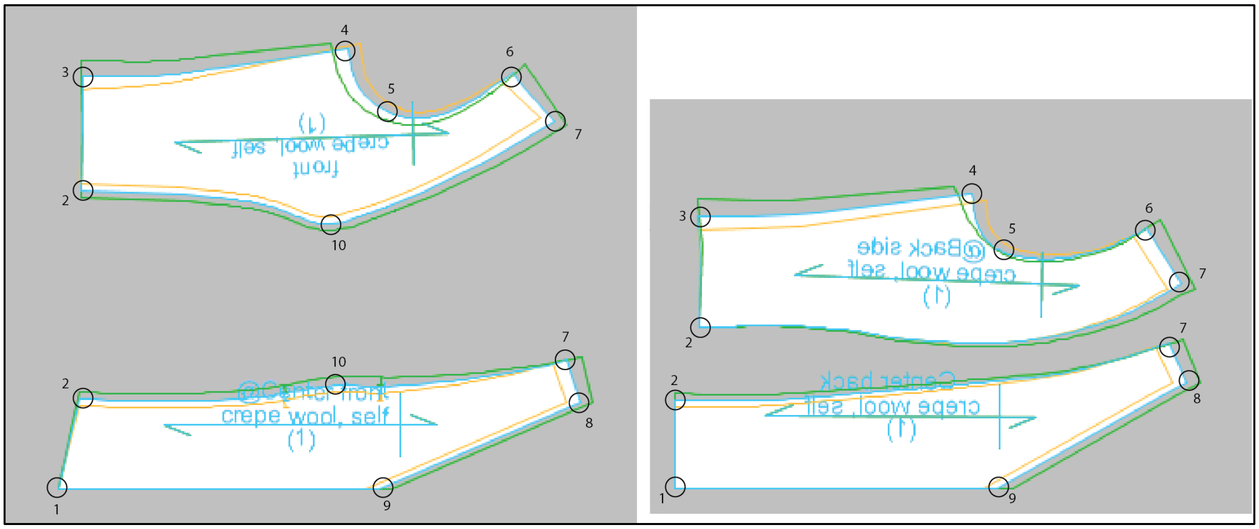
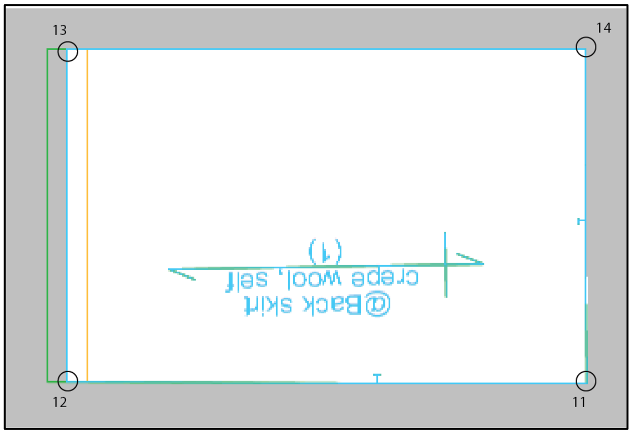
Appendix I
Grade rules

Grade rules for the bodice



Grade rule #		4	8	12
1	X	0	0	0
	Y	0	0	0
2	X	0	0	0
	Y	-1/4	0	1/4
3	X	0	0	0
	Y	-1/2	0	5/8
4	X	-1/4	0	1/4
	Y	-1/2	0	5/8
5	X	-1/4	0	1/4
	Y	-1/4	0	5/16
6	X	-1/2	0	1/2
	Y	-1/4	0	5/16
7	X	-1/2	0	9/16
	Y	-1/8	0	1/8
8	X	-1/2	0	1/2
	Y	0	0	0
9	X	-1/2	0	9/16
	Y	0	0	0
10	X	0	0	0
	Y	1/4	0	5/16

