Engineered repeating prints: computer-aided design approaches to achieving continuity of repeating print across a garment using digital engineered print method

A thesis submitted in fulfilment of the requirements for the degree of Master of Technology (Fashion and Textiles)

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Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis/project is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

Olga Gavrilenko
25.02.2016

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## Contents

Abstract ........................................................................................................................................... 1

1. Introduction ................................................................................................................................... 2
   1.1. Purpose of Research .................................................................................................................. 2
   1.2. Research Objectives .................................................................................................................. 3
   1.3. Significance of Study .................................................................................................................. 4
   1.4. Scope of Study ............................................................................................................................ 4
   1.5. Organisation of Thesis ................................................................................................................. 4

2. Literature Review: Design of Repeating Textile Prints for Digital Engineered Printing Method ........................................................................................................................................... 6
   2.1. Changes in Apparel Market and Digital Technologies Furthering Engineered Printing .............. 6
      2.1.1 Transition from mass production to mass customisation .......................................................... 6
      2.1.2 Digital textile printing technology .......................................................................................... 8
      2.1.3 Computer-aided print design technology ................................................................................. 11
      2.1.4 Vector and raster graphics .................................................................................................... 13
   2.2. Design Process for Textile Prints .............................................................................................. 14
      2.2.1 Printed textile design as a domain ....................................................................................... 14
      2.2.2 The influence of printing methods on design styles ............................................................. 16
      2.2.3 Print design process .............................................................................................................. 18
         Traditional print design process ................................................................................................. 18
         Computer-aided textile print design ............................................................................................ 20
         Print design for digital textile printing ....................................................................................... 21
   2.3. Garment Patterns Design Process ............................................................................................ 22
      2.3.1 Patterns design process ......................................................................................................... 22
      2.3.2 Grading process in CAD environment .................................................................................. 25
   2.4. Integrated Print-Garment Design ............................................................................................... 26
      2.4.1 Engineered print definition ................................................................................................... 26
      2.4.2 Integrated design approach, challenges and opportunities .................................................... 28
      2.4.3 Integrated approach in practice ............................................................................................ 31
      2.4.4 Current challenges involved in adopting engineered design ................................................ 32
      2.4.5 The future outlook for the use of digital technologies for engineered printing .................... 33
   2.5. Summary of Literature Review .................................................................................................. 36

3. Research Methodology .................................................................................................................. 39
   3.1. Introduction .............................................................................................................................. 39
   3.2. Mixed Methods Approach ....................................................................................................... 40
   3.3. Researcher’s Role ....................................................................................................................... 42

4. Qualitative Stage One .................................................................................................................... 43
   4.1. Research Objectives .................................................................................................................. 43
   4.2. Stage One Methodology .......................................................................................................... 43
   4.3. Sample Selection ....................................................................................................................... 44
   4.4. Data Analysis Procedures ........................................................................................................ 44
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5. Validity and Reliability</td>
<td>45</td>
</tr>
<tr>
<td>4.6. Stage One Results: Code-Tree Model and Taxonomy of Repeating Print</td>
<td>46</td>
</tr>
<tr>
<td>4.7. Conclusion</td>
<td>50</td>
</tr>
<tr>
<td>5. General Stage Two Research Procedures and Tools</td>
<td>51</td>
</tr>
<tr>
<td>5.1. Introduction</td>
<td>51</td>
</tr>
<tr>
<td>5.2. Dynamic Editing Tools in Adobe CAD Software</td>
<td>51</td>
</tr>
<tr>
<td>5.3. Analytical and Workflow Tools in Adobe CAD Software</td>
<td>53</td>
</tr>
<tr>
<td>5.4. Wolfram Mathematica Programming Routines</td>
<td>53</td>
</tr>
<tr>
<td>5.5. Statistical Analyses Procedures</td>
<td>53</td>
</tr>
<tr>
<td>6. Experiment One: Dynamic Manipulation of a Repeating Print Formation</td>
<td>54</td>
</tr>
<tr>
<td>6.1. Methods</td>
<td>54</td>
</tr>
<tr>
<td>6.1.1 Introduction</td>
<td>54</td>
</tr>
<tr>
<td>6.1.2 Experiment One objectives</td>
<td>54</td>
</tr>
<tr>
<td>6.1.3 Population and sample</td>
<td>55</td>
</tr>
<tr>
<td>6.1.4 Experimental procedures</td>
<td>55</td>
</tr>
<tr>
<td>6.2. Results and Discussion</td>
<td>57</td>
</tr>
<tr>
<td>7. Experiment Two: Flexible Tiling of a Repeating Print Formation</td>
<td>59</td>
</tr>
<tr>
<td>7.1. Methods</td>
<td>59</td>
</tr>
<tr>
<td>7.1.1 Introduction</td>
<td>59</td>
</tr>
<tr>
<td>7.1.2 Experiment Two objectives and hypotheses</td>
<td>59</td>
</tr>
<tr>
<td>7.1.3 Research design</td>
<td>60</td>
</tr>
<tr>
<td>7.1.4 Population and sample</td>
<td>60</td>
</tr>
<tr>
<td>7.1.5 Variables and measures</td>
<td>61</td>
</tr>
<tr>
<td>7.1.6 Experimental procedures</td>
<td>61</td>
</tr>
<tr>
<td>7.1.7 Statistical analyses procedures</td>
<td>64</td>
</tr>
<tr>
<td>7.2. Results and Analyses</td>
<td>64</td>
</tr>
<tr>
<td>7.2.1 Descriptive analyses</td>
<td>64</td>
</tr>
<tr>
<td>7.2.2 Group comparisons</td>
<td>67</td>
</tr>
<tr>
<td>7.2.3 Additional statistical analyses</td>
<td>70</td>
</tr>
<tr>
<td>7.2.4 Conclusion</td>
<td>71</td>
</tr>
<tr>
<td>8. Experiment Three: Dynamic Manipulation of a Repeating Print Formation with a Distortion Mesh</td>
<td>72</td>
</tr>
<tr>
<td>8.1. Methods</td>
<td>72</td>
</tr>
<tr>
<td>8.1.1 Introduction</td>
<td>72</td>
</tr>
<tr>
<td>8.1.2 Experiment Three objectives and hypotheses</td>
<td>72</td>
</tr>
<tr>
<td>8.1.3 Research design</td>
<td>73</td>
</tr>
<tr>
<td>8.1.4 Population and sample</td>
<td>74</td>
</tr>
<tr>
<td>8.1.5 Variables and measures</td>
<td>74</td>
</tr>
<tr>
<td>8.1.6 Experimental procedures</td>
<td>75</td>
</tr>
<tr>
<td>8.1.7 Statistical analyses procedures</td>
<td>77</td>
</tr>
<tr>
<td>8.2. Results, Analyses and Discussion</td>
<td>77</td>
</tr>
</tbody>
</table>
8.2.1 Descriptive analyses ................................................................. 77
8.2.2 Group comparisons ........................................................................ 78
8.2.3 Correlations .............................................................................. 79
8.2.4 Linear regression .......................................................................... 81
8.2.5 Conclusion ................................................................................. 84

9. Experiment Four: Dynamic Manipulation of a Repeating Print Formation for Engineered Printing of Graded Garments ................................................................. 85

9.1. Methods.............................................................................................. 85
9.1.1 Experiment Four objectives and hypotheses ............................................... 85
9.1.2 Research design ............................................................................. 85
9.1.3 Population and sample ..................................................................... 87
9.1.4 Variables and measures ..................................................................... 87
9.1.5 Rating protocol instrument............................................................... 89
9.1.6 Experimental procedures ............................................................... 89
9.1.7 Statistical analyses procedures ....................................................... 97

9.2. Results, Analyses and Discussion .......................................................... 97
9.2.1 Descriptive analyses ....................................................................... 97
9.2.2 Group comparison tests .................................................................. 101
9.2.3 Correlations .................................................................................. 105
9.2.4 Principal components analysis ......................................................... 105
9.2.5 Conclusion ................................................................................... 108

10. Stage Three ......................................................................................... 110
10.1. Discussion ..................................................................................... 110
10.2. Limitations of the Research ............................................................ 116
10.3. Findings in Relation to Repeating Print Attributes ................................. 118
10.4. Recommendations and Future Research Directions ............................ 119
10.5. Conclusion .................................................................................... 120
References ............................................................................................. 121
Glossary and abbreviations...................................................................... 129
List of Figures

Figure 1  Textile pint design process, adopted from (Powell & Cassill 2006; Studd 2002; Tyler 2005; Wilson 2001) ................................................................................................................................... 19
Figure 2  Comparison between CAD methods for garment patterns development ................. 23
Figure 3  Potential integrated engineered print-garment design process ................................. 30
Figure 4  Initial stage in the development of the code-tree .......................................................... 46
Figure 5  The extended code-tree of repeating prints .................................................................. 47
Figure 6  Examples of actual repeating print images .................................................................. 48
Figure 7  Examples of repeating print attributes identified in an image .................................... 48
Figure 8  Guidelines setup for the template ................................................................................. 55
Figure 9  Placeholder tiles symbols: (a) border corner, (b) border, (c) inside corner border, (d) 1/16 sector ................................................................................................................................. 55
Figure 10  Border corner and border symbol transformations ..................................................... 55
Figure 11  Border module after two transformations resulting in one side border ..................... 55
Figure 12  Border group transformation resulting in complete border module ............................. 56
Figure 13  Inside corner tile transformation ................................................................................ 56
Figure 14  Centre sector module transformation (a) and completed template (b) ......................... 56
Figure 15  Art tiles symbols: (a) border corner, (b) border, (c) inside corner border, (d) 1/16 sector . .............................................................................................................................................. 57
Figure 16  (a) Placeholder tiles are replaced with art tiles forming complete bandana design and (b) second completed bandana ........................................................................................................ 57
Figure 17  Fifteen selected F characters ......................................................................................... 61
Figure 18  Pattern fill swatches for 15 typefaces ......................................................................... 61
Figure 19  Set-up (a) Mainstream model and (b) Flexible Tiling model ....................................... 63
Figure 20  (a) The print areas falling outside of garment pattern were measured with shape layer visible, and (b) the total areas of print were measured with shape layer invisible ........................................................................... 63
Figure 21  Foreground and background areas falling (a) outside, (b) total and (c) inside garment pattern shape ........................................................................................................................... 63
Figure 22  Boxplots for foreground and background elements ..................................................... 66
Figure 23  Distributions for foreground elements of print: (a) outside of garment pattern shape and (b) inside of garment pattern shape................................................................. 66
Figure 24  Distributions for background elements of print: (a) outside of garment pattern shape and (b) inside of garment pattern shape........................................................................................... 67
Figure 25  Error Bar plots for 95% CI: (a) background elements outside garment pattern shape and (b) foreground elements outside garment pattern shape ................................................................. 69
Figure 26  Error Bar plots for 95% CI: (a) foreground to background ratio outside garment pattern shape and (b) foreground to background ratio inside garment pattern shape ........................................ 70
Figure 27  Plot for future sample size determination ..................................................................... 71
Figure 28  Template set-up: (a) Distortion group, (b) control group and (c) ideal print ............. 75
Figure 29  Rotated and aligned garment patterns shown with 100px repeat tiles: (a) Symbols of Front and Back garment patterns with distortion mesh inside positioned over vertical side seam artboard #1, (b) Symbols of Front and Back garment patterns with Pattern Fill as appearance positioned over vertical side seam artboard #2, (c) Rectangular shape over artboard #3 ................................................................................................................................. 75
Figure 30  Edge length calculations ............................................................................................... 76
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>Number of colours calculations</td>
</tr>
<tr>
<td>32</td>
<td>Boxplot comparison of Distortion and Control groups for grey value mean by repeat size</td>
</tr>
<tr>
<td>33</td>
<td>Frequency distributions for Distortion and Control groups for grey value mean</td>
</tr>
<tr>
<td>34</td>
<td>95%CI for grey value mean for two groups</td>
</tr>
<tr>
<td>35</td>
<td>Scatterplot of grey value mean to edge length with regression lines fitted</td>
</tr>
<tr>
<td>36</td>
<td>Fitted linear regression model for colours number for Distortion group</td>
</tr>
<tr>
<td>37</td>
<td>Edge length and motifs number calculations</td>
</tr>
<tr>
<td>38</td>
<td>Number of colours calculations</td>
</tr>
<tr>
<td>39</td>
<td>Snapshots from VStitcher in the same size without avatar for ratings 1 and 2, camera views 05-09. Demonstrated for print 01 (a) yardage group and (b) dynamic group</td>
</tr>
<tr>
<td>40</td>
<td>Snapshots from VStitcher all three sizes together without avatar for rating 3, sorted by camera view. Demonstrated for print 05, camera view 05 (a) yardage group and (b) dynamic group</td>
</tr>
<tr>
<td>41</td>
<td>Snapshots from VStitcher in the same size with avatar for rating 4, camera views 01-04. Demonstrated for print 07 (a) yardage group and (b) dynamic group</td>
</tr>
<tr>
<td>42</td>
<td>Snapshots from VStitcher with avatar for rating 5 all three sizes together sorted by camera view. Demonstrated for print 02 camera view 06 (a) yardage group and (b) dynamic group</td>
</tr>
<tr>
<td>43</td>
<td>Ready-to-print images with seams joined and all sizes together for rating 6. Demonstrated for print 06 (a) yardage group and (b) dynamic group</td>
</tr>
<tr>
<td>44</td>
<td>Ready-to-print images sorted by garment pattern piece for all three sizes together for rating 7. Demonstrated for print 04 front pattern piece (a) yardage group and (b) dynamic group</td>
</tr>
<tr>
<td>45</td>
<td>Ten repeats swatches</td>
</tr>
<tr>
<td>46</td>
<td>(a) Pattern Brushes and (b) Pattern Brush properties</td>
</tr>
<tr>
<td>47</td>
<td>Distorting size 10 JPGs to match sizes 8 and 12 outlines in Photoshop, demonstrated with print 01</td>
</tr>
<tr>
<td>48</td>
<td>Creating size 8 and 12 avatar bodies</td>
</tr>
<tr>
<td>49</td>
<td>Graded dress patterns</td>
</tr>
<tr>
<td>50</td>
<td>Camera settings and views for snapshots of simulated garments</td>
</tr>
<tr>
<td>51</td>
<td>Frequency for accuracy of matching R1</td>
</tr>
<tr>
<td>52</td>
<td>Frequency for print flow R2</td>
</tr>
<tr>
<td>53</td>
<td>Frequency for garment registration 3D R3</td>
</tr>
<tr>
<td>54</td>
<td>Frequency for tile fidelity R4</td>
</tr>
<tr>
<td>55</td>
<td>Frequency for visual proportion in 3D R5</td>
</tr>
<tr>
<td>56</td>
<td>Frequency for RTP flow in 2D R6</td>
</tr>
<tr>
<td>57</td>
<td>Frequency for RTP registration in 2D R7</td>
</tr>
<tr>
<td>58</td>
<td>95% CI for experiment four ratings</td>
</tr>
<tr>
<td>59</td>
<td>95% CI error bar plots for accuracy of matching R1 components separately</td>
</tr>
<tr>
<td>60</td>
<td>95% CI for dynamic and yardage groups by R1 components and garment sizes</td>
</tr>
<tr>
<td>61</td>
<td>Scree plot</td>
</tr>
</tbody>
</table>
List of Tables

Table 1: Principal file formats, adopted from Dawson (2006) .............................................................. 14
Table 2: Ranked and categorised list of universal apparel evaluative criteria, adopted from May-Plumlee & Little (2006) ................................................................................................... 27
Table 3: Cutting-marker utilisation depending on the type of fabric pattern and pattern-repeat size, adopted from Geršak (2013) ................................................................................................... 28
Table 4: Taxonomy for repeating print with quantititative attributes .................................................... 49
Table 5: List of initially collected variables for Flexible Tiling direction ................................................ 62
Table 6: List of selected fonts ................................................................................................................ 62
Table 7: Descriptive statistics, Flexible Tiling group ............................................................................. 65
Table 8: Descriptive statistics, Mainstream print group ........................................................................ 65
Table 9: t-test results for Flexible Tiling experiment ............................................................................. 68
Table 10: Repeat designs ...................................................................................................................... 73
Table 11: List of Distortion experiment variables ................................................................................ 74
Table 12: Distortion study code sheet ................................................................................................ 74
Table 13: Descriptive statistics for grey value mean ............................................................................. 77
Table 14: Tests of normality for Control group .................................................................................... 79
Table 15: Tests of normality for Distortion group ................................................................................ 79
Table 16: Independent samples t-test for grey value mean................................................................. 79
Table 17: Correlations between repeat size and grey value mean ...................................................... 80
Table 18: Correlations between edge length and grey value mean ..................................................... 80
Table 19: Correlations between colours and grey value mean ........................................................ 80
Table 20: Linear regression analyses between grey value mean and edge length ............................ 81
Table 21: Linear regression analyses between grey value mean and colours number ....................... 83
Table 22: Experiment Four, list of variables ........................................................................................ 86
Table 23: Code sheet for Experiment Four ........................................................................................... 88
Table 24: Collected ratings .................................................................................................................... 89
Table 25: Measures of central tendency and variation ........................................................................ 98
Table 26: Tests of normality for experiment four variables ................................................................. 100
Table 27: t-test results for experiment four ratings ............................................................................ 101
Table 28: Correlations analyses for experiment four ........................................................................... 104
Table 29: KMO and Bartlett’s test ..................................................................................................... 105
Table 30: Component matrix\(^x\) ........................................................................................................... 106
Table 31: Reliability statistics ............................................................................................................. 106
Table 32: Parallel analysis based on minimum rank factor analysis ................................................ 108
Table 33: Unrotated loading matrix ..................................................................................................... 108
List of Videos

Video 1  Template set-up for yardage group, demonstrating how artboards were populated with sample repeats ................................................................................................................................94

Video 2  Template set-up for dynamic group, demonstrating how artboards were populated with sample repeats ................................................................................................................................94
Abstract

This Master’s research investigated approaches for engineering of repeating prints using digital textile printing technology and universally available computer-aided design software. Current practices for alignment of designs in yardage printed fabrics at garment seams are wasteful and do not allow for mass customisation. This inefficiency can be overcome with engineered digital printing, a method that allows for an integration of prints with garment patterns to generate Ready-to-Print images. Engineered printing offers more cost-effective use of materials, improved visual appearance, potential for mass customisation and more sustainable manufacturing. Still, technical difficulties exist in the integration of prints with garment patterns. The integration of repeating prints presents even more difficulties. However, the advances in digital printing technology and computer-aided design software call for an examination of possible approaches for achieving improved continuity of a repeating print across a garment.