Grade rules for the skirt



Grade rule #		4	8	12
1	X	0	0	0
	Y	0	0	0
2	X	-3/4	0	3/4
	Y	0	0	0
3	X	-3/4	0	3/4
	Y	-1/2	0	5/8
4	X	0	0	0
	Y	-1/2	0	5/8

Appendix II
Letter to the Participants

Grading Zero Waste Design using Digital and Virtual Methods

Dear Participant,

My name is Sahar Ejeimi, a graduate student in the College of Health and Human Sciences, Kansas State University, pursuing a doctorate degree in the Department of Apparel, Textiles, and Interior Design. The purpose of the following questionnaire is to collect information related to grading zero waste designs, a current issue in sustainable fashion design.

The purpose of the study is to explore the feasibility of grading or sizing zero-waste garments for industry production using digital and virtual methods. The exploration included the application of typical and novel marker making and design tactics for functional utilization of the cuts offs resulting in no fabric waste of the mixed marker of the graded sizes. You will be comparing virtual simulations of graded garments to constructed graded garments, between and across groups. Your evaluation will contribute to understanding the effectiveness of sizing zero waste design and use of 3D virtual simulation as a visualization method.

Your completion of the survey will indicate your acceptance to participate in this study. The information gathered from this questionnaire will be used in a research study as partial completion for a doctoral degree. Participant codes will be assigned, and no names will be used during the study.

Please take 30 minutes to respond to the statements. If you are not certain of an exact answer, please provide a close estimate. If you feel uncomfortable assessing any statement, please skip that question. The questionnaire includes two parts. The first part seeks demographic information; the second part seeks your evaluation of graded garments between and across constructed and virtual garments. Please view the video at the beginning of each comparison set and then respond to the statements that follow. Also, please consider using a computer monitor to view the videos, instead of using a cellphone. There are five comparison sets.

Follow this link to the Survey:
${l://SurveyLink?d=Take the Survey}

Or copy and paste the URL below into your internet browser:
${l://SurveyURL}

Follow the link to opt out of future emails:
${l://OptOutLink?d=Click here to unsubscribe}

On behalf of the entire research team, we would like to sincerely thank you for participating in this study. Your responses will be a valuable contribution to this and future work in grading Zero Waste Design garments.

Sincerely,

Sahar Ejeimi, Graduate student	Sherry Haar, Professor
(970) 402-9203 sejeimi@ksu.edu	(785) 532-6993 haar@ksu.edu

Rick Scheidt, IRB Committee Chair
(785) 532-1483
rscheidt@ksu.edu

Appendix III
Online Qualtrics Survey

Grading Zero Waste Design using Digital and Virtual Methods

For any questions regarding this survey, contact Sahar Ejeimi at sejeimi@ksu.edu Definitions of the key terms used in the survey. **Zero Waste Design (ZWD)**: refers to items of clothing that generate little or no waste in their production. **Zero Waste Jigsaw Patterns:** design patterns that are interlocked on fabric with 100% utilization of fabric. **Grading:** the process of systematically increasing and decreasing the size of a master (control) pattern to create a range of sizes. **Control:** pattern size 8 in this study. **Graded:** pattern sizes 4 and 12 in this study. **Virtual:** the 3D simulated garments that were virtually stitched and draped by the researcher using Optitex. **Constructed:** the actual garments that were constructed by the researcher.
PART ONE: Background **Directions.** Please respond to the statements or select the best response to the statements regarding your background. Space is provided at the end of Part One for optional comments.

(1). What is the highest degree or level of school you have completed? If currently enrolled, highest degree received				………………..
(2). What is your current job title?				………………..
(3). How many years have you been working in this profession?				………………..
(4). How would you rate your knowledge and experience with zero waste design?				
Very Low	Low	Average	Below average	Very High
1	2	3	4	5
(5). How would you rate your knowledge and experience with digital pattern grading? and virtual simulation?				
1	2	3	4	5
(6). How would you rate your knowledge and experiecne with virtual simualtion?				
1	2	3	4	5
(7). Optitional comments regarding your experience with zero waste, digital grading, or virtual simualtion.				…………………..