The research used a three stage mixed method approach. The first qualitative stage examined current practices for design of repeating prints and mainstream and digital printing. By examining the literature and undertaking Applied Thematic Analysis the diversity of meanings assigned to words describing attributes of repeating prints as a result of historical and current usage were identified. The analysis consolidated the terminology and established a taxonomy of repeating print attributes. Three levels of taxonomy were observed: a superordinate level for a printed surface, a basic level for a repeat, and a subordinate level for a motif. Quantifiable attributes of repeating prints were assigned to each level. The analysis also suggested three potential directions for engineered repeating prints: Modularity Design, Flexible Tiling and Distortion.

The second quantitative stage of this project evaluated suggested design directions in four separate experimental studies: one for each of the three directions and a final study combining all three directions to engineer repeating prints for a graded garment. Practical computer-aided design techniques, based on accessible Adobe software tools, were developed for integration of repeating prints with garment patterns. The techniques were then tested in comparison with traditional practices associated with rotary and screen printing. In each experiment, repeating print attributes such as repeat size, complexity, and number of colours and motifs in a repeat were examined for their impact on the adaptability of repeating prints for engineered printing. All three directions were validated as suitable for engineering of repeating prints. Statistical analyses revealed relationships between repeating print attributes and their impact on the adaptability of repeating prints for the engineered printing method.

The final stage analysed the combined results of the previous two stages. Existing computer-aided design solutions were found to offer opportunities regarding their ability to be integrated into current digital production for innovative and sustainable engineered printing. While the suggested techniques require knowledge of more advanced dynamic editing tools, the research highlights the benefits for both fashion and textile designers to utilise such tools in order to fully embrace the potential digital printing technology has to offer. The research also highlights the need for dedicated software solutions for integration of repeating prints with garment patterns. The findings on the impact of repeating print attributes on the adaptability for engineered printing can help in the development of dedicated software.
Chapter 1 Introduction

1. Introduction

1.1. Purpose of Research

Innovation in visual appearance can promote differentiation and create a competitive edge for a fashion garment (Tyler 2005). Concerning visual aesthetics, colour and decorative pattern are identified as two of the most significant attributes that affect customer choices (May-Plumlee & Little 2006). At the same time, efficient fabric utilisation is important, as almost half of garment cost is related to the materials used (Bond 2008). Currently, a standard practice is to cut yardage printed fabric using a cutting marker with garment pattern pieces positioned to ensure the repeating print aligns at key positions of the garments, such as centre neckline and the main seams. Such practice enhances the garment’s visual appearance, but also increases the amount of fabric used (Geršak 2013). A way to overcome this inefficiency and improve the visual continuity of a repeating print across the whole garment would be to utilise digital printing technology. If digital printing is used instead of the mainstream printing technologies, print alignment can be achieved through an engineered printing (EP) method (Lamar 2011). An EP method could also allow for optimum utilisation of base fabric and colouration agent.

The engineering of a print design involves the integration of a design with garment patterns for aesthetic purposes. Traditionally, the EP method has been used for printing designs onto one-off garments for a fashion show. It is only the successful designs that were later adapted into repeating prints for production (Braddock & O’Mahony 1998). Improvements in digital printing technology allowed extending the method to include Ready-to-Print (RTP) images, which are digital images of garment pattern pieces with print designs inside. For the EP method, non-repeating print designs are engineered to fit within garment pattern pieces and continue across garment seams (Parrillo-Chapman 2004).

The commercial application of the EP method using RTP images has, however, been hindered by the inadequate manufacturing techniques for such print-integrated garments, the lack of technical expertise of practitioners necessary for such integration, and limited access to technology or dissatisfaction with capabilities of computer-aided design (CAD) technologies (Parrillo-Chapman 2008). RTP images still require manual positioning of print elements inside each garment pattern to achieve continuity of print across seams and manual scaling of print elements for the preservation of the original design intent between graded garment sizes. Such highly iterative practice also requires extensive collaboration between designers and technicians (Parrillo-Chapman & Little 2012), resulting in escalation of the product development cost and reducing the EP commercial application for the mass market.

For repeating prints, such necessary manual alterations can be even more complicated and time-consuming. However, if manual alterations can be handled by a programming solution, then the feasibility of the EP method for repeating prints could be improved. In fact, development of dedicated programming solutions for engineering of repeating prints has been anticipated (Briggs-Goode & Russell 2011). Software solutions for the generation of decorative designs have been explored (Russell 2014; Zamani, Amani-Tehran & Latifi 2009), but engineering a repeating
print to fit within garment pattern shapes remains unresolved. Alternatives, such as surface texture mapping tools used for computer animation or gaming applications have also been investigated (Gomes, Velho, Frery & Levy 2009; Kaplan 2009; Magnenat-Thalmann & Thalmann 1987). However, to date the complexity of 3D garment shapes and the precision required for EP of repeating designs exceed the capabilities of these tools.

The various stages of technological innovation in textile printing methods can be characterised by distinct print design styles (Ujiie 2006). So far, design directions for EP have focused on exploiting the digital printing potential for achieving photographic image qualities, non-repeating placement type designs and mirrored designs. These design styles highlight the advantages of unlimited colour range and absence of repeat requirement compared to traditional printing methods of rotary and screen printing. However, in the area of repeating prints only limited research has been undertaken. There is significant scope to develop design directions that utilise an EP method for the repeating print design to continue across the garment’s seams.

In considering an EP method for repeating prints, the key attributes for a repeating print need to be identified and understood regarding how these attributes may affect a given print’s adaptability for an EP method. Currently, there is limited literature about the effect of attributes of repeating prints on their adaptability for the EP method. In addition, there are currently no universally available dedicated software solutions to achieve engineering of repeating prints.

This Master’s research proposes potential design directions for engineering of repeating prints and suggests possible CAD approaches to achieve improved continuity of repeating print design across a garment. In doing so, the research examines how processing of repeating prints for RTP images can be streamlined with existing advanced tools of universal CAD software to develop techniques for generating RTP images that provide improved print continuity over a garment’s surface across seams and preserve the original design intent between graded garment sizes. These suggested design directions and processing techniques were examined and validated in four experimental studies. Moreover, attributes of repeating prints were identified, quantified and statistically analysed to determine their impact on the adaptability of repeating prints for EP methods.

### 1.2. Research Objectives

This Master’s thesis examines the effect of repeating print attributes on the adaptability of repeating prints for EP method and identifies potential design directions for engineered repeating prints. In doing this, the objectives of this research are to:

- examine current practices for mainstream and digital pre-printing and printing;
- establish a taxonomy of repeating print attributes;
- identify potential design directions for repeating prints adaptable for EP;
- suggest approaches for design directions, based on existing CAD tools, for integrating repeating prints with garment patterns and generating RTP images for graded garments;
- validate these directions experimentally by testing hypotheses;
- examine the impact of repeating print attributes on the adaptability of repeating prints for EP;
• contribute to the advancement of EP towards mainstream digital production by increasing the adaptability of repeating prints.

1.3. Significance of Study

This study suggests potential directions for design of repeating prints for EP and a more streamlined workflow for integrating repeating prints with garment patterns. In doing so the research will provide:

• textile designers with information on potential directions for design of engineered repeating prints, and attributes of repeating prints that can impact their adaptability for EP method;
• fashion designers with a streamlined workflow for integration of repeating prints with garment patterns and a demonstration of the potential for integrated repeating print-garment design;
• software developers with information on repeating print attributes that can assist in the development of dedicated programming solutions for EP or upgrades of the existing garment and textile CAD modules.

This research highlights the advantages of digital printing and promotes its acceptance as a mainstream printing technology for repeating prints by the apparel industry. The research could also assist a mass customisation fashion business to:

• gain a competitive edge through improving the product’s visual aesthetics with continuity of repeating print across the garment’s seams;
• support their existing Just-in-Time solutions and reduce the time that is currently required for engineering of repeating prints for graded patterns;
• support more sustainable manufacturing methods by reducing fabric and colourant consumption.

1.4. Scope of Study

At the moment, universal and proprietary software packages are used in the apparel industry. For new or small businesses, however, it is often not feasible to invest in expensive proprietary software or plug-ins for universal software. In order for this research to have applicability to a wider community of users, the CAD techniques used were limited to universal software as a more available and popular option for potential users of these methods. The techniques were demonstrated using only Adobe CC applications, namely Photoshop, Illustrator and InDesign, but similar workflows can be created using Corel Draw. In addition, Browzwear VSticher software was used to simulate the garments virtually to support data collection for statistical analyses.

1.5. Organisation of Thesis

The organisation of this thesis is as follows:

Chapter One outlines the research study including the study objectives, the significance of the study, its scope and key definitions for the main concepts.
Chapter Two reviews the current literature on technologies and methods utilised for industrial printing and textile and garment design processes in regards to their relevance for engineered printing of repeating prints.

Chapter Three provides an overview of the mixed-method methodology and its application in this study.

Chapter Four sets out the qualitative Stage One of this project presenting the taxonomy of repeating print attributes and identified potential design directions for the development of engineered repeating prints.

Chapter Five explains the methods used for quantitative Stage Two of the research.

Chapters Six, Seven, Eight and Nine outline the four experiments that investigate potential directions for the engineering of repeating prints. Each conducted experiment is reported with a set of hypotheses, results, analysis and the discussion.

Chapter Ten provides a final discussion of the key findings of the results of Stages One and Two. Conclusions are given and future research directions considered.

References cited in this study are given, and the Glossary and Abbreviations are provided.
Chapter 2 Literature Review

2. Literature Review: Design of Repeating Textile Prints for Digital Engineered Printing Method

This chapter investigates the latest developments and current challenges for the integration of repeating prints with garment patterns for digital textile printing (DTP) using a computer-aided editing approach. Such an approach is referred to as an engineered printing (EP) method.

Digital technologies in textile and apparel industries are developing rapidly. But the full potential of these technologies is not yet fully realised, and changes are required in design and manufacturing processes. In particular, the current methods for integration of repeating prints with garment patterns are insufficient. In the textile print domain, three digital technologies are of particular interest: DTP, computer-aided design (CAD) and 3D virtual prototyping environment. The current advances in these technologies indicate a possibility of wide commercial application for engineered printing, as well as point towards the practicality of such method due to its sustainability and aesthetic appeal.

This chapter will start by looking at apparel market changes and business strategies that can utilise the full potential of DTP, such as engineered printing. Digital printing will be examined and compared with the current mainstream printing methods in regards to their capabilities, limitations and influence on the evolution of textile print design styles. The textile print and garment product development will be reviewed starting with traditional methods and progressing to digital technologies, and also as separate or integrated processes to clarify what these processes are and how these processes can be altered to support EP. The role of CAD, including 3D virtual environments, in the development of textile print and garments, will be reviewed. Current methods for EP will be examined for inadequacies and efficiencies and to suggest possible solutions for further adoption.

Topics not directly focused on EP and integrated product development are included in the scope of this literature review to allow for a deeper understanding of the issues under investigation. The users in the field of textile print design and employed methods are diverse, and it was important to examine traditional methods in textile print and garment design as these methods are still used by today’s designers. These methods were also studied for their impact on the evolution of textile print design styles, the terminology currently used in the field of textile print design, and to draw parallels with the development of engineered printing style.

2.1. Changes in Apparel Market and Digital Technologies Furthering Engineered Printing

2.1.1 Transition from mass production to mass customisation

This section reviews the transition in modern apparel manufacturing from mass production to a mass customisation business model. Possible gaps in the apparel supply chain still operating under mass production supply chain constraints and potential directions for conversion to a mass-customised business model are considered.
From the beginning of the mass production period in the apparel industry, the emphasis has been on delivering a commercially competitive product that takes advantage of the contemporary technological advances. At the same time, mass production technologies had been imposing limitations. Consumer demand for products outside those limitations created a drive for new materials, improved manufacturing methods and business strategies (May-Plumlee & Little 2006). Today for an apparel company to remain competitive, strategies such as Just-in-Time (JIT) manufacturing and mass customisation have to be employed together with emerging supporting digital technologies. Flexibility and information flow in the system are essential since efficient and cost-effective mass customisation of the apparel products depends on manufacturers’ ability to communicate consumer requirements to production facilities and on skills and supporting technologies available to the production staff. In the consumer-driven market, digital technologies such as DTP and CAD are well positioned as these technologies are easily reconfigurable to accommodate diversity (Fralix 2006).

Mass production dominated the apparel industry until the 1980s. As a business model, it required substantial inventories in raw materials, unfinished and finished products, long lead times and delivery commitments along the supply chain, and often resulted in unsold goods being marked-down at the end of a season (Fralix 2006). Advances in information technologies allowed for Quick Response and JIT initiatives to be introduced in the mid-1980s. These initiatives aimed to improve the accuracy of data, speed of information flow and to reduce manufacturing cycles to meet consumer requests. Even so, the mainstream printing technology still required committing to fabric purchases months in advance with minimum quantities of at least 1000m.

In the early 1990s a mass customisation model first emerged as a business practice. It combined mass production manufacturing with an ability to modify each item based on individual requests, which allowed wider differentiation and better customer satisfaction. Loker (2007, p. 246) stated that ‘The goal of mass customisation is to achieve choice at a low cost through the use of technology’.

Emergence of DTP technology in the late 1990s presented some cost-effective solutions for the rising demand for short-run print production and JIT delivery (Cahill 2006; Tyler 2005). DTP started to replace mainstream manufacturing techniques. For niche markets, it became possible to supply demand-driven exclusive printed designs in short times of 2-3 weeks with average production runs of 500 metres or less (Holme 2006). At present, it is possible to extend customisable features of the apparel product to individual sizing and fit, colour, fabric type, textile print design and garment style variations without significant increase in the price for a consumer (Nayak et al. 2015; Senanayake & Little 2010). But to do so, the apparel industry supply chain had to be transformed.

The typical industry supply chain follows the steps of processing the raw materials into a fibre, yarn and fabric, followed by finishing of fabric, garment design, cutting and sewing, finishing, wholesaling and retailing to consumers. These steps can be handled by different organisations, or a few consecutive steps can be completed as an internal part of the organisational supply chain. In her analysis, King (2006) has commented on the competitive nature of the printed textile market that stipulates significant risk with marked down or rejected inventory. King further identified DTP as a key process within apparel manufacturing that supports a JIT model of business.
King (2006) also acknowledged Wantuck’s (1989) principals of JIT strategy and examined DTP technology in the context of these principals, drawing attention to DTP’s ability to print a length of fabric for a single garment based on consumer preferences. It was pointed out that individual garment printing can be done consecutively for multiple different products without the change-over, typical for mainstream printing, that requires downtime and produces waste associated with the set-up process. Additionally, DTP was described as a rapidly developing technology that expanded creative design space, supplemented mainstream textile printing with digital strike-offs sampling and had a potential for an effective and streamlined full digital manufacturing (King 2006; Ujiie 2006). Moreover, production runs in DTP workflow are easily scalable, as manufacturing can be handled by multiple small-scale, or large high-speed units or by combination of both approaches. Therefore, it became possible to convert parts of traditional supply chain into digital supply chain, where colouration could be done directly at the cut and sew location, free from constraints of the minimum run size (Fralix 2006).

Nonetheless, this conversion and successful implementation of JIT approach with DTP production technology required integrated solutions for product development and manufacturing. To optimise the use of DTP, the supporting range of processes in product design and development, fabric preparation, printing and finishing and the following cut and assemble methods had to be reviewed and modified (King 2006). In particular, re-development of processes, still operating under traditional supply chain constraints, would be required to integrate them into the digital workflow that allows for a more efficient and streamlined apparel design and manufacturing (Fralix 2006). At the start, information flow was converted to a digital form that can be easily stored, retrieved and edited to fit any requirements. Ink chemistry, colour management software as well as in-line fabric pre-treatment and finishing facilities became the subject of research and rapid development (King 2006). For flexible short-cycle manufacturing, multiple-ply cutting and progressive bundle product assembly methods were proposed to be replaced by alternative single-ply cutting (King 2006).

The process of printing a length of fabric for a single garment was further extended to the possibility to generate engineered Ready-to-Print (RTP) images of prints integrated with garment patterns, made for a customer’s individual body measurements. The process allowed for customised RTP pattern pieces to be digitally placed into an optimised marker and printed onto a single length of fabric (Bae & May 2006; Lamar 2011; Parillo-Chapman & Istook 2002; Parsons & Campbell 2004). The particular value of such method for the upholstered furniture market was noted (King 2006), but the much wider printed apparel market can also utilise this method for mass-customised products. However, existing CAD methods for such integration were developed within limitations of the mainstream printing and are not practical for engineered printing of apparel products due to required iterative manual processing. Therefore, rather than retro-fitting existing mainstream-oriented CAD methods, it is evident that further solutions are required.

### 2.1.2 Digital textile printing technology

This section examines the progress of DTP technology and gives an overview of the main contributors and key elements. Advantages and disadvantages of DTP are analysed and aspects of the technology that are relevant to engineered printing are further investigated.
In the last 15 years, DTP for apparel progressed from slow fabric printers with unreliable colour management to powerful industrial manufacturing facilities, operating at volume speeds comparable to mainstream printing. In his overview of DTP, Ujiie (2006) defines the evolution of any technology as consisting of three stages: discovery, the first application as a commercial product and wide adaptation. He identified the first commercial Milliken Millitron carpet printer in 1975 as the beginning of industrial adaptation, and proposed that digital textile technology is moving into the wide industrial expansion stage. This expansion stage presents innovation opportunities in areas of:

- new textile design styles outside of the constraints of mainstream printing methods;
- expansion of digital creative space for textile design;
- integration of digital printing into existing supply chain or evolution of the new digital supply chain;
- new sustainable and cost-effective production and distribution strategies.

The origins of digital printing were linked to the progress in fluid dynamics in the 1600s that provided the theoretical basis for ink-jet printing (Cahill 2006). The first patent for an ink-jet printing system was registered in 1867 by Lord Kelvin for use as an electric telegraph recording device. However, digital textile printing didn’t start until 1973, when a sublimation process for transfer printing of digital images to fabric was developed by RPL Supplies Inc. The first digital textile printers, initially expensive and with limited capabilities, were commercially available in the mid-1990s. These printers provided a model for designing, printing, and processing textiles digitally (Cahill 2006; Tippett 2002). By the early 2000s many commercially successful digital printing systems emerged. Currently, the main contributors to DTP technology include:

- Italian textile printing and equipment manufacturing companies (DGS, Reggiani, Robustelli, MS, AlgoteX, ATP Color, Colorprint and Monti Antonio) in the area of adoption of digital printing for textile printing;
- Japanese companies (Epson, Sharp, Seiko Instruments and Konica Minolta) in the key print head and printer technology development;
- US and UK manufacturers (Milliken, RPL Supplies Inc., Sawgrass, US Screen Printing Institute and Hewlett-Packard) with primary technology and business development.

In parallel to DTP technology developments, there have been changes in the workflow of strike-off/sampling and full printing production, with two new digital workflows established in textile printing. These digital workflows offer advantages in comparison with mainstream printing methods. Mainstream strike-off/sampling is a costly and time-consuming process that requires colour separation and screens manufacturing. This cost can be a waste considering that only a fraction of designs may go into production. In contrast, digital strike-offs/sampling can be accomplished in hours with no additional cost of screens manufacturing, and printed fabric can be used for design verification and marketing. As minimum quantity orders for print runs of 500m are becoming the norm (Holme 2006), and the relative cost of screens making raises, DTP becomes a viable, cost-effective printing option. However, a priority with this workflow is the accurate imitation of the intended mainstream printing method as a digital strike-off (George et al. 2006; Ujiie 2006).
Provost (2012) reported that production performance of digital printing is approaching the levels of flat screen printing machines and is comparable with levels of short-run rotary screen production. As the speed of digital printing becomes comparable with mainstream printing methods, the full digital production workflow also becomes economically competitive (Ujiie 2012). This workflow is adaptable to rapid changes in market demands and can handle single garments, and short or medium production runs. The printing can also be done in a wide range of design styles, many of which are not reproducible within mainstream printing (Lamar 2011). As a result, conversion to digital printing workflow has allowed for re-establishment of printing production in Europe and North America for high-end apparel and furnishing markets (Ujiie 2006).

These two digital workflows are also available as globally accessible services. DTP service bureaus such as the Centre for Advanced Textiles (Glasgow, UK), Print Unlimited (Boxmeer, the Netherlands), RA Smart (Macclesfield, UK), First2Print (New York and Los Angeles), Direct Digital Printing (Sydney, Australia) or Seiren Viscotec (multiple locations around the world) supply printing facilities for sampling and full digital printing production mode. In addition, small-scale custom textile design digital printing facilities are available to individuals or small businesses through on-line services such as:

- Spoonflower (http://www.spoonflower.com/welcome);
- Karma Kraft (http://www.karmakraft.com/);
- Inkindrop Printing Service (http://www.inkdropprinting.com/);

Another consideration of DTP technology for this investigation is colour agent and management. Colour management for printing and ink fixation is critical for achieving colour targets in finished products (Collis & Wilson 2010; Dawson 2006a; George et al. 2006; Kim 2006). Colour calibration is essential, as the final colour is affected by many physical factors such as types of inks, fabric properties, and fixing regime. This complex area of DTP needs to be acknowledged, but it is outside the scope of this research. CAD image pre-processing methods must be considered to support colour management throughout the workflows.

**Raster Image Processing (RIP)** software handles conversion of file formats from textile industry CAD and screen separation programs with proprietary formats of CST, MST, PUB, GRT, SEP, SCN and XPF, and universal computer graphics formats of TIFF, PSD, EPS, AI, BMP and TGA to the printer instructions (Dawson 2006b). RIP software is also capable of managing colour, repeats and colourways, scaling, rotating and batching. Although RIP software is capable of handling printing instructions in the form of an engineered RTP images marker, it is still unable to generate such images from print image data such as repeats.

Printing instructions from RIP software control print ink jetting heads that are connected to a range of ink reservoirs (Briggs-Goode & Russell 2011). A digitally printed image is formed by an optical mixture of tiny drops of ink of different colours on the surface of a substrate. At least three primary subtractive colours, cyan, magenta and yellow, are used with the addition of black. The printable range of colours (gamut) can be extended by increasing the number of inks to six or seven, and most commercial textile printers use 6-8 process inks (Tyler 2005). Digital print systems can use pigmented inks, acid, reactive, disperse and disperse-sublimation transfer dyes.
Using process inks instead of pre-mixed spot colourants means that the number of colours in a design is not limited and the registration is not required as all colours are printed simultaneously. However, digital printing ink types and substrate fabric variety are still limited compared to mainstream printing methods. Also, effects such as glitters, flocks, puff or devoré require hybrid printing (Siser, 2014). On the other hand, digital printing can produce photo-realistic effects, higher levels of light and shadow rendering, texture, trompe-l’œil, moiré and other effects that are not achievable with mainstream methods (Lamar 2011). Smooth, gradual tonal effects and fine lines are also possible due to the higher resolution of digital printing (Bowles & Isaac 2009). Also, there is no constraint as to the size of repeat or scale of an image, and in the case of an engineered print the concept of print repeat itself can be abandoned in favour of non-repeating continuous designs or controlled irregular tiling of repeating designs. This potential of DTP to handle manipulated repeat formations for engineered printing is of particular interest to this research.

Finally, environmental advantages of DTP technology were also considered. The TIEPRINT project (technology transfer of low environmental impact ink-jet printing for the production of textile products) reported 60% reduction of needed production space; 60% reduction of noise; 80% thermal energy savings; 60% reduction of waste water; 30% reduction in electricity consumption; 100% reduction of excess dyestuff compared to mainstream screen printing (TIEPRINT 2002). Tyler (2005) commented on the lesser environmental impact of DTP with no wasted water-based ink, and a higher fixation rate of 90% compared to the typical for mainstream printing of 65-70% due to washing off and dumping of premixed surplus dyestuff. As Briggs-Goode and Russell (2011) emphasise:

‘There have been many cost and efficiency savings with the advent of digital printing ... ink-jet printing can make a real contribution is in relation to design and the environment.’

Provost (2012) pointed out that DTP is likely to replace traditional technology when old print machinery is updated or new capacity is considered, as mainstream printing remains one of the largest users of chemicals and generators of pollution in the textile industry. Even so, that replacement can be stimulated further if the methods existed to utilise fully the capabilities of DTP. In view of that, Ujiiie (2014) highlighted the lack of communication between printer's manufacturers and users and mentioned the need for innovative approaches to integration of DTP technology instead of retro-fitting it into mainstream design/printing workflow. EP could be one of such innovative approaches.

### 2.1.3 Computer-aided print design technology

This section investigates historical developments in computer-aided textile print design and issues/advantages in comparison with the traditional print design. Industry and universal CAD software packages are examined in regards to their features and users.

‘Textile computer technology has truly evolved into a meta-medium that reinforces a generation of processes to become one flawless workflow’ (Treadaway 2004a).
Following integration of digital technologies in apparel supply chain, the traditional textile print design has been widely replaced by CAD and digital media. New methods were developed, allowing for better efficiency and quality, rapid prototyping and design modifications, and facilitating communication within the supply chain or with consumers (Ujiie 2011). Computers have been described as a tool that replaced the paintbrush for many textile print designers, providing an environment for experimentation with complex designs, scale and colour schemes and integration between printed textile and garment (Braddock & O’Mahony 1998).

The first textile CAD systems appeared in the late 1980s following the development of creative design applications within proprietary software systems on the UNIX platform. Such systems, though specifically geared to cater for textile design, were expensive and often imitated traditional print design workflow. Rapid improvement of personal computers allowed for the systems adaptation to Windows and Mac OS. The increasing popularity of personal computer as a design environment created demand for functional and affordable hardware and software, and many universal graphic software packages were introduced. Through competition that number was later reduced to a few leading providers both in proprietary and universal software markets (Ujiie 2011). Use of computer technology for textile print design has grown exponentially in the last 30 years and is preferred to traditional processes. Consequently, a level of familiarity with CAD and related technologies is expected of the new designers entering the job market (Hui 2011). CAD skills are necessary for the creation of digital portfolios and work for apparel companies. Such skills are also valuable in order to establish successful business practices in a new or growing apparel company (Polston, Parrillo-Chapman & Moore 2015).

‘Although the underlying technology is very complex, a uniquely digital printing path from design to manufacture offers the opportunity of a significantly simplified and quickened workflow’ (Briggs-Goode & Russell 2011, p. 121).

Today both universal and proprietary types of software are used by textile designers. The preference towards universal or proprietary software creates two distinct communities of users separated by differences in techniques and vocabulary. Proprietary software manufacturers offer modules specific to print development stages and are continually adapting to the users’ preferences, but the cost of software is high. On the other hand, universal software is affordable, accessible and popular. As Bowles and Isaac (2009) commented:

‘Software programs such as Adobe Photoshop and Illustrator present the perfect platform for textile design. These have become the industry standard tools for textile designers, offering them the freedom to work with both bitmap and vector based imagery, manipulate drawings and photographs, and create accurate details and graphic effects’ (p. 7).

Proprietary programs, usually with an icon-based user interface (i.e. based on buttons with visual clues rather than text), are often complex and require a considerable time to master. Initially, proprietary systems provided additional colour management support for accurate and reliable reproduction of colours, and options for textile print-specific functionality, such as tiling tools or texturing effects (Dawson 2006b). In contrast, current commercial universal software packages
such as Adobe Photoshop and Illustrator and Corel Draw and Paint are not specifically geared to cater for textile print design. However, universal packages are operating within familiar operating system interfaces and are readily available at a minimal cost. Colour Management System became a regular feature in universal software, and pre-calibrated printer profiles are typically included or can be downloaded from online manufacturer’s resources. Additionally, universal packages provide functionality to replicate most print design processes and give freedom to experiment with new print design methods (Briggs-Goode & Russell 2011). Such functionality can be enhanced with proprietary plug-ins, but it can come at considerable cost.

Also, for new or small companies it might not be feasible to invest into proprietary packages at initial stages of a business. The capital investment required for proprietary software and hardware packages can be especially prohibitive for new businesses in developing countries. With this in mind, students in relevant university programs can benefit from deeper understanding of the issues related to establishment and use of CAD-related technologies in new and small businesses as many of them aspire to become entrepreneurs on the completion of their degree. Practical experiences in the use of CAD and related technologies can also help them to make the right decision in selecting appropriate software for their business.

New CAD processing methods combined with DTP technology have removed two main constraints that have been demanding for textile print designers: limited colours palettes and the need for design repeat. However, the potential of DTP combined with new CAD processing methods is still emerging. Design methods need to evolve with the introduction of new technology to allow the design process itself to change. Some innovative approaches have been demonstrated by Bowles and Isaac (2009) in tutorials about the use of Photoshop and Illustrator for textile print design. The demonstrations nonetheless focused on typical printed surface design development tasks, such as duplicating the elements of design, scaling and recolouring etc.

Ease of editing in a CAD environment stands out as the main advantage compared to the traditional design process. This editable nature of digital print design also makes it adaptable for engineered printing. Also, prints can be designed specifically for engineered printing, with potential design styles for it still emerging. In this regard, the aim of this research will be to propose CAD methods utilising advanced tools in universal graphic software. The techniques developed by this research will be focusing on engineered design approach that integrates repeating print and garment patterns by fitting artwork to the structure and form of the garment.

2.1.4 Vector and raster graphics

This section reviews two available types of digital graphics (vector and raster) and the principal file formats used for these types.

Until recently one of the first CAD decisions that textile designers had to make was related to the choice of types of graphics to be used in print. That choice would then determine the selection of software module and affect visual characteristics of the output. However, modern programs are capable of processing both graphic types within their native application as well as integrated editing of complex parts via relevant dedicated modules of the package.

There are two types of graphics used in computer graphics design: raster and vector. In raster graphics the image is made out of pixels set in a grid formation. Raster graphics are resolution
dependent and are best for images with continuous tones. They can also be used for simulating textures such as a weave or knit. **RGB** (Red, Green, Blue) 24-bit colour space is typically used for CAD textile design. However, conversion to 8-bit limited colour space might be required at colour-reduction stage (Ujiie 2011). Vector graphics, on the other hand, use mathematical equations to describe points and curves and are resolution independent. Industry and universal software packages can work with both types of graphics and designers utilise both methods based on the desired outcome (Dawson 2006b) or personal preferences.

Principal file formats used in universal and proprietary software and their descriptions are presented in **Table 1**.

### Table 1: Principal file formats, adopted from Dawson (2006)

<table>
<thead>
<tr>
<th>Acronym</th>
<th>File format description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMP</td>
<td>Bitmap. Standard digital image format for Windows OS. Large file sizes.</td>
</tr>
<tr>
<td>GIF</td>
<td>Graphic Interchange Format. Compact image format limited to 8-bit colour. Widely used for web graphics, but being replaced by PNG.</td>
</tr>
<tr>
<td>PNG</td>
<td>Portable Networks Graphics. Supports 8, 24 bit colour and transparency. Supports meta-data.</td>
</tr>
<tr>
<td>EPS</td>
<td>Encapsulated Postscript. Legacy format for text, graphics and desktop publishing, largely replaced by PDF.</td>
</tr>
<tr>
<td>PDF</td>
<td>Portable Document Format (Adobe).</td>
</tr>
<tr>
<td>RAW</td>
<td>Device-specific file formats for storing pixel data from CCD devices.</td>
</tr>
<tr>
<td>DNG</td>
<td>Digital Negative Format (Adobe). Device independent RAW data format.</td>
</tr>
<tr>
<td>DXF</td>
<td>Drawing Exchange Format. CAD data file format for enabling data interoperability between CAD programs.</td>
</tr>
<tr>
<td>CDR</td>
<td>Corel Draw. Proprietary file format developed by Corel Draw for vector graphics.</td>
</tr>
</tbody>
</table>

#### 2.2. Design Process for Textile Prints

##### 2.2.1 Printed textile design as a domain

This section gives an overview of the evolution of printed textile design domain. The methods in the domain are further analysed, and the environment for innovation in methods is considered. The potential gap in current processing methods is identified as the lack of advanced techniques for generation of RTP images of engineered repeating prints.

Textile print designers operate today within a well-established design domain. Its evolution can be traced from prehistoric examples of hand imprints, followed by the use of printing blocks to the invention in 1761 of copper plate printing, engraved rollers printing in 1783, silk screens...
printing in 1920, rotary screens printing in 1954, and ink-jet printing in 1973 (Moxey 1998). The ability of a creative individual to generate new ideas can be augmented by the understanding of the evolution of theories and concepts within the domain and skills acquired through experimentation and practice. For a printed textile designer that includes the understanding of historical and current printing methods and their specific limitations and capabilities.

Li (1997, p. 109) defined domains as

‘...bodies of discipline knowledge that have been structured culturally, and which can be acquired, mastered, practised, and then advanced through the act of creating.’

Li (1997) then listed five parameters as most central to the discussion about domain and creativity: aim, methods, symbol system and uses, rules, and standards. Creative processes in a printed textile domain specifically were surveyed by Moxey (1998), who concluded that apparel textile print designers follow a paradigm of aesthetic conventions. These conventions can be examined and related to the five parameters of a domain (Li 1997; Moxey 1998)

I. The aim refers to an identified objective and a scope of a domain, which in the case of textile print could be expressed as a partly explicit understanding of design requirements, for example, a design brief.

II. The methods of the textile print domain are of particular interest to this research. Methods set boundaries for the domain practice and, due to their inherent ever-evolving nature, present opportunities for innovation and creativity to practitioners. In regards to apparel and textile design domains, methods can be intangible, such as problem-solving approaches and workflow procedures, or tangible, such as materials and tools (Li 1997), which would then include digital technologies like CAD and DTP. Methods of the DTP technology can expand the aesthetic conventions of textile print design as well as transform the paradigm itself (Ujiie 2001).

As these technologies become understood and used by the field innovators, new design styles emerge. Several researchers presented creative practice studies that demonstrated new specific for DTP styles through experimentation (Carpio 2014; Parillo-Chapman & Istook 2002; Ujiie 2014). Mainstream and digital printing can also be combined to get the best of their characteristics in one product (Bae & May 2006). That experimentation is not just limited to unique pieces, for example, Bowles and Isaac (2009) reported that Como print houses such as Mantero and Ratti had been using traditional printing methods together with the latest technology for manufacturing luxury textile products. The emergence of new challenges and an inability of old methods to solve these challenges can then stimulate the invention of the new methods. Innovative methods that extended 2D textile design domain to 3D surface design are an example of this (Campbell & Parsons 2005; Carpio 2014; Miles & Beattie 2011; Parillo-Chapman & Istook 2002; Parrillo-Chapman 2004; Parrillo-Chapman & Little 2012; Townsend 2004). Such domain expansion nonetheless requires broader creative and technical abilities from textile designers.

III. Symbol system and uses are formed from common symbols, with some shared with other domains and some domain-specific. Symbols represent implicit conventions of
textile design domain, which are based on core design principles such as appreciation of historical design styles and colour harmonies. For example, visual symbols for ‘Navy’ theme in textile design typically include the use of navy blue, white and red colours, the combination of solid colours with two-colour horizontal stripes, and images of anchors, ensigns, ropes and knots.