PART TWO: Comparison Sets

Directions. You will be comparing sets of constructed and/or virtual Jigsaw zero waste dresses. There are **five** comparison sets. View the videos and respond to the statements regarding the degree of similarity between the dresses. It is recommended to view the embedded videos with the highest quality setting in YouTube. To adjust the quality, select the settings icon at the lower right of the YouTube screen and then the quality option. Please provide additional comments in the space provided that clarify your assessment.

Comparison Set 1: Constructed Control and Virtual Control
Directions. Play the following video to compare the Control Virtual dress simulation to the Control Constructed dress. Respond to the statements by selecting one option and provide comments explaining your assessment in the space provided.
Constructed Control and Virtual Control

Strongly Disagree 1	Disagree 2	Neutral 3	Agree 4	Strongly Agree 5
(1). Overall, the virtual dress simulation appears the same as the constructed dress.				
1	2	3	4	5
(2). The fabric of the virtual simulation has the same appearance (structure and thickness) and response to the form (drape and ease).				
1	2	3	4	5
(3). The virtual simulation provides enough visual information that sampling in actual fabric is not a necessity.				
1	2	3	4	5
Please add comments to clarify your assessment.				

Comparison Set 2: Control Constructed and **Graded Constructed Dresses.**
Directions. Play the video to compare a Graded Constructed dress to the Control Constructed dress. The control dress is the one on the left. Respond to the statements by selecting one option

and provide comments to explain your assessment in the space provided. There are two comparison pair sets in this section.

Pair 1 Constructed Control and Constructed Small

Strongly Disagree 1	Disagree 2	Neutral 3	Agree 4	Strongly Agree 5
(1). The silhouette or overall shape of Graded appears the same as Control (Compare the outline of the two dresses).				
1	2	3	4	5
(2). The drape or hang of Graded appears the same as Control (compare the folds and falls over the body).				
1	2	3	4	5
(3). The fit and ease Graded has the same proportional distribution as Control (compare the looseness or tightness at waist and bust levels).				
1	2	3	4	5
(4). Dimensions of parts or pieces of Graded have the same proportional dimensions of Control (compare the similarity between sleeve dimensions, bodice dimensions, and skirt dimensions).				
1	2	3	4	5
(5). The location of internal seam lines of graded appear the same as control (compare, center, princess, side, and armhole seams).				
1	2	3	4	5
(6). The distribution of gathers in the skirt of Graded appear the same as Cotnrol (compare the fullness of the skirt).				
1	2	3	4	5
(7). Overall, Graded is acceptable in appearance compared to Control for grading a ZWD design.				
1	2	3	4	5
(8). Please add comments to clarify your assessment				
Pair 2 Constructed Control and Cosntructed Large				

Strongly Disagree 1	Disagree 2	Neutral 3	Agree 4	Strongly Agree 5
(1). The silhouette or overall shape of Graded appears the same as Control (Compare the outline of the two dresses).				
1	2	3	4	5
(2). The drape or hang of Graded appears the same as Control (compare the folds and falls over the body).				
1	2	3	4	5
(3). The fit and ease Graded has the same proportional distribution as Control (compare the looseness or tightness at waist and bust levels).				
1	2	3	4	5
(4). Dimensions of parts or pieces of Graded have the same proportional dimensions of Control (compare the similarity between sleeve dimensions, bodice dimensions, and skirt dimensions).				
1	2	3	4	5
(5). The location of internal seam lines of graded appear the same as control (compare, center, princess, side, and armhole seams).				
1	2	3	4	5
(6). The distribution of gathers in the skirt of Graded appear the same as Cotnrol (compare the fullness of the skirt).				
1	2	3	4	5
(7). Overall, Graded is acceptable in appearance compared to Control for grading a ZWD design.				
1	2	3	4	5
(8). Please add comments to clarify your assessment				

Comparison Set 3: Virtual Control and **Virtual Graded** dresses.
Directions. Play the video to compare a Graded Virtual dress to the Control Virtual dress. The control dress is the one on the left. Respond to the statements by selecting one option and provide comments to explain your assessment in the space provided. There are two comparison pair sets in this section.