IV. The rules of a domain are the guiding principles that stipulate how the work is carried out, thus preserving the boundaries of the domain and presenting it as unique. In the textile design domain, the rules can be determined by technological limitations, for example of possible repeat sizes, layouts and finesses of detail. The rules are changed or broken when the domain expands.

V. The standards refer to the quality expectations applied to work produced within a domain. Community in a domain employs the standards to assess the work and either accepts or rejects it. For a textile design, the community includes apparel and retail industry practitioners and consumers. The standards, therefore, are also influenced by consumers’ expectations expressed as market trends.

For a design work to be accepted as a successful innovation, the ideas are developed to either fit within these conventions, expand them or break the rules to expand the domain itself. Printed textile designs are assessed based on their commercial viability and originality, and marketed in two different strategies depending on attributes of the design (Ujiie 2006). Following the first strategy, many commercially successful textile designs originated with popular historical textile designs that were representative of their contemporary printing methods. DTP currently allows for easy modification and production of these prints as yardage. The second strategy is for the new modern aesthetics that emerge as a reflection of the spirit of the time and with the support of digital technologies expand the domain of textile design. DTP already has been described as the most significant advance in fabric printing technology since the invention of the silk screen printing (Bowles & Isaac 2009). However, to take full advantage of digital printing technology and thus expand or even transform the printed textile domain further development is required for new design styles and CAD processing methods for them. Engineered repeating prints for RTP images can be one of these new design styles.

Technological innovations present designers with new possibilities as well as challenges. Lamar (2011) commented that throughout its history printed textile domain has been impacted and expanded by technical innovations causing style innovations. Such an impact has been significant with the recent addition of innovations in DTP, and innovation in technology combined with innovation in the application of traditional methods could further expand the design domain. The expansion of the domain could also be driven by application of traditional technologies and methods in innovative ways or combining traditional and digital technologies.

2.2.2 The influence of printing methods on design styles

This section provides a closer investigation of the design style’s concept and the relationship between contemporary printing technologies and relevant print design styles. Examples are given of the impact of changes in industrial printing methods on design styles and methods. Main visual
attributes of repeating prints are outlined, and limitations for developing repeating prints for printing with mainstream and digital printing methods are summarised.

Designers need to have a good understanding of how their design will look when reproduced based on base fabric properties and types of dyestuff (Wilson 2001). Moreover, the manufacturing technology utilised to transfer decorative designs to fabric affects the design style of a print, as Ujiie (2006) commented that:

‘Throughout history, textile designs have been tailored to the production methods in use, and each technological innovation has led to a change in the visual vocabulary.’

The advent of industrial contact printing methods stimulated the use of repeating designs, allowing for faster mechanical replication and promoting the transition from a woodblock design style to a wider range of design styles of copper plate/roller and screen printing that still required exactness in repeats. This connection can be further illustrated by following common printing methods and their typical design styles:

Block printing originated in China in the 300s (Meller & Elffers 2002) and became a prominent method for printed household textiles in the 1200s in Gujarat, India (India Crafts). It uses separate blocks for each colour/motif and final output is achieved by overlaying multiple layers of colours and motifs, allowing for complex designs. Each block has to be small enough to be handled by a single person. The half-drop repeat structure is often used with block printing to disguise the movement of the blocks (Phillips & Bunce 1993). The traditional look of the technique has been replicated with modern screen printing methods, but within the limitations to the number of colours.

Engraved copper plate was introduced in the late 1800s and soon evolved into engraved roller printing. Roller printing remains one of the mainstream printing methods (Wilson 2001). Design styles for the method are characterised by fine lines and dots, and can produce more sophisticated rendering and seamless repeats (Ujiie 2006). The perfect historical examples of the method application are represented by the ‘toile’ prints with subtle and smooth tonal variations not achievable with the other mainstream methods.

Screen printing together with previously mentioned engraved roller printing are the current mainstream printing methods. In the early stages of technology, table flatbed screen printing had registration issues, and, as a result, the design styles were developed with intentionally wide trapping or unprinted areas around motifs (Campbell 2008; Ujiie 2006). The aesthetic of this look is still accepted and replicated in modern screen printing that has a higher precision of screen registration. In the 1950s and 60s, rotary screen printing was developed. Rotary printing uses cylinder screens allowing for continuous application of the colour agent to the substrate, making it highly efficient for long print runs. Its ability to print wide areas of flat colour and control over the amount of applied dyestuff also influenced aesthetic of printed fabrics of that time.

Concerning mainstream printing methods, the main constraints are the requirements for fixed repeat sizes and limited colours palettes. These two constraints often define how textile designers work today, as most designs are created in repeat or with an intent to be converted into a repeat (Phillips & Bunce 1993). Only rarely is an artwork designed outside these constraints produced to
serve mostly as an inspirational source. Separate screens or rollers for each of the spot colours in a design are required, and so the manufacturing cost rises with each additional colour. Up to eight spot colours per design is typical for a reasonably sophisticated artwork. Also, different base fabric structures will ultimately produce a different appearance in printed textile. All contact printing methods have resolution limitations, but additional colour gradations are possible with overprinting or half-toning techniques. However, processing of such art into screen separations requires technical expertise (Briggs-Goode & Russell 2011). Accordingly, textile designers need to be aware of processes that take place in pre-production and production of printed textiles to make their design less subjected to interpretation by technical staff.

McNamara and Snelling (1995) specified the most commonly used repeat systems: full drop, half drop and diamond repeats, with a mirror or turn variations. These repeat systems became popular because they work well with the mainstream printing methods. For these methods, the vertical dimension of a repeat has to match the fraction of the circumference of the rotary screen/roller. Repeat size is also determined by end-use of the fabric, as well as the size of motifs and their layout. For example, in a co-ordinate range of fabrics the same motifs can be used with the different amount of white space in different layout (Wilson 2001). Repeat structures are used to create continuous print over fabric width and length, and in some end-uses repeat structures can also be nested (Phillips & Bunce 1993; Wilson 2001). The concept of nesting used for development of complex repeats can be further expanded with DTP technology, for example to a nesting template engineered to fit within particular garment pattern pieces, and to be used with repeating and non-repeating structures.

As a style, engineered prints are designed to flow continuously across pattern pieces around the 3D form of a garment. Some aspects of engineered design can be observed in placement prints, which are designed to fit within a pattern shape at a specific location and can be applied to a finished garment or before assembly to a pattern piece. Advancement of engineered printing methods would allow for the integrated digital textile/garment design approach even for repeating prints. In these approaches, 3D virtual visualisation would ensure the translation from flat fabric to garment form, and CAD processing would be applied to generate RTP images for DTP. Such approaches can make both DTP and engineered repeating print design style accessible to a wider apparel market.

### 2.2.3 Print design process

The following sections examine design processes and methods used by textile print designers in the traditional manual, CAD supported or engineered design workflows. Framework models for traditional and CAD printed textile **product development** (PD) for manufacturing within the mainstream and digital printing methods are reviewed, and a comparison framework model is shown in Figure 1. Possible stages in these processes where engineering of repeating print with garment patterns might occur are considered.

**Traditional print design process**

PD processes for textile print have been a subject of extensive research in the field. Powell and Cassill (2006) reviewed a number of global textile companies for their new products, including processes for both development and following launch and management. Although studied
companies labelled their processes differently, the PD stage was typically divided into five main steps:

- initial need or idea inception;
- investigation;
- concept development;
- testing and evaluation of alternatives;
- final design.

Wilson (2001) likewise described the textile design process as consisting of five stages covering similar tasks. Studd (2002) did a case-study examination of professional practices of a world-renowned textile design house, a global textile manufacturer, an international furnishing company, a freelance textile designer, a textile design consultant, and a small textile design studio and mapped out the generic framework for the textile design process. Again, the design process was shown to be broken up into similar five stages.

More detailed examination of the descriptions for the concept development stage in the literature (Briggs-Goode, A. & Townsend 2011; McNamara & Snelling 1995; Wilson 2001) has shown that in general textile prints are designed as a balanced composition and put in repeat later by a technician. Traditionally such compositions were hand-painted with potential repeat sizes, the

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**Figure 1**

Textile print design process, adopted from (Powell & Cassill 2006; Studd 2002; Tyler 2005; Wilson 2001)
number of colours in a design and the intended printing method considered, as not all artistic mediums can be reproduced truthfully on fabric. This stage could also include considerations for a possible adaptation of the created composition for engineered printing.

The following stages of testing and evaluation of alternatives, and the final design must allow for a lengthy time-line up to 8-12 weeks due to typical processes required with mainstream printing:

- artwork for textile print is translated into a limited number of spot colours (maximum 24, usually up to eight);
- repeat sizes are defined based on roller/screen sizes and end-use of product;
- artwork is separated into spot colours by a skilled technician;
- screens/rollers are made, one for each colour;
- screens accuracy of design and registration are proofed by means of sample strike-offs;
- spot colour inks are verified, and correct ink formulae are recorded;
- spot ink for each colour is applied upon the base fabric in consecutive steps;
- alternatively, placement prints can be applied to the finished garment or before assembly to a garment pattern piece;
- the printed fabric is cured to fix the inks.

Even though a typical sample length can be 2-5m, it requires the manufacturing of production-ready screens. Screens, base cloth and printed fabric stocks have to be stored, but only 15-20% of design samples presented at trade fairs are later selected for production (Nicoll 2006). For rejected or unsold designs, screens/rollers inventory has to be written off and screens destroyed. Additionally, during production runs, the first 50m of fabric are printed to check the process and discarded (Provost 2012). Correction of printing problems due to screen changes between different designs might require up to 60% downtime (Tippett 2002). Accordingly, the traditional print design process can be time-consuming and expensive due to the cost of screen manufacturing and use of production machinery for sampling (Ujiie 2006; Wilson 2001).

**Computer-aided textile print design**

Computer-aided design is used in several stages of the textile design process for concept research, development of original design, modifications and refinement of design, final design presentation and communicating finished designs to the pre-production team for technical processing (Ujiie 2011). Initially, designs were hand-drawn and later scanned. Digitised designs then were processed in a workflow similar to traditional textile development. Rendering of a hand-drawn design in a digital form, however, can be a time-consuming exercise, and in any case current CAD systems are capable of truthfully reproducing many types of painting medium. In addition, CAD functionality facilitates generation of complex repeat structures and evaluation of variations of print designs including colourways. Also, printed or electronic output can be communicated to collaborators along the supply chain, and 2D and 3D visualisation tools can facilitate the development and marketing of designs. Subsequently, many practising textile designers have already transitioned from a hand-drawn to an electronic textile design (Polston, Parrillo-Chapman & Moore 2015).

Regardless of the design process used, potential manufacturing printing method still needs to be considered during print development. Even with advances in DTP technology, 90% of all
printed textiles are still manufactured on screen printing machines (Dawson 2006b). Converting CAD-generated designs, sampled using unlimited colours in DTP, to mainstream manufacturing, can be challenging. The need for designers to create with the final output method in mind, which well might be one of colour-limited mainstream printing methods has been documented (Nicoll 2006). The better digital print development workflow, therefore, would be the one where the colour separation is considered and stipulated from the start. A digital design should be developed as colour separated and in repeat so there is no ambiguity in translation to screens allowing the final output to retain the original design intent.

**Print design for digital textile printing**

This section further investigates textile design specifically for DTP to identify the traditional processes that have been retro-fitted into digital printing workflow as potential gaps to be examined in this research.

The impact of digital technologies on printed textile design, production and distribution has been compared to the arrival of the Jacquard loom, bringing on the changes in characteristics and quality of textile products and empowering the creativity of textile designers (Nicoll 2006). The introduction of the DTP technology though has created a need for better understanding of the capabilities and limitations of the new design space and for development of design styles geared towards these characteristics. Furthermore, designers require sufficient technical expertise to maximise the potential benefits of creating for digital output (Polston, Parrillo-Chapman & Moore 2015).

The advantages of using DTP technologies as a creative medium were observed during case studies of practices of innovative printed textile artists (Treadaway 2004a). The study also highlighted the link between textile design practice and production methods and tools, and differences in comparison with creating for mainstream printing methods. One example raised was the separation between a designer and a final product due to the involvement of the technical personnel. Interestingly, the study showed that compared to mainstream printing methods, the combination of DTP and CAD technologies brought designers closer to the textile product reversing the trend of separation.

The adoption of digital design tools and printing methods can be complicated due to rapid technological changes including software development. Consequently, designers find it hard to keep up with updates and often only use the most basic functionality (Polston, Parrillo-Chapman & Moore 2015; Treadaway 2004b). The technical aspects of utilising DTP are often blamed for textile designers’ inertia to implement the technology. Tyler (2011) describes pre-printing processing required for DTP workflow as sorting between flat and tonal designs, development of repeats, colour matching and colour separation, and simulation of textural effects. As issues reported by printing bureaus Tyler names stray pixels, unclear boundaries between areas of different colour, tonal effects grading into flat colour and incorrect resolution, colours out of gamut. The problem of the technological complexity of the digital working environment, therefore, requires the development of tools or techniques that supply necessary functionality without the overwhelming learning curve for the practitioners in the field.

Another advantage of the digital printing method is that design processes can be accomplished in much shorter time compared to mainstream methods. Citing previous research (Choi et al. 2003),
Tyler (2005) provides such comparison. Critically a shorter digital printing timeline (one week compared to 6-8 weeks for mainstream methods) places the print design and manufacturing stage considerably closer to potential garment production, shown in Figure 1. Tyler also points out that implementation of concurrent PD of textile prints and garments would allow taking advantage of the full potential of DTP. For concurrent PD, Tyler further suggests that the options at every stage need to be identified and evaluated for full utilisation of capabilities of digital technologies. One of such options might be the integration of repeating prints with garment patterns, which this research aims to address. In this case, the print can be developed as adaptable to the EP method from the start, and integrated with garment patterns directly. However current techniques for such integration are impractical due to iterative manual processing involved, and the impact of repeating print attributes on its adaptability for EP has not yet been established.

King (2006) suggested that two main strategies exist in design preparation for DTP. The first requires pre-processing for colour reduction and separation that is similar to mainstream printing model. This pre-processing would be done to facilitate the development of designs within seasonal colour palettes, to make designs more easily editable for colourways generation and to simplify adaptation for coordinates and mass-customised products. The pre-processed designs can also be later reproduced with comparable results using mainstream printing methods, if large quantities are required. The second strategy is used for designs that can only be reproduced by DTP methods, such as photo-realistic or subtle tonal variations prints, and engineered non-repeating prints (King 2006). It also could be used for engineered repeating prints, but the design preparation would require even tighter editing control. In the absence of dedicated software solutions, such control would be possible with understanding what attributes make repeating print more adaptable for EP, and development of more easily editable prints. Also, techniques for integration of repeating prints with garment patterns are needed.

### 2.3. Garment Patterns Design Process

#### 2.3.1 Patterns design process

This section investigates processes employed for the development of garment patterns.

Traditional apparel product development (PD) involves the combined input from both designers and garment technicians. The typical workflow includes the following steps:

- a garment sketch is created by a designer;
- the sketch is then translated into 2D base size patterns by a skilled technologist, taking intended fabric properties into account. The base patterns are usually constructed by modifying existing block patterns to assist with correct fit;
- the patterns’ construction is followed by physical prototyping of garment, fit evaluation and pattern alteration until the satisfactory fit is achieved (Baciu & Liang 2011; Bond 2008);
- after acceptable fit is achieved, a pattern grading process is used to produce a range of required sizes. A 2D base size pattern is graded by application of calculated grading increments at grading points of garment pattern pieces with the intent of preserving original proportions of the garment design features.
In this workflow, the interpretation of design intent by a pattern technologist from a design sketch into two-dimensional patterns is the essential step that requires her/him to have extensive tacit knowledge.

For industrial applications, the traditional pattern design approach has largely been replaced by CAD technology, earlier by 2D CAD and more recently by 3D. Framework models are shown in Figure 2.

The use of 2D CAD for pattern specification, grading and marker making is well established. The technology includes proprietary hardware and software systems that are available as separate modules for various PD and manufacturing tasks. However, investment in sophisticated and expensive hardware and software systems doesn’t mean that full functionality of that system is going to be utilised. Workflows have to be set up to maximise the use of a software system rather than restrict it, and sufficient training for users is required (Tyler 2008). The necessary extensive training for CAD technology and pattern design was similarly emphasised by Baciu and Liang (2011). They also identify gaps in current Pattern Design Systems (PDS) technology due to the lack of ‘high-level interactive’ features. It was suggested that one way to overcome such challenges is through the development of a new type of intelligent interactive design interface that is user-friendly and offers technical and creative functionality (Baciu & Liang 2011). This gap appears to be indicative of the current CAD technology, and this research proposes the application of existing CAD tools in a novel way that combines technical and creative functionality with increased interactivity.

![Comparison between CAD methods for garment patterns development](image-url)
The processes in current CAD pattern-making mostly follow the traditional workflow. The differences are in the integration provided by CAD technology between garment design, pattern construction and PD processes. The functionality of PDS is organised for product design, pattern construction, grading, and markers drawing processes (Bond 2008). A typical CAD workflow involves the following steps:

- garment sketch is translated into 2D patterns by a skilled technician;
- patterns are constructed based on CAD block patterns. Block patterns are created using body sizing information and a set of instructions, and verified to have correct fit;
- alternatively, a verified set of instruction can be used as a construction method for a particular size range to generate intelligent block patterns within PDS;
- sizing and grading information is included in the intelligent block patterns and is transferred into styled patterns;
- styled patterns are created using basic techniques of modelling, draughting, suppressing and flaring. The modelling technique, previously only possible in the physical world by draping fabric over a dressmaker model now becomes a reality in the 3D virtual environment;
- the construction method can be recorded as a set of instructions to be used to re-draft styled patterns based on a different initial set of measurements;
- grading rules are formulated based on sizing charts information with intent to preserve original proportions of the garment design features while maintaining correct fit;
- graded set of patterns is generated based on styled patterns.