Pair 1: Virtual Control and Virtual Small				
				
Strongly Disagree 1	Disagree 2	Neutral 3	Agree 4	Strongly Agree 5
1). The silhouette or overall shape of Graded appears the same as Control (Compare the outline of the two dresses).				
1	2	3	4	5
(2). The drape or hang of Graded appears the same as Control (compare the folds and falls over the body).				
1	2	3	4	5
(3). The fit and ease Graded has the same proportional distribution as Control (compare the looseness or tightness at waist and bust levels).				
1	2	3	4	5
(4). Dimensions of parts or pieces of Graded have the same proportional dimensions of Control (compare the similarity between sleeve dimensions, bodice dimensions, and skirt dimensions).				
1	2	3	4	5
(5). The location of internal seam lines of graded appear the same as control (compare, center, princess, side, and armhole seams).				
1	2	3	4	5
Comments explaining evaluation:				
(6). The distribution of gathers in the skirt of Graded appear the same as Cotnrol (compare the fullness of the skirt).				
1	2	3	4	5
(7). Overall, Graded is acceptable in appearance compared to Control for grading a ZWD design.				
1	2	3	4	5
(8). Please add comments to clarify your assessment				
Pair 2: Virtual Control and Virtual Large				

Strongly Disagree 1	Disagree 2	Neutral 3	Agree 4	Strongly Agree 5
1). The silhouette or overall shape of Graded appears the same as Control (Compare the outline of the two dresses).				
1	2	3	4	5
(2). The drape or hang of Graded appears the same as Control (compare the folds and falls over the body).				
1	2	3	4	5
(3). The fit and ease Graded has the same proportional distribution as Control (compare the looseness or tightness at waist and bust levels).				
1	2	3	4	5
(4). Dimensions of parts or pieces of Graded have the same proportional dimensions of Control (compare the similarity between sleeve dimensions, bodice dimensions, and skirt dimensions).				
1	2	3	4	5
(5). The location of internal seam lines of graded appear the same as control (compare, center, princess, side, and armhole seams).				
1	2	3	4	5
(6). The distribution of gathers in the skirt of Graded appear the same as Cotnrol (compare the fullness of the skirt).				
1	2	3	4	5
(7). Overall, Graded is acceptable in appearance compared to Control for grading a ZWD design.				
1	2	3	4	5
(8). Please add comments to clarify your assessment				

Comparison Set 4: Constructed Graded and **Virtual Graded** dresses.
Directions. Play the video to compare one of the Virtual Graded dresses to its corresponding size of the Constructed Graded dress. Respond to the statements by selecting one option and provide comments to explain your assessment in the space provided. There are two comparison pair sets in this section.

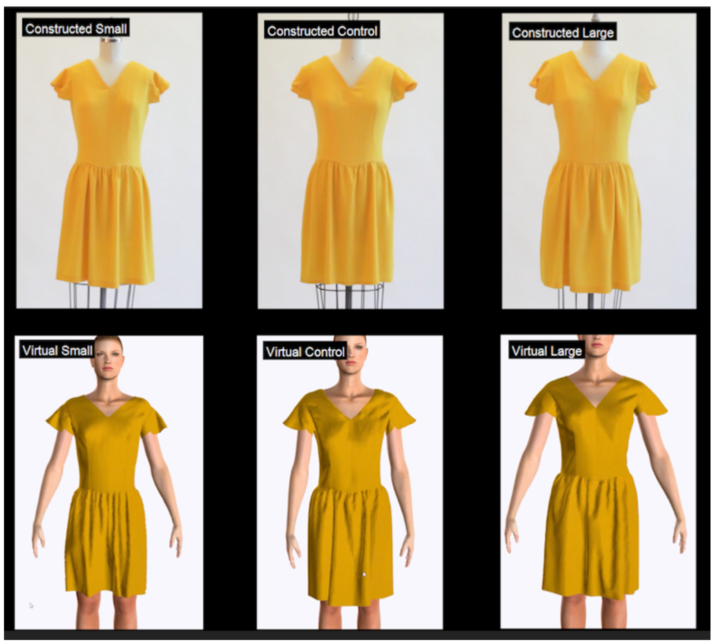
Pair 1: Constructed Small and Virtual Small