More recent advances in PD include a 3D virtual environment that facilitates visualisation of prototypes and eliminates time-consuming manual sampling. Baciu and Liang (2011) discussed three possible garment CAD approaches based on the application of 2D and 3D tools. In the first approach, 2D CAD technology was used to generate patterns from an initial garment design concept taking selected fabric properties into consideration. The patterns were then tested in a traditional sampling/fitting cycle, final prototype was approved and finalised patterns were graded for production. This approach, however, posed challenges regarding flexibility and can be time-consuming.

A second integrated 2D/3D garment design approach suggested by Baciu and Liang (2011) combined fabric draping properties with 2D CAD patterns to simulate 3D garments, thus allowing replacement of the physical sampling with virtual. For this approach, however, virtual 3D body models are generated across ranges of sizes and morphological groups. Also, for the development of sizing strategies, these models should be verified against aggregated data obtained from 3D scans of real human bodies (Istook, Newcomb & Lim 2011). An advantage of the 3D scanning technology for the development of sizing strategies is that it can provide a wider range of exact measurements that are not assessable with manual measurement methods. The collected data can also be utilised for the generation of individualised body models for made-to-measure applications. The approach of rebuilding individualised body models directly from scan data is, however, labour intensive and in many cases can be simplified by morphing individual data with a pre-build generic models database (Bye, Labat & Delong 2006). The same approach can be used for accurate size prediction based on a minimal number of customer measurements in the virtual shopping environment.
Another challenge has been the rigidity of the virtual model surface compared to soft deformable human tissues over skeletal bone structure, and dynamic simulation of interaction between a moving body and a garment. It’s been addressed with pre-build generic models that incorporate surface and skeletal information, and can be combined with individual data for an immediate animate-able custom model. These models have additional functionality such as weight loss/gain and distribution, and posture adjustment (Istook, Newcomb & Lim 2011).

Apart from virtual body models, key elements of such 3D virtual environments are fabric draping properties and visual textures, stitching functionality, editing functionality in 2D or 3D interfaces, tools for communication of visuals, and analytic tools such as cross-sections and pressure or tension maps. 3D simulation programs can also include libraries of the basic blocks that can be a starting pattern development point for 2D CAD patterns directly in the integrated 2D/3D environment. This approach allows for shorter lead times, deals with fit concerns, reduces material costs and enhances e-retailing and communication.

Virtual body models are also used in the third 3D to 2D approach, described as drawing patterns directly in a 3D window on a virtual model body followed by flattening and editing in a 2D window (Baciu & Liang 2011). One of the current 3D modelling packages that can facilitate this workflow is Browzwear VStitcher (Browzwear, 2016). Similar functionality is provided by a rival system from Optitex (Optitex, 2016).

Lectra includes a 3D modelling Modaris application as a part of PDS. In this approach, the physical process of design and fitting is transferred into the virtual environment, and results can be visualised immediately in 3D simulations. When required fit is achieved, flattened 2D patterns can be used for physical prototyping if required or communicated to a production team. Even so, the virtual environment still lacks tools for integrated textile design-garment development.

Regardless of the used approach, CAD technology became an essential tool required to achieve integration and communication between various phases of apparel supply chain (Bond 2008). Although the use of the virtual environment has been utilised in several industries, many challenges were encountered in apparel industry research and development of the 3D software due to the complexity of simulation of draping properties of textile materials. Briggs-Goode and Russell (2011) commented that the existing CAD processes need to be examined to achieve a satisfactory functional relationship between users and computer, followed by the development of tools and techniques to suit these processes and enable ‘efficient, effective and safe interaction’. This research proposes that the examination of the existing processes needs to include critical evaluation of the processes themselves. Rapid digital technology progress in textile and garment design and textile printing presents opportunities for research into new processes that utilise capabilities of these digital technologies to the full extent.

### 2.3.2 Grading process in CAD environment

Digital garment patterns are vector files that contain information about a pattern’s boundary that is defined by points with precise co-ordinates on a 2D plane and lines between these points. Various proprietary file formats are used by different software vendors, but conversion utilities are provided to transfer files between systems. The systems also have the ability to import information in universal digital graphics formats such as dxf. Each boundary point has attributes related to grading properties (grading point or not) and to the shape of the line passing through
the point (straight or curved line, smooth or corner). These properties can be assigned to pattern piece points during digitiser input of a manually constructed pattern, or at any time in PDS. The manual process of digitising can be upgraded to automated scanning systems that capture multiple pattern shapes and output patterns digitally.

In an apparel development workflow, following the fitting and base size patterns alterations, approved base patterns are graded to a required set of sizes, with either standard or custom size measurements used. A typical pattern grading process involves application of grading rules, which are calculated increments, at grading points of a garment pattern piece, or by re-drafting styled patterns to a required size using a pre-recorded construction method (Aldrich 2004; Schofield 2007). Also, mass customisation of styled patterns is possible for made-to-measure (MTM) garments by calculating grading information for custom body measurements from a basic pattern or by re-drafting patterns using a pre-recorded construction method (Bye et al. 2008). Successful implementation of a MTM manufacturing model, therefore, relies on a reference database of graded patterns, construction methods and customised grading rules (Bond 2008).

Grading also contributes to key challenges for the integration of prints with garment patterns and preservation of the original design intent throughout the whole size range of a garment. During grading, garment patterns are not scaled proportionally as the grading rules are applied to compensate for body changes between pre-determined sizes, and these changes are not proportional in different parts of a body (Schofield & LaBat 2005). The irregularity between garment patterns of different sizes can be even more pronounced if custom grading rules are used to modify patterns (Bye et al. 2008). Therefore, engineering of the print design to fit within garment patterns can only be done for a specific garment. This engineering can be first done for a base size garment to achieve the desired design intent, with the following grading, while preserving this intent to the rest of the sizes in the range. Development of a CAD technique that enables construction of a print template engineered for a specific garment’s patterns, then grades this template into required sizes and repopulates it with a variety of prints would, therefore, facilitate application of the EP method. Alternatively, a construction method, similar to a garment pattern construction method, can be developed to rebuild the engineered print for each size, however, this technology is still unavailable.

2.4. Integrated Print-Garment Design

This section investigates the development of engineered print definition and examines the integrated print-garment design approach that is used for EP. The reasoning for the adoption of the integrated approach is presented, and practices employing the approach, current opportunities and issues with integrated textile print-garment design approach are investigated.

2.4.1 Engineered print definition

The term ‘engineered print’ traditionally referred to textile designs developed for specific products:

‘Design printed directly onto fashion garment, usually for catwalk designs, by the textile designer. It can be placed with exactness, avoiding seams, etc. A successful design that goes into production is reworked and printed on a continuous length of fabric’ (Braddock & O’Mahony 1998).
The definition for engineered print has been revised by Parillo-Chapman and Istook (2002) to ‘ready-to-print textile surface design images within garment pattern pieces’. Parrillo-Chapman (2004) commented on the changes in textile design domain and emphasised the need to take advantage of both conventional and emerging digital technology. The latter definition of engineered textile design was used in her creative practice study that combined CAD with DTP to allow for a seamless print to continue across shape and surface of the garment. The engineering process was described as starting with importing garment patterns into Photoshop to be used as guides when creating a digital image. Completed engineered prints were then adjusted for fabric shrinkage, compiled into the RTP marker and printed directly onto the base fabric. The usual fixating stage and regular cut-and-sew procedure to produce a garment then followed. The described process allowed for the creation of textile designs that were an integral part of the garment. However, as Parrillo-Chapman (2004) commented, this meant for a time-consuming collaboration with the garment designer. A wide range of technical skills was also required from the textile designer to manage the design/production processes in collaboration with the technical team.

In her Ph.D. study, Parrillo-Chapman (2008) developed a framework for engineered design process based on capabilities of ink-jet printing and integral knitting technologies and showed that engineered design required a different approach from traditional PD approaches. A further definition by Parrillo-Chapman (2008) stated that engineered design was

‘... a process or product where the fabric formation and/or design are produced simultaneously and/or purposely for the end product. The purpose of an engineered design is to i) improve the performance of the product and/or, ii) to improve the aesthetics of the design.’

For engineered printing, the aspect of improving aesthetics could be critical. The study by May-Plumlee and Little (2006) ranked and categorized a list of universal apparel evaluative criteria influencing the consumer purchase decision, presented in Table 2. The highest ranking intrinsic design criteria were colour/pattern and style/design/uniqueness. For these criteria, EP can provide for tailoring of print designs to specific pattern pieces and creating a product with enhanced aesthetic attributes.

Table 2: Ranked and categorised list of universal apparel evaluative criteria, adopted from May-Plumlee & Little (2006)

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<td>Colour/pattern</td>
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<td>Price</td>
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<td>Style/design/uniqueness</td>
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Parrillo-Chapman’s (2008) aspect of improved performance of a product relates closer to the reduced materials consumption of the EP method. Around 50% of garment cost is associated with used fabrics (Bond 2008). For apparel made from traditionally printed fabric, a design matching process is utilised during the generation of a cutting marker to ensure that repeating design aligns across main seams. Markers are generated based on a set of variables such as number and ratio of graded sizes, material properties, blocking and buffering allowances and restrictions on flip and rotation of garment patterns. Geršak (2013, p. 137) gives an example of the effect of a fabric’s pattern and repeat size on the efficiency of the cutting marker for mainstream printed fabric, shown in Table 3. In DTP workflow for engineered RTP images many of these restrictions can be removed or reduced, as garment patterns can be positioned in an optimum marker comparable with a plain colour fabric marker. This would allow for a saving of base fabrics as well as colouration agents (Lamar 2011).

Another interesting approach for such optimum markers has been demonstrated by Rissanen (2008) with the ‘jigsaw puzzle’ concept of interlocking pattern development to fit within a single piece of fabric with no waste. Combining this approach with CAD/DTP framework can open up innovation opportunities for integration of surface design over garment shape with unmatched ‘no waste’ sustainability of such fashion garments. The approach can even be strategically adopted to produce unique products for a sustainable fashion brand.

### 2.4.2 Integrated design approach, challenges and opportunities

Markham and Kingon (2004) define three types of technology-based advantages for new products: ‘1) higher performance, 2) lower cost, and 3) new, needed capability’. The authors also comment that the technical gap exists in the development of a continuum between scientific discovery and product introduction that might prevent technology users from accessing technology sources. The Technology-to-Product-to-Market (TPM) model is then proposed as a process to recognise promising technologies, express technical specifications as capabilities and translate them into product features and benefits. Another important feature of the model is the identification of the most receptive market. Thus, technical development is guided by the clear understanding of the products and markets. If the TPM model is applied to current fashion products, and markets and available digital technologies are assessed for their capabilities, the strong need for integrated surface-form apparel is apparent.

Innovations in textile design and manufacturing technologies have always created opportunities for designers and fashion businesses, for example following fashion market fragmentation in the
early 1990s, designers turned to the most innovative textiles to differentiate themselves and their products (Colchester 1996; Moxey 1998). However, as an integration of innovation creates potential for development of new products, it also presents challenges from changing design processes (Parsons & Campbell 2004). On the other hand, Gardner (1994, p.152) commented that at the times when practitioners disagree on 'the appropriate problems, methods, and solutions in any particular domain’, the innovative breakthrough is more likely to occur. It could be argued that such innovative breakthroughs are therefore likely in the current printed textile design and apparel creative domains.

Although underlying technology is complex, DTP expands design perspective, provides a streamlined workflow and offers unlimited colours, non-repeating patterns, short runs, customisable designs, and reduction in environmental impact (Briggs-Goode & Russell 2011). Combined with innovations in CAD, digital printing offers great creative possibilities for designers including potential integration of a garment’s 3D shape with printed surface. Furthermore, creating prints for integration with garments could be a way for designers to have control over the final appearance of a mass-customised product. Parrillo-Chapman (2008) makes an interesting point about the mass customisation opening up input venues for consumers, which can lead to undermining the original design intent. She then adds that engineered design, while supporting mass customisation, allows designers to retain control over the look of their product.

‘From a design perspective the ability to print full-colour, detailed designs using any scale using repeat or non-repeating elements, engineered printing gives this method plenty of scope to have an impact’ (Bowles & Isaac 2009, p. 178).

Lamar (2011), referring to Studd (2002), comments that historically textiles products were developed in a separate process and marketed to apparel producers. The producers then would select the fabric and turn it into garments, but rarely have involvement with the textile design process. Still, there are similarities in the design processes for textile and apparel products, including design concept development and review, colour development, and employment of CAD technology for design and visualisation. A typical way to start textile and garment concept development is by manipulation and experimentation with design elements: for garment design it might be draping over a model, moving or folding the fabric to assess its qualities, for textile print design by combining elements of colour, texture, or shape. Another way is by sketching silhouettes of a garment or compositions of prints. Concepts are then evaluated and refined or rejected: in the case of garment design, prototypes are produced for further modification and adaptation in the iterative refinement process. For textile print design, initial ideas have to be prepared for the selected manufacturing process and sampled as strike-offs. In the similar pre-production processes, the finalised garment prototypes or fabric samples are then supplemented with detailed specifications that provide required information for subsequent manufacturing. The separation between textile print and garment product development can result in an inferior product, for example when a print design is distorted once printed fabric is draped over a human body, especially with stretchy fabrics (Moxey 1999). However, the similarities in the development processes can be exploited to create integrated product.
In fact, creative interaction between textile and garment designers is achievable during product development. Kunz (2010) included the fabric selection step in concept and design stages of line development, which can provide garment designers with an opportunity to participate in print development. The author proposed the possibility of such interaction within the mainstream printing, when yardage printed fabric was used with a bundle cut-and-sew mass production method. The interaction scenario would be even more plausible if DTP were used as the printing method, as DTP doesn’t require long lead up times compared to the mainstream printing. The importance of technical design, which is defined as ‘perfecting styling and fit, finalizing patterns, testing materials and assembly methods, developing style and quality specifications, developing detailed costs, and grading patterns’, is additionally emphasised in post-adoption product development as a process used for perfecting technical requirements of products to avoid possible issues during production (Kunz 2010, p.87). If digital engineered printing approach is adopted, this technical design stage could also include integration of surface print with garment patterns.

Tyler (2005, p. 49) commented on the potential for concurrent development of print and garment design not yet being realised by designers and pointed out that

‘Apparel designers can now work closely with print designers to develop textile products that are engineered for specific garment concepts.’

Interestingly, the separated textile print-garment approach for mass fashion has been historically contrasted with the holistic approach to couture fashion design, when sourcing and development of fabrics are parallel to the development of a garment and both are created to complement each other (Moxey & Studd 2000). Such holistic approach is now possible for the mass market. Even though textile designers have been mostly concerned with the importance of two-dimensional geometry considering regularly repeating designs (Horne & Hann 1998), the 3D shape of an apparel product might be just as important as 2D surface print design (Wells 1997). Designers will have to change their perception of the relationship existing between textile print and garment shape (Lamar 2011). In engineered design, 3D shape and construction of the garment would then determine boundaries of print composition, and continuation of print across garment surfaces can be achieved by placement of the print elements. The potential workflow chart for integrated textile print-garment is presented in Figure 3.

In summary, advances in digital technologies have expanded printed textile and apparel domains and created numerous opportunities for collaboration between textile and fashion designers. The textile-garment design approach redefines traditional workflow processes between two industries and allows for the development of apparel products with a sophisticated level of integrated printed surface design. Currently,
mass customisation and fast-fashion strategies rely on flexibility and speed in design, development and manufacturing processes, and, therefore, the development process for the integrated product needs to be dynamic. To identify the parts of the development process that need to be made dynamic, the current use of an integrated development process can be examined regarding design possibilities, manufacturing methods and presented challenges.

2.4.3 Integrated approach in practice

The concept of design engineering is not new. Development of a decorative design to accommodate a particular garment shape has been historically practised, often as a collaboration between textile and fashion designers. For example, embroideries are typically developed to work within a specific garment pattern piece. Placement prints are often designed to fit in a specific location of a garment (Russel 2011). Then, if complementing printed textile is required for continuous yardage print, elements of design are reworked to create a repeat (Lamar 2011). However, within the mainstream printing the engineered print technique has been historically used for high-end fashion or apparel with simplified construction such as scarves, bed linen, etc.

Progress in technology does not imply an instant modification in design styles. The changes are more likely to come gradually as the practitioners adopt the innovation. With advances in DTP technology allowing printing of RTP images, the integration of textile and garment design into one seamless process has been a focus of many researchers in the field (Briggs-Goode, Amanda, Townsend & Northall 2010).

A practice-led research was undertaken by Townsend (2004) to investigate possible new digital printing styles. The manual stand modelling technique was combined with the Lectra 2D Pattern Design System and raster graphic software to explore the creative potential of CAD and to develop new surfacing and garment structuring strategies. Based on precedence of the textile, garment or both elements, Townsend (2004) suggested three design approaches for integration between 2D textile design and a 3D shape of the garment: ‘textile-led’, ‘garment-led’ and ‘simultaneous’:

• The textile-led approach of garment design relies on prior fabric selection and is often inspired by the appearance and properties of a fabric. Here a 3D shape of a garment is usually constructed to emphasise print design characteristics and to accommodate placement of specific details, use of print repeats or direction. Although this approach can motivate the development of innovative fashion garments, it also carries limitations and issues. This approach is common in the mainstream printing framework that doesn’t allow for printed design modifications after fabric is printed.
• The garment-led approach, on the other hand, focuses on the construction of the 3D shape of the garment, while surface design considerations are secondary. This approach often relies on textile design with minimal surface decoration to complement the 3D shape of the garment.
• The simultaneous approach is based on careful consideration of the aesthetic relationship between textile surface, fabric draping characteristics and garment shape. The garment is designed to benefit from this relationship. This approach can be realised through EP.
Jennings (2003) commented on adding another dimension to size customisation by creating personalised textile designs to fit tailored pattern pieces. The author suggested that strategic placement of graphic designs on each pattern piece could accentuate or downplay figure characteristics, and prints could be scaled or distorted to match seams. Vector garment patterns were imported into Adobe Illustrator, and designs representing traditional PDS marks were manually positioned over patterns as prints. The resulting RTP images were digitally printed on fabric and cut and sewn into a garment. However, the study used only basic CAD tools and the process of grading was not attempted.