Strongly Disagree 1	Disagree 2	Neutral 3	Agree 4	Strongly Agree 5
(1). The silhouette or overall shape of Virtual appears the same as Constructed (Compare the outline of the two dresses).				
1	2	3	4	5
(2). The drape or hang of Virtual appears the same as Constructed (compare the folds and falls over the body).				
1	2	3	4	5
(3). The fit and ease of Virtual has the same proportional distribution as Constructed (compare the looseness or tightness at waist and bust levels).				
1	2	3	4	5
(4). Dimensions of parts or pieces of Virtual have the same proportional dimensions of Constructed (compare the similarity between sleeve dimensions, bodice dimensions, and skirt dimensions).				
1	2	3	4	5
(5). The location of internal lines and construction techniques of Virtual appear the same as Constructed (compare, center, princess, side, and armhole seams).				
1	2	3	4	5
(6). The distribution of gathers in the skirt of Virtual Graded appear the same as Constructed Graded (compare the fullness of the skirt).				
(7). Overall, Virtual is acceptable in appearance compared to Constructed for grading a ZWD design.				
1	2	3	4	5

(8). Please add comments to clarify your assessment

Pair 2: Constructed Large and Virtual Large				
 				
Compare the Graded virtual dress to the graded Constructed dress.				
Strongly Disagree 1	Disagree 2	Neutral 3	Agree 4	Strongly Agree 5
(1). The silhouette or overall shape of Virtual appears the same as Constructed (Compare the outline of the two dresses).				
1	2	3	4	5
(2). The drape or hang of Virtual appears the same as Constructed (compare the folds and falls over the body).				
1	2	3	4	5
(3). The fit and ease of Virtual has the same proportional distribution as Constructed (compare the looseness or tightness at waist and bust levels).				
1	2	3	4	5
(4). Dimensions of parts or pieces of Virtual have the same proportional dimensions of Constructed (compare the similarity between sleeve dimensions, bodice dimensions, and skirt dimensions).				
1	2	3	4	5
(5). The location of internal lines and construction techniques of Virtual appear the same as Constructed (compare, center, princess, side, and armhole seams).				
1	2	3	4	5
(6). The distribution of gathers in the skirt of Virtual Graded appear the same as Constructed Graded (compare the fullness of the skirt).				
1	2	3	4	5
(7). Overall, Virtual is acceptable in appearance compared to Constructed for grading a ZWD design.				

1	2	3	4	5
(8). Please add comments to clarify your assessment				

Comparison Set 5: Constructed Graded Dresses and Virtual Graded Dresses Directions. Play the videos to compare the Constructed three dresses to the Virtual three dresses. Respond to the statements by selecting one option and provide comments to explain your assessment in the space provided.				
				
Strongly Disagree 1	Disagree 2	Neutral 3	Agree 4	Strongly Agree 5
(1). Overall, the virtual dress simulations appear the same as the constructed dresses across the graded and control sizes.				
1	2	3	4	5
(2). The fabric of the virtual simulation has the same appearance (structure and thickness) and response to the form (drape and ease).				
1	2	3	4	5
(3). The virtual simulations provide enough visual information that sampling in actual fabric is not a necessity.				
1	2	3	4	5
Please add comments to clarify your assessment.				
(4). Do you have any final comments?				

Appendix IV

Qualitative data

The qualitative data for the visual accuracy between the physically constructed control garment and the virtually control garment.	
Assessment criteria	
Overall similarity	▪ There are some slight differences, but the overall look is close enough that you know without a doubt that it is the same dress.
Fabric visual similarity	
Sufficient visual information	▪ I'm not 100% sure that sampling is not necessary though. ▪ I think with enough experience in the apparel category and with the fabric, one can eliminate sampling in lieu of virtual prototypes. With less experience, more actual samples will be needed to confirm virtual garment. ▪ Because I have worked with Optitex virtual draping, I know it is difficult to lay the virtual garment as cleanly as you can on a physical dress form with an actual sample. Therefore, I am not too concerned about the pulling at CF and CB near the neckline of the virtual sample or at the armhole. If you could more easily adjust the garment on the avatar AFTER virtual draping, it would look nearly identical to the physical sample. I am hesitant to say that I strongly agree with the second statement (fabric appearance) because you can not press seams in a virtual simulation. The skirt of the dress lays differently on the avatar because of this, particularly at CB. This is also because you can not control gathering as easily or exactly, and Optitex tends to simulate gathers projecting outwards versus laying flat against the body of the avatar. I agree with the final statement (not needing a physical sample) because this simulation gives me enough information about how the garment will look on a consumer that I don't need a prototype. I would still like to have a Fit sample to ensure the garment fit on different body types, or that the fabric behaved how I expected against skin rather than an avatar. This virtual sample is appropriate for confirming styling, but perhaps not total fit or production readiness.

The qualitative data for the visual accuracy between the physically constructed control garment and graded physical constructed garments		
Assessment criteria	Constructed size 4 compared to constructed control	Constructed size 12 compared to constructed control
Silhouette		
	▪ Also sweep looks larger in the smaller size but probably only to a discerning eye.	
Drape		
		▪ The sleeve hang and looks different.
Fit and ease		
	▪ There appears to be some difference in bust fit between the two.	
Dimensions of dress parts		
	▪ Neckline grading seems a little bit off. Neck is higher and narrower on the small than I would expect. ▪ I also noted that the neckline appears proportionately smaller on the graded size than the control. It is not too significant, but again, should be noted. ▪ It looks like the hem is a little longer on the Small (I cannot see part of the horizontal wire frame at the base of the form on the Small where i could on the control).	▪ I was immediately struck by the neckline depth difference. The larger size is not as open in the front neck, not as deep. ▪ Once again, the neckline appears proportionately smaller on the graded than the control. Depending on the needs of the larger consumer, this may be acceptable, but if there needs to be an exact proportional difference, this does not quite fit the need. ▪ The back neck drop looks higher on the Large. The length also appears longer than the control. ▪ The sleeve proportion to the whole looks different. ▪ the proportions are not the same
Internal seams location		
	▪ My only problem with the graded version of the dress is that the waist line appears to have a slightly different slope on the wearer (the control has a slight slope back while the graded is parallel to the floor). This could be dependent on how the researcher dressed the two forms, but it is worth noting. ▪ Again, there are differences in the waistline, with the control sloping to the back more. The waist of the graded model is not even; it hikes up in one place.	▪ The waistline also has the same difference in slope that I noted for the smaller graded sample. ▪ Same problems as before; waist of control drops in the back more (a more flattering line) ▪ Also, the scoop of the waistline in the front seems more pronounced in the control

Distribution of gathers		
	▪ It also looks like the skirt may be a little more gathered than the control. ▪ The gathers are either not proportional between the two models, or are not evenly distributed.	▪ I also note fewer gathers in the large skirt back. ▪ The graded skirt appears to have tighter and more numerous gathers than the control. ▪ It either looks like there are more gathers at the waist or that they are distributed disproportionately towards the front. ▪ gathers are uneven making it hard to compare the fullness of the two models. ▪ The skirt gathering is not the same in the back. ▪ I felt the large also had issues with the distribution of gathering along waist.
Overall acceptability		
	▪ I don't understand this statement: "Overall, Graded is acceptable in appearance compared to Control for grading a ZWD design." ▪ There were a few issues that I would want to address - the shape of the neckline - particularly the neck width, the ease around the bust, and the pitch of the waist seam.	