Parsons and Campbell (2004) collaborated on creating art for garments using an integrated digital textile-apparel design method focusing on three areas: art-to-wear, custom design and mass customisable design in order to explore new methodologies of design process. The great potential of the integrated approach was reported with a steadily expanding range of creative possibilities. However, the change also brought challenges such as complexity of possible outcomes based on decisions, differences in production methods and in products themselves. Parsons and Campbell (2004) concluded that a more systematic research and practice was needed to facilitate the adaptation of the approach.

These examples demonstrated that textile print CAD combined with DTP provides a means of integrating surface print within pattern shapes that allows for enhanced 3D appearance of the garment. However, the examples also showed that editing of this appearance or replication of that appearance across garment sizes required iterative manual processing that limits the use of the technique outside of unique garments. For that reason, manual processing needs to be replaced with a software-driven one in order to realise the full potential of DTP for integrated product development approach.

2.4.4 Current challenges involved in adopting engineered design

Globalisation, rapid changes in the industry needs and digital technologies such as CAD and DTP created a need for textile designers to have good computer skills to enhance their creativity rather than to limit it (Treadaway 2004b). Combining DTP with virtual visualisation technologies can expand opportunities for design experimentation. However, this design potential can be underutilised due to lack of skills in practitioners, lack of supporting technologies or difficulties in interaction with technology (Easters 2012). The fashion and textile designers in the field, therefore, require a better understanding of technical aspects of CAD, digital printing and visualisation technologies, and the possibilities for collaboration these technologies present. Thus, technical knowledge is becoming a must have skill for textile and fashion design practitioners in the field. Such skills will take the textile design to a new level and allow an optimal use of DTP technology. Still, the adaptation of digital tools is complicated by rapid technological changes, as designers find it hard to keep up with updates (Treadaway 2004b). Parrillo-Chapman and Little (2012) also commented on the iterative time-consuming nature of current techniques for EP and the high level of collaboration required from creative and technical team members during design development and integration within a garment shape. Designers will, therefore, need expert technical knowledge to operate successfully within an EP model. Lamar (2011) describes technical expertise required from designers for effective solution development as
‘...a unique and extensive range of design and development skills, and a knowledge base that extends beyond what is typical for both garment and textile designers and developers.’

Technical skills and practical familiarity with digital technologies should become an indispensable part of textile and fashion designers’ education. In addition, clear and standardised language is required to enable designers to communicate efficiently and keep up to date with the latest knowledge (Hui 2011). Furthermore, Ujiie (2002) suggests that the DTP environment creates opportunities for the development of cutting edge design concepts for higher education. Similarly, educational benefits from practical experiences with DTP including hardware, design and printing software, and colour management for fashion and textiles students and practitioners in the field supported by multiple studies (Parrillo-Chapman 2004; Polston, Parrillo-Chapman & Moore 2015; Wilson 2001). Such education is essential, as textile designs for digital printing should be developed or processed using CAD methods to a high-quality digital art.

Also, Parrillo-Chapman’s (2008) Ph.D. study identified the lack of support for integrated product development in the existing production assembly methods as a challenge. Lamar (2011) also points out that industrial changes such as modifications in cut and assembly processes and equipment are required for the adoption of integrated textile-apparel design. Outside of the collaborative approach mostly used for labour-intensive unique garments, the solution for large-scale implementation is challenging. Lamar (2011) also commented on impacts of the traditional separation existing between textile and garment design domains. For textile designers, the established workflow is based on the creation of repeating prints rather than a composition suitable for a particular pattern shape, and often complicated by the lack of garment design experience. To integrate textile surface design into a 3D garment form, a textile designer needs to understand garment construction and how pattern pieces are assembled and drape on a 3D body, so surface design continuity can be preserved. Garment designers, on the other hand, construct pattern pieces to accommodate cutting them out of fabric with continuous yardage print instead of developing pattern pieces that can fit efficiently across a fabric width as RTP images.

Difficulties also exist in integration between vector-based PDS and raster-based digital printing that need to be addressed. PDS software generates pattern piece information in a form of vector-based files. Used in apparel design software proprietary formats or specific modification of the generic graphics exchange file formats carry additional pattern piece information, which can cause a problem when importing these files into graphics software, such as loss or distortion of garment pattern data. Graphics software can use both vector and raster file formats, however, industry software for textile print design are mostly raster-based. Furthermore, Lamar (2011) comments on limitations of industry software components for visualisation of engineered designs as most are geared towards the display of repeating prints and suggests that further development of supporting technologies is necessary.

2.4.5 The future outlook for the use of digital technologies for engineered printing

Cross, Naughton and Walker (1981) defined technology as

‘...application of scientific and other organised knowledge to practical tasks by social systems involving people and machines.’
CAD, DTP and 3D visualisation technologies offer the potential to facilitate the application of the engineered printing method not just for unique garments, but for mass customisation of printed apparel. The similarity exists in processes that are used for prototyping and manufacturing methods when utilising digital technologies (Parrillo-Chapman 2008), and that enables the transition from development to the production stage. At the development stage, the ability of CAD digital workflow to facilitate design exploration is enhanced with the addition of DTP, as prototypes can be tested immediately (Parsons & Campbell 2004). Then the prototyping stage can be scaled up and replicated in the production stage.

Traditional 2D CAD development of garment patterns depends on physical prototyping for verification of fit. The cost of the prototyping stage contributes to 4-6% of total garment cost (Farber 2002). On the other hand, there is a noticeable increase in interest in apparel 3D CAD systems that is driven by advances in virtual 3D body and cloth modelling (Istook, Newcomb & Lim 2011). Many analysts also predict dramatic changes in PD methods and consumer purchasing behaviour related to 3D virtual digital technologies (Kim & Labat 2013; Magnenat-Thalmann 2010). Development of interactive 3D systems capable of integration of mechanical, physical and environmental information are suggested as future research directions.

If critical components of 3D CAD such as visual and technical accuracy of the virtual model, fabric properties and garment patterns can be simulated realistically, and a program can evaluate garment style and fit, greater efficiency and speed can be achieved in product design and development stage (Sayem, Kennon & Clarke 2010). These advantages are especially important for MTM apparel, and can create a competitive advantage for the companies that adopt the mass customisation business model. Once a visualisation environment can provide a realistic simulation of the critical components, new methods of interactive virtual design/fit evaluation are predicted to emerge (Istook, Newcomb & Lim 2011; Kim & LaBat 2013). Designing for a 3D surface is a developing field with new possibilities. The emergence of 3D CAD and modelling techniques and a 3D simulation environment for virtual visualisation presents an opportunity for integration of surface print with 3D garment form (Baciu & Liang 2011; Townsend 2004). Countless graphic assets exist in well-established physical and digital print archives as repeating prints. The software interface could be built to facilitate the integration of such assets with a garment form creating seamless repeating or non-repeating 3D surface prints.

This research focuses on developing techniques based on existing CAD tools for engineering of repeating print over the surface of garment and preservation of original design intent by grading of RTP images.

‘…artists have always developed their own technology - whether it be pigments or the engineering and machining of contemporary sculpture. In spite of the apparent demise of the Renaissance man and the increasing compartmentalization of knowledge, I believe a creative artist - or scientist - cannot be detached from the tools with which he works. Sometimes, he or she needs to be an engineer or computer programmer’ (Field 2014).

Some programming solutions for integration of print designs with shapes have already been suggested. A generative software has been used to place elements of print into a fabric-wide
infinite non-repeating design (Russell 2014). An interactive genetic algorithm has allowed the generation of designs for a rectangular carpet shape (Zamani, Amani-Tehran & Latifi 2009).

Nevertheless, automatically engineering a repeating print within garment pattern shapes is still unresolved. Alternatives, such as texture mapping tools in computer animation and 3D gaming applications were also considered (Gomes, Velho, Frery & Levy 2009; Kaplan 2009; Magnenat-Thalmann & Thalmann 1987). However, these solutions are more concerned with either mapping to regular objects or mapping of textures that do not require the precision needed in EP for complex 3D garment shapes.

The possible solutions for engineered repeating prints are likely to come with better understanding of print attributes. For the construction of repeating prints, the principles of geometrical symmetry are employed. The symmetry of repeating prints has been addressed by many researchers. All-over repeating designs were categorised in 1910 by Christie (1969 ed) as two main types: those comprised of isolated motifs surrounded by background space and those with a continuous mass of repeating motifs. The systematic classification continued in the 1930s with the comprehensive review by Woods (1935) from the University of Leeds to encourage understanding of the principle of geometrical symmetry by practising textile designers. In the 1980s and 1990s, a number of scholars including Stevens (1980), Washburn and Crowe (1988), and Hann and Thomson (1992) enhanced the conceptual framework introduced by Woods and extended the classification for counter-change patterns. A flow-chart for the identification of any of 17 classes of all-over patterns was compiled by Hann (1992). Horne (2000) contributed to the area of regular tiling and tessellations, and Hann and Russell (2003) examined the potential value of geometric concepts as solution tools for repeating patterns and tiling problems.

Four types of symmetry operations are used to generate repeating prints: translation, rotation, reflection and glide-reflection. Translation repeats a motif at a regular distance and can be in a single direction to produce a border design, or be bidirectional resulting in all-over design; the structure of all-over repeating designs is also determined by the underlying grid. Rotation repeats a motif at a specified angle around a predefined rotation centre and can be expressed as a fraction of 360 degrees. Reflection replicates a mirrored motif across a reflection axis. Glide-reflection combines translation and reflection and generates a mirrored motif shifted along a reflection axis by a non-zero translation. The combination of four symmetry operations can generate two classes of finite repeating designs, seven classes of border designs and 17 classes of all-over designs (Hann & Thomson 1992; Washburn & Crowe 1988). Rotation and reflection are also applied for construction of symmetrical motifs.

Furthermore, Hann (2013) discussed the possibility of a repeat being nested in a repeating design as well as geometrical tiling comprising of differently shaped tiles, which is the method historically practised in some cultures. Hann (2013) also suggested the idea of a modularity concept for engineered design and reviewed the application of the principle across the natural environment and man-made fields such as art, architecture or industrial sectors. The modularity concept is described as a system where a few modules can be added, subtracted and recombined in different ways to achieve several varied configurations.

Modularity, however, works better with regular geometrical shapes, and further manipulation might be required to provide continuity of repeating print over garment seams for
graded garments. If the limitation of a fixed repeat size is removed when the repeating print is constructed, other methods, such as distortion or variations in the way that a repeat configuration is formed, may be required.

Outside of the textile print design, distortion is employed in computer graphics for geometric operations, which are used in image processing for modifications of images geometry by repositioning the parts of images in relation to each other. Typically, they would be used to correct unwanted geometric distortions, to apply wanted geometric distortions or for image match, when an alignment of common elements of multiple images is required (Marques 2011).

Geometric operations follow a two steps procedure:

• mapping, where spatial transformation is performed based on a specified function;
• interpolation, where the value of image part is re-computed.

In graphics software such as Adobe Illustrator or Photoshop, geometric distortion can be managed with the range of dynamic tools that employ a warping function. Gomes et al. (2009) describe warping distortion as if the image was printed on a rubber sheet, which was then stretched with some parts contracting and some expanding, but without tearing or ripping the sheet. The warp transformation can also mean an expansion in one direction and contraction in another. Marques (2011) defines warping as the ‘transformation of an image by re-parametrization of the 2D plane’ and suggests two methods for warping. Polynomial warping is done by mapping key points from the source image to new locations in the destination image and re-calculating displacement of other points. Alternatively, piecewise warping can be done with a control mesh by moving selected intersection points of the mesh to new positions.

Another approach is possible if, before transformations, the image is assessed to establish areas of the image that can be removed with the minimal loss of meaningful content. Marques (2011) describes a ‘seam carving’ method, which allows re-scale of the design without changing important content by expanding or reducing seams area. That approach is supported by content-aware tools in Photoshop or Pattern Tool in Illustrator. Background elements of the suitable textile designs can be subjected to seam carving technique while foreground elements are preserved. Alternatively, a repeat can be divided into a continuous background and non-continuous foreground elements. Then the distortion is applied to background grid, transforming the uniform grid into irregular. Then the foreground of repeating print gets reconstructed with affine transformations determining relative position, scale and rotation of foreground elements of each repeat. Such method can work equally well with grids based on geometry different from rectangular.

However, these other methods would break the rules that are currently applied to the construction of repeating prints. A better understanding of repeating print attributes as well as their impact on the adaptability of a repeating print for the EP method is needed to retain the output standard for such engineered design.

2.5. Summary of Literature Review

The visual appearance of a printed garment is important and innovation in this area presents opportunities for product differentiation and competitive edge (Tyler 2005). Over 10 billion metres of printed fabric is manufactured annually for apparel products, and increases at least 1% per year due to the acceleration of fashion cycles and continuous world population growth. The
annual worldwide market for fashion fabrics is around $33 Billion, but only 1% is printed digitally (Ujiie 2012). However, DTP has reached the production speed and reliabilities for volume production, with the average speed of 400-600 m² per hour, and within a few years the expected market penetration could reach 2-5% (Ujiie 2014). Around 50% of a garment cost is associated with fabrics, making efficient material utilisation a priority (Bond 2008). For traditionally printed fabric, garment patterns are positioned within a cutting marker as to ensure print alignment at the main seams. This practice improves a garment's visual aesthetics but raises the fabric waste up to 30% (Geršak 2013). In contrast, engineered printing allows for matching of prints while achieving optimised utilisation both in substrate and colouration agent (Lamar 2011).

It can be said that the apparel industry is driven by changes in trends and consumer preferences, and traditional mainstream printing methods cannot satisfy mass customisation requirements in JIT manufacturing model (Fralix, 2006). Mainstream printing, which is still accounting for 90% of all printed textiles (Dawson 2006b), must allow for a lengthy lead-up timeline up to 8-12 weeks (Briggs-Goode & Russell 2011) and can require up to 60% downtime (Tippett 2002). However, mainstream printing can be supplemented with digital strike-offs sampling or replaced with the full digital production allowing for an efficient and streamlined manufacturing (Ujiie 2006).

Lamar (2011) notes that digital printing can produce photo-realistic effects, higher levels of light and shadow rendering, textured, trompe-l’œil, moiré and other effects that are not achievable with mainstream methods. There is no constraint on the size of repeat or scale of the image, and in the case of an engineered print the concept of repeat can be abandoned in favour of customised tiling. DTP technology, therefore, is creating opportunities for innovations in apparel mass customisation, surface colouration methods, new design styles and printed textile design processing for engineered printing (King 2006; Tyler 2005). Currently, an increasing market share of printed textiles is produced digitally and with growing demand for short-run production and JIT delivery required for mass customisation, DTP can offer the cost-effective solutions (Cahill 2006).

The potential of mass customisation relates to providing for individual printed garment size variations by integrating printed textile design with garment patterns to generate RTP images for engineered printing. Processing is currently done by utilising CAD methods that were developed to comply with the limitations of mainstream printing and retro-fitted into DTP that is not constrained by these limitations. Parrillo-Chapman (2004) described textile design engineering as creating a design within a garment pattern shape, the technique that was historically used for clothing decoration and diminished due to constraints of mass production processes. Such design engineering allows for a better synergy between the 3D shape of a garment and print design (Parrillo-Chapman 2004). Parsons and Campbell (2004) also note that EP allows for personalisation of textile print designs, and optimised material utilisation both in substrate and colouration agent.

The EP method was traditionally used for printing directly onto a fashion show garment with a view of modifying a successful design into a continuous print for production (Braddock & O’Mahony 1998). With advances in digital printing technology the method was adopted for RTP images. The 3D simulation environment for virtual visualisation presented additional tools for integration of printed textile design with 3D garment form (Baciu & Liang 2011; Townsend 2004). Still, the adoption of the EP method is hindered due to the lack of support for integrated product development in the existing manufacturing methods, the lack of required technical expertise of
practitioners, and limited access to technology or dissatisfaction with capabilities of CAD technologies (Lamar 2011; Parrillo-Chapman 2008).

Key existing challenges with engineered digital printing that have to be addressed relate to the matching of print elements at seams for all graded sizes, preservation of the design intent between graded sizes, and integration between vector-based garment patterns and raster-based digital printing images. The iterative nature of current manual techniques for engineered printing is time-consuming, and a high level of collaboration is required from creative and technical team members during design development and integration with a garment shape (Parrillo-Chapman & Little 2012). Current processing techniques increase the cost of product development and diminish engineered printing method commercial application for the mass market. Nonetheless, textile and apparel designers have an opportunity to reconsider the connection between the textile print and garment. Horne and Hann (1998) suggest that textile designers have been concerned with the importance of two-dimensional geometry when creating regularly repeating designs. However, Wells (1997) argues that the 3D shape of an apparel product is just as important as 2D surface design. The integrated design process that combines DTP, CAD and 3D visualisation technologies will allow designers to develop products with unique attributes.

Available CAD technologies have been explored to suggest programming solutions to manual alterations currently required for the generation of RTP images such as generative software (Russell 2014) and interactive genetic algorithm (Zamani, Amani-Tehran & Latifi 2009). These solutions, however, could not automatically engineer a repeating print over the more complex surface of a garment. Research into the relationship between the 3D shape of a garment and 2D print has been undertaken from a creative framework perspective (Parsons & Campbell 2004). The introduction of small random variations in the repeat formation with a programming solution has also been anticipated (Briggs-Goode & Russell 2011). However, none of such programming solutions for mapping of repeating textile prints has yet been introduced or successfully commercialised. Alternatives, such as texture mapping tools in computer animation and 3D gaming applications are more concerned with either mapping to regular objects or mapping of textures that do not require the precision needed in EP for complex 3D garment shapes. In this regard it is clearly evident that there is a need for the development of dynamic methods for EP with existing CAD tools. Such methods are expected to reduce manual alterations required for the fitting of repeating prints within garment patterns which is currently a challenge in product development. The tools for such methods would be selected for their ability to support non-destructive CAD editing. Non-destructive editing, also known as dynamic editing, allows modification of the appearance of a digital graphic object without changing its underlying structure.