The qualitative data for the visual accuracy between the virtual control garment and graded		
Assessment criteria Silhouette	Virtual size 4 compared to virtual control	Virtual size 4 compared to virtual control
	▪ I am not entirely sure whether this appearance is happening because of how the sample was virtually draped on the avatar (positioning on shoulder could drastically change how the sample falls) or whether the samples have different proportional amounts of ease. ▪ It looks like the dress is sitting lower on the shoulders of the graded sample. ▪ Skirt silhouette is closer in the graded, fuller in the control. ▪ The main issue I felt was the fullness in the skirt. If that was corrected, then the graded version may be acceptable in only virtual form.	▪ The large appears to be baggy on the body. ▪ The graded version appeared to be fuller with less shaping. ▪ Differences in silhouette of skirt

Drape		
	▪ graded one does appear to drape differently. ▪ The skirt side seam of teh graded does nt fall smoothly.	▪ The skirt side seam of the graded also kicks forward
Fit and ease		
	▪ Fit also different in side back piece with graded looking large x-back to x-chest. ▪ The graded small appears to have much more ease around the bust line while the control appears to have more ease around the chest line. ▪ Fit looks looser in the bodice in graded than control.	▪ Again, the bodice fit of the graded looks looser. ▪ The fit problems in the graded garment seem exaggerated. ▪ Some difference in fit at bust, but slight. ▪ I also felt that there was too much of a difference in the amount of ease seen between the 2 samples.
Dimensions of dress parts		
		▪ The armhole of the graded large looks much smaller on the body than the control. It looks as if the armhole drop is not proportional, and this is causing draping issues around the side seam and the bust. ▪ Necklines appear the same in virtual.
Internal seams location		
		▪ The side seam also looks proportionately longer on the graded large than the control.
Distribution of gathers		
	▪ distribution of gathers is difficult to evaluate with quality of rendering, but since that is same for both skirts ▪ It also looks like the distribution of the fullness was shifted from the across front to the side front. ▪ Gathers just look strange; hard to judge.	▪ The gathers are very uneven, with an actual flat place in the skirt of the graded. The skirt appears to be less gathered. ▪ noticeable difference in skirt gathers ▪ The graded large appears to have significantly fewer gathers around the waist than the control, which surprises me since the constructed samples are the opposite. ▪ Differences in distribution of gathers
Overall acceptability		
	▪ Difficult to assess as the simulated fabric in both skirts seems unlike fabric.	▪ This looks like the best one so far.

The qualitative data for the visual accuracy between the two graded physically constructed garments and their corresponding virtual simulation sizes 4 and 12		
Assessment criteria Silhouette	Virtual size 4 compared to constructed size 4	Virtual size 12 compared to constructed size 12
	▪ Differences in, silhouette of skirt ▪ The sleeves stand out more on the virtual sample than on the constructed. ▪ Difference in angle of neckline ▪ Sleeves look quite different-- the virtual ones are really sticking out, as compared to the constructed ones hanging down.	
Drape		
	▪ It's easier to see the drag lines on the virtual sample. ▪ The virtual skirt does not hang like fabric. ▪ the sweep just doesn't lay right along the hem. ▪ The virtual skirt does not hang like fabric.	▪ The drape on the body looks more frumpy on the virtual sample, and because the waist line is being pushed up by the placement of the avatar's hip, the side seam looks disproportionate.
Fit and ease		
	▪ The virtual does not accurately depict the fit. ▪ Differences in fit of bodice,	▪ The shoulder and hip sit on the virtual avatar differently from the constructed sample, and this affects the analysis of the fit considerably.
Dimensions of dress parts		
	▪ I also don't feel the neckline shapes match between the two. ▪ The sleeve length on the 3D model seemed longer than the constructed garment.	
Internal seams location		
Distribution of gathers		