It can also be argued that some repeating prints would be more adaptable for integration within garment patterns. Furthermore, even for the existing repeating prints it would be useful to understand how attributes of repeating prints affect their adaptability for the engineered printing method. However, the impact of the prints’ attributes on adaptability for the EP method has not yet been established. Also, it would be useful to know potential design directions that allow a designer to create repeating prints that are more adaptable.
3. Research Methodology

3.1. Introduction

This research examined the latest developments and issues existing for the adaptation and integration of repeating prints with garment patterns or the engineered printing (EP) method. The research aimed at the engineering of repeating prints with the aid of a more streamlined, driven by software editing approach. As the research was situated on the cusp of technology and design, processes related to both creative and technical design domains were explored to establish the conceptual framework, within which the subject matter could be considered. This research was approached from a post-positivist worldview, and as such has been designed to allow for a multidimensional nature of the study’s object, acknowledge my personal involvement as a researcher and compensate for inevitable bias, and yet support a structured objective examination of an identified reality with experimental methods, which were based on computer and statistical modelling. The exploratory-sequential mixed method approach was used.

This research started with a qualitative investigation into issues that affect the adaptation and integration of repeating prints within garment patterns. The investigation allowed separation of these issues into processing methods used for textile print design and manufacturing, and attributes of repeating prints. Also, it established potential design directions for the next stage of analysis. Through qualitative analysis a selection of print attributes were identified as distinct quantifiable variables that could be examined in quantitative experimental research. Quasi-experiments were designed to test specific combinations of these variables with computer-aided engineering techniques based on the proposed design directions. Statistical analyses of the experiments’ results allowed me to verify and refine my position and understanding and to contribute to the current knowledge on the subject of engineered printing. Then the future research directions were suggested.

This research aimed to suggest potential design directions for repeating prints to make them more readily adaptable for EP. Selected attributes of repeating prints are examined for the effect on the adaptability of repeating prints for the EP method. The project also aimed to examine how processing of repeating prints for Ready-to-Print (RTP) images can be streamlined with existing advanced tools of universal computer-aided design (CAD) software. Techniques were developed for generating RTP images that provide 3D print continuity over garment seams and preserve the design intent between graded garments. The objectives of this research were to:

- examine current practices for mainstream and digital pre-printing and printing;
- establish a taxonomy of repeating print attributes;
- identify potential design directions for repeating prints adaptable for EP;
- suggest approaches, that are based on existing CAD tools, for design directions for integrating repeating prints with garment patterns and generating RTP images for graded garments;
- validate these directions experimentally by testing hypotheses;
- examine the impact of the identified attributes on the adaptability of repeating prints for EP;
- contribute to the advancement of EP towards mainstream digital production by improving the understanding of the engineered repeating prints subject.
The research suggested potential solutions that mass customisation fashion businesses might utilise in order to adapt and integrate repeating prints with garment patterns. Such integration can improve fashion product appearance and sustainability. These solutions are demonstrated on existing and readily available CAD tools that make them accessible to a wide audience within the fashion industry. There is an opportunity to extend the concept of engineered print to include repeating prints. The developed design directions and processes used in experiments can be applied to generate innovative engineered repeating prints. The data collected in the research also provides empirical evidence about relationships between repeating print attributes. Additionally, the information about the attributes’ impact on the adaptability of repeating prints for the EP method can be used to develop dedicated software tools.

A number of researchers studied current processes in textile design for mainstream printing methods, and research has been done to build a model for the engineered design process (Parrillo-Chapman 2008). However, no substantial research has been conducted that:

- identifies the taxonomy of repeating textile prints for engineered printing in a digital textile printing (DTP) environment;
- provides possible design directions for engineering of repeating prints;
- suggests dynamic methods, based on existing software tools, for creating Ready-to-Print (RTP) images that can be utilised for the EP of repeating prints.

For this research, taxonomy is defined as a particular system of classifying things including hierarchical relationships between these things. With a taxonomy established, the hierarchical set of quantitative variables can be derived and possible new design directions for engineering of repeating prints suggested. Then, the feasibility of these directions can be validated, hypothesised relationships between variables experimentally tested and acquired empirical data statistically analysed. The results of this research then can be used by textile print designers to inform their decisions when new print designs are created, or existing print designs are adapted for engineered printing. The results can also be used in future research to build dedicated software tools for engineered print product development (PD).

### 3.2. Mixed Methods Approach

Based on the theoretical framework and the author’s background in CAD, an exploratory sequential mixed methods research approach was adopted in this research. Many different terms are still used for this approach, for example, multi method, mixed methodology, but more recent publications prefer the term ‘mixed methods’ (Creswell 2014). This section investigates research methods in fields of textile and clothing design, provides more detailed justification for selecting mixed method and exploratory sequential approach in particular, and demonstrates how it was applied in this research.

Innovative product design is often motivated by advances in technology, and this connection has been acknowledged in theoretical debate. Cross, Naughton and Walker (1981) observed the close relationship between design and technology and provided examples of daily use objects influenced by science, but clearly created by technology experts using non-scientific methods. Cross (1984) compiled an overview of design methodology describing historical developments in the field of design epistemology and main paradigms of design research, and later character-
ised design methodology as a process-oriented ‘study of principles, practices and procedures of design’ with the objective of improving design practice. The two distinctive fields of design research as rational problem solving and design as reflective practice were then acknowledged (Cross 1993). However, the design research can be differentiated from creative work by the presence of identified need or an existing design problem (Moxey & Studd 2000). Owen (1998) situated product design among other disciplines in traditional fields of study and practice, showing product development to be positioned in the real world phenomena and more oriented towards the synthetic procedure. Owen also suggested that the intentional construction of product design research towards more analytic procedure and symbolic inquiry would provide a more balanced approach and opportunities for knowledge building that are currently unexplored.

Lennon and Burns (2000) provided an extensive review of research methods in the fields of textile, clothing and human behaviour, suggesting 5 dimensions for research structuring: (a) type of strategy used, (b) time frame, (c) origin of data, (d) technique of data collection, and (e) qualitative or quantitative processing of data. They also examined the potential consequences of adopting some of the popular approaches and suggested that limitations of these methods can be minimised when a ‘multi-method’ approach is taken. The application of a triangulation method for the multi-method approach was further illustrated for each of the dimensions. In this research, triangulation was applied on dimensions of data origin (exploration or experimentation), and qualitative or quantitative processing of data as a validation method. The multi-method approach was also reported as suitable for the development of taxonomy models (Lennon & Burns 2000).

The mixed methods methodology originated around the late 1980s in the work of researchers from diverse fields of study. More recently, it has been used in textile design and technology fields and taken an important position as evident from publications including theses (Anderson 2006; Ho 2011; Moser 2004) and discussions found in the relevant science journals (Lennon & Burns 2000). The strength of the mixed methods approach lies in drawing on advantages of both qualitative and quantitative research and minimising the limitations of both approaches (Tashakkori & Teddlie 2010). Also, the inherent complexity of the approach allows for the development of the new research procedures if the existing procedures fall short. The mixed method is ideal when both qualitative and quantitative datasets are available for the researcher allowing more comprehensive understanding of research problems by comparing two viewpoints. Conducting a qualitative part of the research before quantitative also helps in developing better instruments and allows for the integration of the researcher’s expertise in the analysis of experimental stages. The following aspects of the exploratory sequential mixed-method were also considered and influenced this selection:

- qualitative and quantitative data can be collected and analysed separately in response to research questions or hypotheses making the process manageable for a single researcher;
- the integration of two forms of data can be achieved by connecting the results of the qualitative phase in the design of instruments for the quantitative phase and proposing the directions for experimental studies, followed by the final analysis stage of both approaches;
- the procedures for both qualitative and quantitative data collection and analysis stages can be designed to be rigorous and provide adequate sampling and sufficient sources of information and to ensure validity and reliability;
• the procedures can be developed to utilise exploratory sequential mixed methods design including the timing of the data collection and emphasis for each stage.

Therefore, the mixed methods approach was selected as it could provide the optimal framework for this research. The following research stages were planned within the selected framework:

**Qualitative Stage One** involved a review of the literature and the identification of key themes using Applied Thematic Analysis (Guest, MacQueen & Namey 2012a). A code-tree was developed to produce a taxonomy of repeating print attributes. A limited number of repeating prints were then examined based on the created taxonomy, followed by refinement of the taxonomy to a set of distinct quantifiable variables. Potential design directions for engineered repeating prints were suggested.

**Quantitative Stage Two** involved the development of a series of instruments for experimental studies. Each of the suggested design directions was then experimentally validated, and the impact of repeating print attributes on the adaptability of repeating prints for the EP method investigated. In the following main experiment, the combination of the proposed design directions was tested as a method for the engineering of RTP images for graded garments. Specific hypotheses were proposed and tested for each of the confirmatory experiments, and the collected data was further statistically analysed.

Then in **Stage Three** the combined results of Stages One and Two were analysed. Existing CAD programming solutions, tools and methods that could be integrated into the current digital design and printing process to engineer repeating prints and to eliminate or minimise manual alterations necessary for grading of RTP images were discussed. Suggestions for future research directions for the development of dedicated programming solutions for engineered repeating prints were also made.

### 3.3. Researcher’s Role

The possibility for engineered repeating prints provided critical opportunity to review the diversity of print design styles and approaches, employed by designers, in order to increase adoption of DTP as a mainstream technology. The researcher’s experiences as a practicing textile and graphic designer and accumulated CAD expertise allowed for the understanding of the current issues in the commercial printed textile design and provided tacit knowledge to appreciate the complexity of the chosen problem. The researcher has worked for many fashion companies as an apparel and printed textile designer and had over 15 years of personal experiences with universal and proprietary CAD/CAM applications in the fields of textile and fashion design.

Application of the researcher as a key instrument for data collection is identified as one of the core characteristics defining qualitative research (Creswell 2014). For this research, CAD skills in particular has shaped the approach to data collection procedures and design of experimental stages with the interest directed towards looking for the evidence through a combination of design and analytical computer tools. Nonetheless, due to previous experiences, biases may have been introduced to the study, and such biases might have affected my view and understanding of the collected data and subsequent interpretation of the findings. Therefore, care was taken throughout this research and particularly in the qualitative stage of the study to account for personal assumptions and biases by validation of findings (Guest, MacQueen & Namey 2012b).
4. Qualitative Stage One

4.1. Research Objectives

This Qualitative Stage One consisted of critical literature review using Applied Thematic Analysis (Guest, MacQueen & Namey 2012a) and the development of a code-tree to produce a model of taxonomy for repeating prints. A limited number of repeating prints was also examined based on the taxonomy model, followed by the refinement of the taxonomy. Repeating print attributes were reduced to a set of distinct quantitative variables. Potential design directions for engineering of repeating prints were proposed.

Stage One Objectives:

- develop a taxonomy of repeating print attributes by examining common terminology in current practices for mainstream and digital pre-printing and printing;
- use the taxonomy to identify quantitative variables for the development of instruments in Stage Two;
- suggest potential design directions for repeating prints adaptable for EP for testing in Stage Two.

4.2. Stage One Methodology

Considerable knowledge already exists about repeating prints, but this research was conducted to investigate them in the context of their adaptability for EP. For this, a structured iterative approach with on-going data analysis was believed to be most fitting. Exploration of relevant methods pointed towards an Applied Thematic Analysis (ATA) approach, which is defined as ‘a rigorous, yet inductive, set of procedures designed to identify and examine themes from textual data in a way that is transparent and credible’ (Guest, MacQueen & Namey 2012a). ATA is described as the most common method in qualitative research. ATA also supports both positivist and interpretive traditions of inquiry and can be used for a wide range of datasets sizes, by a single researcher or a team. When content-driven, exploratory ATA can also be structured to generate findings suitable for practical applications (Popping 2000). ATA allows identification of key categories and codes in textual sources through techniques of word searches and data segmentation/reduction, and can additionally be used for the construction of the theoretical models (Kuckartz 2014). The ATA as the methodological approach, therefore, was applied to address the research objectives, and to conduct the data collection and analysis procedures.

In Stage One qualitative data was collected from multiple diverse data sources. Text sources were purposefully selected during the literature review and combined with images of repeating prints. The inductive analysis was then applied to build a comprehensive hierarchy with a more abstract idea at the top. The deductive analysis was also used to evaluate sufficient support of themes and categories in the collected evidence. It was anticipated that the research process itself would emerge and be refined during data collection. As such a method of analysis often uses a visual representation of the relationship between codes and categories in the dataset, a visual model of a code-tree for repeating print was used to facilitate the development of understanding.
4.3. Sample Selection

Approximately 50 sources were selected to be thematically analysed, containing peer-reviewed articles, book chapters and books, five professional websites with multiple pages, which were converted to PDF format, and software manuals. All of the selected sources were related to print design and specifically to repeating prints or graphic software that can be used for the design of repeating prints. The sources also contained descriptions of textile print development practices for the mainstream, digital and engineered printing and definitions of terms. Advantages of such secondary documents analysis were that precise words could be obtained as sources existed in digital textual format or could be digitised using optical character recognition to ensure the use of computer tools for data analysis. It was an unobtrusive source of information available in the public domain, and the quality of data was high as documents were authentic and accurate. Documents came from a wide range of academic and professional industry publications. Sources were analysed in order to establish and consolidate common terminology, develop the code-tree and to define repeating print attributes. The analyses continued until the saturation (Creswell 2014) was reached.

Digital images of repeating prints were also selected to provide an additional visual dimension to the analysis and the identified codes and their hierarchy and relationship were validated against actual repeating prints. Personal visual images were chosen to address possible copyright issues.

4.4. Data Analysis Procedures

Text segmentation was applied to selected documents to facilitate the exploration of thematic content. In the early stages of analysis, a ‘key-word-in-context’, or KWIC approach was used to identify and retrieve relevant sections of text, followed by reading and segmenting during coding process (Guest, MacQueen & Namey 2012b). Categories were also identified through repetition and distinct or specific terminology.

The analysis was focused on specific categories in a code-based approach. The content of the selected sources was driving the development of codes and the visual code-tree, allowing the sorting and analysing of the data iteratively. The visual model of the coding tree was modified as new information was added, which allowed examination of commonalities, differences and relationships between codes and categories (Kuckartz 2014). Sections of text from selected documents were also incorporated into initial code descriptions in the visual code-tree model, providing additional help in clarification and consolidation of the meaning. A refined code-tree model was then modified into the visual model of taxonomy, which was later validated against images of repeating prints.

Analysis steps included:

**Step 1.** The raw data including documents/websites/images was collected during the literature review. Initial themes for analysis were also identified;

**Step 2.** The collected data was organized and processed to import as digital sources into Scrivener software (version: 1.8.6.0), with additional scanning and optical character recognition for hard-copy publications. Where possible, sources were converted to Word
documents to facilitate the KWIC approach. In addition, sources were sorted and arranged depending on the origin of information;

**Step 3.** The general sense of the information and reflection on overall meaning was achieved through reading all of the data. Reading also allowed verification that data was sourced from academic, industry and design professional, and software developer’s backgrounds, and that the data was credible and gave sufficient depth for analysis. Documents were read with the following initial themes in mind:

- prints terminology;
- prints attributes;
- applicability for engineered printing.

**Step 4.** Segmentation and coding of data with the aid of KWIC and manual techniques into initial categories, generating labels for categories and codes based on the terminology of data sources and preliminary codes derived in the previous reading step was performed. Scrivener software features allowed for the segmentation of text and the application of various types of meta-data for coding;

**Step 5.** Simultaneously, a visual code-tree model was built to extract and consolidate the categories and to refine descriptions of them, and to add emerging codes. A mind-mapping software Simple Mind (Desktop version 1.9.5) was used for this task. Sections of text from the selected documents were included as original descriptions for the emerging codes;

**Step 6.** Documents were searched to locate text and illustrations located around the initial code words, with the reading of the text and analysis allowing to build interrelated codes and establish relationships between codes. Further development of the code-tree allowed relationships to be established between categories;

**Step 7.** Interpretation of the code-tree allowed refining it into the visual model of taxonomy. This process also led to the aggregation of information on potential design directions for the engineering of repeating prints. The repeating print attributes were also extracted as a set of distinct quantitative variables for the following Stage Two research.

### 4.5. Validity and Reliability

Triangulation of multiple data sources of information was performed by including publications from academic and industry backgrounds, websites, software manuals and images, in order to strengthen reliability as well as internal validity (Popping 2000). Reflexivity was applied to the data collection, the analysis and interpretation of the finding to clarify the bias the researcher brought into the study and also to utilise the researcher’s in-depth understanding of the textile print phenomenon.

Reliability was also strengthened by using the visual code-tree model. The code-tree allowed the definition of the codes to be monitored to prevent drifting of the meaning of the codes, which was especially important due to anticipated diverse terminology. Generalisation of the developed taxonomy model was validated against repeating prints images. The design directions for the engineering of repeating prints were to be validated in the Stage Two experiments.
4.6. Stage One Results: Code-Tree Model and Taxonomy of Repeating Print

The initial code-words used for a KWIC search were repeat, yardage and motif. The code-tree started with separating types of printed designs into repeating prints, croquis, placement and engineered prints. The similarity between descriptions of engineered and placement prints allowed positioning them initially together under a shared description. General characteristics of repeating prints were then separated into symmetry type, repeat size, repeat direction and repeat layout, which were further divided. The initial code-tree is shown in Figure 4. It is worth noting that with descriptions of repeating prints often different meanings were assigned to the same words describing attributes of repeating prints as a result of historical and current usage and the context in which they are used. For example, words yardage, motif and pattern were often placed together with repeat or used to replace repeat. As the objective was to build a taxonomy of repeating print attributes for EP, the decision was made to reserve pattern to mean garment pattern in this thesis, unless it was used as part of a proper name. There were also noted differences between scientific, graphic software and textile design terminology for types of repeating prints, for example block, drop and brick repeats were based on the same symmetry operation, and in the case of graphic software all of these types were converted to block repeat swatch. The extended code-tree that emerged through ATA is presented in Figure 5. The definitions for the codes were included in the visual model, verified against actual repeating print images (examples are demonstrated in Figures 6 and 7) and refined during analysis.