	▪ Differences in, distribution of gathers ▪ The gathering is possibly okay, but it's the way it's rendered in the 3D version that makes it so different from the original -	▪ as before, acceptable for grading validation however distribution of gathers very difficult to assess virtually. ▪ The constructed sample definitely showcases the gathers better than the virtual - the virtual sample makes them look large and billowy but the constructed shows there are lots of little gathers. ▪ Differences in distribution of gathers
Overall acceptability		
	▪ virtual is acceptable for checking the grade, yes. But not good enough to replace sample for sales. ▪ The physical and virtual samples look very similar, but I feel as if I am making excuses about how similar they look because I know the virtual sample does not sit on the shoulder how the researcher desires it too, all because of how you can manipulate the garment on the virtual avatar	

The qualitative data for evaluations by ZWD designers and technical designers regarding the visual accuracy between the control garment and the sized garments for both constructed and virtual garments

Assessment criteria	ZWD judges	Technical design judges
Overall Similarity between physical and virtual dresses	▪ These are multiple differences in proportions and fit. ▪ Virtual dresses appear to have a lot of needed fit corrections, due to the visible gapping (shadows). The sleeve appears to really stick out, which it does not actually do.	
Fabric visual similarity	▪ there is considerable color difference between the real and virtual. Plus texture of virtual fabric appears to have slight sheen. ▪ The fabric of the virtual appears thicker and	

	drapes less smoothly than the actual fabric.	
Sufficient visual information	▪ The virtual simulations (across samples) give an illusion of ill fit (pulling of fabric) that is not present/visible in the actual sample. The textile in the VS also appears to have a greater sheen and less body/structure than observed in the physical sample. ▪ Simulation is a good tool to make quick assessments of potential problems but again, it doesn't replace the need to make a sample. In zero waste, making a sample of every size is likely essential.	▪ Because of the drape of the virtual fabric and the positioning of the shoulder, I would be comfortable seeing these as styling confirmation, but not fit confirmation for this style. ▪ 5The virtual samples and the constructed sample share enough similarities that I feel the constructed samples would not be needed, especially for a size run. ▪ Again, it's all about the intent of the physical sample. For fit, I would not approve these. However, if the grading was tweaked, then it might be acceptable. In other words, it may be an issue with the grading more so than the actual concept of using virtual samples in place of physical samples. The virtual samples will allow you to make those comments so much quicker than waiting on an actual set of physical samples. ▪ I believe that 3D rendering is a great way to reduce sampling and to visualize details/fit across a range of sizes that may not always be accessible in dress form/fit model. Rendering the fabric seems to be one of the bigger challenges and leads to most of the discrepancies between 3D and constructed.

Final open ended question: you have any comments?

Technical design judge: I think this shows the distinct shortcomings of Optitex virtual draping. It is difficult to position the garment correctly on the body, and therefore difficult to use Optitex as a Fit confirming software. Style confirming yes, but not as accurate for Fit or production readiness.

ZWD judge: Even if these were a closer match, fitting in fabric for at least the control size will be necessary. Small fit issues that are not apparent in an image can be identified by a trained live fit model. It is certainly possible to reduce the number of fitting with a live model using virtual technology, but the way the garment fits and moves with the body in different fabrics cannot be assessed with current technology. This may noever be possible, unless the technology begins to actually model fabric behavior instead of mimicking it.

ZWD judge: I highly recommend looking Veronica Glitsch (Norway) for her research on grading. While not specifically about zero waste fashion design, her research is significant for the field. I also suggest giving feedback to the software developer as there is an opportunity to better simulate the hang of the fabric. Thank you for the opportunity to respond.

Technical design judge: Great survey! Thanks for including me!

Technical design judge: I believe that 3D rendering is a great way to reduce sampling and to visualize details/fit across a range of sizes that may not always be accessible in dress form/fit model. Rendering the fabric seems to be one of the bigger challenges and leads to most of the discrepancies between 3D and constructed.