The following definitions were established for Stage Two:

- repeating print - a continuous print, constructed from sets of distinctive or identical motifs (number of motifs in a set ≥1) organised systematically;
- repeat - a set of distinctive or identical motifs (number of motifs in a set ≥1) that recur systematically to create a repeating print;
- repeat size - the horizontal or vertical distance between identical sets in a print;
- foreground - the part of a repeat that appears to be in front of other elements;
- background - the part of a repeat that appears to be behind the elements;
- direction - presence or absence of identifiable direction of print;
- motif - any distinctive or identical elements that are used to compose a repeat;

![Figure 4](image)
Initial stage in the development of the code-tree
Figure 6
Examples of actual repeating print images

Figure 7
Examples of repeating print attributes identified in an image
• motifs number – the number of motifs within a repeat;
• inner symmetry – presence or absence of symmetry within a motif;
• complexity – intricacy of motif/s in repeat;
• colours number – number of distinctive colours used in a repeat.

Through the completion of the code-tree, a taxonomy hierarchy had emerged, and quantitative variables were identified for Stage Two of the research. A taxonomy model with quantitative variables was extracted and presented separately as shown in Table 4. The information collected at this stage demonstrated three distinct levels of hierarchy in repeating prints and level-specific attributes. The levels and attributes were then further examined with an intention to extend existing relationships in a way that would facilitate the transition to an engineered printing method. The following observations were made:

• Starting from the subordinate and into the basic levels, the elements of repeating prints could be regarded as increasingly complex modules. Extending the module principle into the superordinate level will permit complex repeat formation consisting of different repeats arranged with symmetry operations into required engineered repeating print.

• The elements of a repeat could be prioritised in relation to the overall print appearance. More important elements could be preserved to maintain print appearance, while less important elements can be manipulated to adjust repeat formation to fit a specific garment pattern/s.

• Although affine transformations were sufficient for these two previous approaches, seamlessly fitting two-dimensional repeating prints into irregular three-dimensional garments would also require distortion.

Based on the literature review and these observations three directions were identified in Stage One as potential for engineered repeating prints development and further investigation in Stage Two:

**Modularity Design (MD)**, in which print is formed from repeating interchangeable modules. Modules can be used to construct higher level modules. Transformations can include finite, linear and planar symmetry operations or combinations of operations;

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### Table 4: Taxonomy for repeating print with quantitative attributes

<table>
<thead>
<tr>
<th>LEVELS</th>
<th>Quantitative attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SUPERORDINATE</strong></td>
<td></td>
</tr>
<tr>
<td>Arrangement within surface</td>
<td>Repeat system</td>
</tr>
<tr>
<td></td>
<td>Repeat size vertical</td>
</tr>
<tr>
<td></td>
<td>Repeat size horizontal</td>
</tr>
<tr>
<td><strong>BASIC</strong></td>
<td></td>
</tr>
<tr>
<td>Arrangement within repeat</td>
<td>Foreground/background ratio</td>
</tr>
<tr>
<td></td>
<td>Direction</td>
</tr>
<tr>
<td></td>
<td>Motifs number</td>
</tr>
<tr>
<td><strong>SUBORDINATE</strong></td>
<td></td>
</tr>
<tr>
<td>Arrangement within motif</td>
<td>Inner symmetry</td>
</tr>
<tr>
<td></td>
<td>Complexity</td>
</tr>
<tr>
<td></td>
<td>Colours number</td>
</tr>
</tbody>
</table>
Flexible Tiling (FT), in which print repeat formation can be dynamically manipulated to fit within garment patterns with a programming solution. FT programming solutions for adjustment of repeat formation should mostly change background elements while preserving and dynamically fitting foreground elements inside pattern pieces;

Distortion, which can be used to fine-tune fitting of repeating prints to a garment pattern, but should be used with caution as appearance might suffer visually from obvious distortions. Use of an orthogonal deformation mesh should allow for alignment on both axes and continuity of the repeating print across seams.

These three directions were further investigated in Stage Two experiments to test relationships between print attributes and their impact on the adaptability of a repeating print for the EP method.

4.7. Conclusion

This stage identified that traditionally different meanings were assigned to the same words describing attributes of repeating prints and were context dependent. Through the generation of repeating print taxonomy this research has defined repeating print attributes as well as categorised them into three distinctive levels. Three directions were proposed for the development of engineered repeating prints: Modularity Design, Flexible Tiling and Distortion. The decision was made to select specific sets of repeating print attributes to be tested in a separate experimental study for each of the proposed directions. The main follow-up study was nominated to test the combination of all three directions.
Chapter 5 General Stage Two Research Procedures and Tools

5. General Stage Two Research Procedures and Tools

5.1. Introduction

This chapter gives an overview of research procedures, computer-aided design (CAD) and analytical tools used for experiments.

For experimental Stage Two, the existing CAD tools of universal graphics software were adopted to achieve the objectives of this research. A problem-solving design approach, framed around the identification of the need and evaluation of the developed method through testing, was employed. Universal graphics software package Adobe CC was chosen based on its popularity, accessibility, and its range of in-built editing and analytical tools. The decision was made not to use any additional plug-ins in order to extend the functionality of Adobe programs, as these plug-ins might not be accessible to many users. 3D design application VStitcher v.6.0 from Browzwear package was used for virtual prototyping of garments with engineered repeating prints. 3D prototyping was done to further evaluate and validate the research, but access to 3D modelling software is not required for implementation of developed engineering methods. Wolfram Mathematica v.10 was used for image processing. Microsoft Excel was used to clean the data and SPSS v.22 for statistical analyses.

Adobe editing tools were selected for their ability to support non-destructive editing techniques and demonstrate the proposed directions for engineered repeating prints. Non-destructive editing, also known as dynamic editing, allows modification of the appearance of a graphic object without changing its underlying structure. The tools included Symbols, Appearance Panel, Transform Effect, Pattern Fill and Brush, Blend and Envelope tools in Illustrator, Smart Objects, Smart Filters and Warp tool in Photoshop, and Adobe Composer in InDesign. Analytical and workflow tools include Action Panel in Illustrator and Photoshop, and Histogram Panel and Measurement Log Panel in Photoshop.

VStitcher is a 3D design application from Browzwear that allows streamlining of the garment design, fit and merchandising. VStitcher is used for true-to-life draping, fit and design simulation of a garment on a virtual human body in a 3D environment based on actual patterns, fabric physical properties and body measurements. Wolfram Mathematica is a technical computational program, based on symbolic mathematics, and used in scientific, engineering, mathematical and computing fields. Mathematica image processing commands allow extraction of a wide range of numerical image data. Microsoft Excel was used for compiling the spreadsheets from collected data for import into SPSS, which is a widely used program for statistical analysis, data management and documentation. Additional software applications, such as Factor v9.2 (Lorenzo-Seva & Ferrando 2006) and G*Power 3.1.9.2 (Faul et al. 2009), were used to supplement statistical analyses.

5.2. Dynamic Editing Tools in Adobe CAD Software

The techniques developed for engineering of repeating prints in the experiments relied on dynamic editing tools available in Adobe applications. Dynamic editing allows separation of the visual appearance of an object and its underlying structure for their individual modifications. The following section describes selected dynamic tools and their features.
The concept of Symbol or Smart Object is used in Adobe Illustrator or Photoshop respectively to indicate reusable, self-contained objects, instances of which can be added to a document multiple times. The use of such objects for a recurring piece of art in a file provides consistency, ease of editing and can significantly reduce file size for the complex art. Symbols are managed through the Symbol panel and can be saved as external libraries, which facilitates distribution and reuse of symbols as templates. Instances of symbols in a document are linked to each specific ‘master’ symbol in the panel and are instantly updated with the edits in the master symbol. In the case of the Smart Objects in Photoshop, the original raster images or vector files from other applications can be preserved inside a container while their appearance can be modified by dynamic non-destructive Smart Filters. Similar non-destructive appearance modifications can be added to Symbols as attributes with the Appearance panel.

The Appearance panel in Adobe Illustrator allows the application of fills, strokes, transparency and dynamic effects to any object, group or layer in a document in order to change their appearance without altering their underlying structure. The Appearance panel also manages the order in which attributes are applied to the artwork. All attributes including dynamic effects or smart filters can be removed, duplicated, stacked or copied to another object and their settings can be edited and viewed live. Dynamic Transform Effect allows the user to apply affine transformations as appearances to a source object or the required number of copies of the source object. The combination of multiple applications of Transform Effect thus can generate variations of repeating prints using a single repeat as a source object and a sequence of symmetry operations. The sequence of applications of Transform Effects as appearances can be built to construct symmetry operations required for all classes of repeating designs. The ability of such a sequence to work as a repeating algorithm within a design template constructed from symbol modules was evaluated in Modularity Design direction in Experiment One.

The second direction, Flexible Tiling, and Experiment Two used Adobe Paragraph Composer, which is an existing programming solution for adjustment of type formation in a paragraph text. This tool was adopted to examine possible effects of dynamic adjustment of repeat formation by variation in spacing between foreground elements by increasing or decreasing background elements. The Adobe Paragraph Composer tool works by considering all breakpoints for a paragraph text and optimising spacing between characters and words in the lines of text to produce a visually balanced block of text. Type character was employed as a substitute for a repeat, and a string of identical characters produced a block of repeating motifs inside a garment pattern shape. The tool was selected for its ability to simulate required functionality for manipulation of repeat formation by small variations of background elements while preserving and dynamically fitting foreground elements inside a shape.

The third direction, Distortion, and Experiment Three employed the Envelope tool in Illustrator to distort repeating prints to fit within garment pattern shapes. Similar to symbols, the Envelope tool also uses the concept of a container, which can be made out of an object, a preset warp shape or a mesh grid. Anything placed inside such envelope is distorted in the same pre-defined way, and envelopes can be edited independently from the contained inside objects. In recent versions of Illustrator, the tool can also optionally work on Pattern Fills of contained objects.

The final Experiment Four combined the three directions and drawn on tools and techniques explored in experiments one to three. Additionally, Blend and Pattern Brush tools were used to...
generate a template for uninterrupted repeating print within Front and Back pattern pieces of a
dress. Pattern Brush applies a repeat along a path, and any updates to the definition of a brush
can be propagated to existing objects carrying that attribute. Blend allows the user to create
transitional objects and distribute them between two original objects, including two open paths
with Brush stroke attribute applied, or two instances of symbols. If original objects are edited or
replaced, the Blend updates accordingly.

5.3. Analytical and Workflow Tools in Adobe CAD Software

The Histogram Panel in Photoshop was used to provide tonal and colour information about
images. The validity of the Histogram Panel instrument was investigated by means of construct
and content validity, and the reliability by a test-retest procedure. Validity is a measuring instru-
ment property, which determines whether a test measures what it is supposed to measure and,
therefore, can be used in making accurate decisions (Field 2009). As the Histogram Panel is an
instrument specifically designed to measure intensity levels, the construct and content validity
were consequently deemed satisfactory. Reliability of a measuring instrument is the ability of the
instrument to produce the same results under the same conditions (Field 2009). In the case of
Histogram Panel both inter-rater reliability and test-retest reliability were satisfactory.

One of the objectives of the Flexible Tiling experiment was development and evaluation of new
procedures and instruments in preparation for the subsequent experiments. The conversion from
vector to raster graphics, which was a part of the experimental procedures in experiments two
to four, can be a source of measurement error due to rasterisation noise. Following normality
testing in the Flexible Tiling experiment that was conducted in Red Green Blue (RGB) colour
space, the measurement error was verified by a two-tailed, one-sample t-test. The test was
found to be statistically significant, and future experiments were designed to use single-channel
Greyscale colour space. To eliminate the recording errors, collecting of tonal and colour infor-
mation in an image or selected parts of an image was handled by the Measurement Log panel,
which allowed for the accumulation of data points for pre-set measurements and the export of
collected data in a comma-delimited text file for processing in Excel.

5.4. Wolfram Mathematica Programming Routines

Images for each repeat in experiments three and four were assessed using the Wolfram Math-
ematica environment. The programming routines were written to measure edge length of
elements of each repeat image as a number of pixels, and to count the number of individual
motifs and the number of colours for each repeat image as an integer.

5.5. Statistical Analyses Procedures

The desktop and on-line software tools that were used for statistical analyses are as follows: SPSS
v.22 was used for descriptive statistics, drafting of necessary plots and graphs, normality testing,
t-tests, correlation and linear regression analyses, and principal components analysis; G*Power
3.1.9.2 was used for power and effect size calculations for future research hypotheses testing
(Faul et al. 2009); Factor analysis package, (Factor v9.2), was used to re-analyse the data as SPSS
has limited options in regards to data rotation (Lorenzo-Seva & Ferrando 2006); 95% CI for the
statistically significant correlation coefficients r were calculated with on-line tool The Confidence
Interval of rho (http://vassarstats.net/rho.html?).
6. Experiment One: Dynamic Manipulation of a Repeating Print Formation through Modularity Design Method

6.1. Methods

6.1.1 Introduction

The Modularity Design (MD) experiment investigated the construction of a complex nested repeat formation using symmetry operations from geometrically different interchangeable modules. MD proposes that modules can be used to construct higher level modules and transformations can include finite, linear and planar symmetry operations or combinations of operations. For the validation of the MD method, types of apparel products that required an engineered print were explored, and a bandana was selected. A typical bandana product, measuring 56cm by 56 cm, was chosen with key elements or modules of print such as borders, corners and a centre. The design process was then divided into manageable and logical steps in two stages. A template was developed in the first stage, that allowed for the construction of a repeating algorithm. This was followed by the second design development stage where engineered print alternatives were visualised and evaluated.

The template development stage involved sectioning of the design area into modules, refining of the underlying repeat structure, precise geometrical sizing of the placeholder modules and converting the modules into dynamically editable symbols. Single instances of placeholder symbols were placed in their initial positions. Sequences of Transform Effect through the Appearance panel were applied to the placeholder symbols to construct the necessary symmetry operations and to complete the dynamic template.

Geometric dimensions of the placeholder modules were used as guides for the development of the art modules, which were subsequently converted into art symbols. In a new copy of the dynamic template, the placeholder modules were replaced with the art modules. Live visual updating provided verification of the seamless interconnection between art modules merging into the bandana’s key elements.

It was also expected that the modular nature of the template would allow interchanging and combining modules from established templates to generate several variations. This was validated with the second version of the bandana design generated with the same dynamic template.

6.1.2 Experiment One objectives

This experimental study aimed to evaluate the MD method as a direction for engineering of repeating prints. The study had objectives to:

- explore dynamic editing tools in Adobe Illustrator;
- examine the symmetry operations used for generation of repeating prints;
- develop the procedures for dynamic templates set-up for subsequent experiments;
- develop a dynamic template and generate repeating prints employing the template;
- validate the application of the MD method as a direction for engineering of repeating prints for all four basic symmetry operations and the use of geometrically different modules.
6.1.3 Population and sample
A bandana was selected as an example of an apparel product that requires an engineered repeating print. The composition of the print followed a traditional bandana layout that included a border on all four sides, inner corners and a finite central design. One template was created containing geometrically different modules, and two bandana prints were generated by replacing template modules with art modules.

6.1.4 Experimental procedures
The print area was divided with guidelines into sections and geometrically different placeholder modules drawn up based on the guides, shown in Figure 8. The dimensions of the modules were determined based on section dimensions, intended number of repeats within each section and inner symmetry of a module. Modules were given descriptive visual labels and converted into symbols with the position of the reference point (marked with black cross in Figure 9) nominated to work with subsequent transformations. The symbols were also given descriptive labels. Placeholder modules were then placed in the initial position, and transformations applied in steps as separate appearances using the Appearance and Transform Effect panels to generate repeating prints.
Chapter 6 Experiment One: Modularity Design

For the selected template design, a copy of the corner border symbol was reflected along the x-axis and rotated 90° clockwise producing a corner module. Similarly, a border symbol copy was reflected on the right side in the first application of Transform Effect (Figure 10).

The second application of Transform Effect translated two copies of the resulting border module along the x-axis to the right (Figure 11) producing one side border module. The results were grouped with the corner module and a ‘Move and Rotate’ transformation was applied to three more copies to complete the border part of the template (Figure 12). The inside corner module was rotated with three more copies completing this part of the repeat template (Figure 13).

The centre sector module was reflected first on the right side along the x-axis, producing symmetrical motif (Figure 14a), and a subsequent transformation rotated the resulting motif at 45° and generated seven copies required to complete the circle. This completed the set-up stage of the bandana template (Figure 14b).

The next stage in the workflow was to create art for each repeat module using additional instances of the placeholder symbols as guides. The size of the art modules and the reference point position were matched to the placeholder modules. The art modules were cropped to the placeholder module’s dimensions, with black crosses indicating the reference point position (Figure 15).
Finally, the repeat template was copied, and each of the four placeholder modules was replaced with matching art modules using the Symbol Panel options menu (Figure 16a). Then the next prototype was produced by creating a second set of art modules and using another copy of the template, shown in Figure 16b.

### 6.2. Results and Discussion

The MD experiment investigated the generation of complex nested repeat formation using symmetry operations from geometrically different modules.

In this experiment, engineered repeating prints, comprised of nested repeats of geometrically different modules, were generated using Adobe Illustrator. Symbols were used for the placeholder and art modules, and symmetry operations sequences were built by several applications of dynamic Transform Effect. A typical bandana design that consisted of three top-level modules of outside border, inner corners and a central rosette was selected. These modules were analysed for their symmetry and deconstructed into lower level modules, i.e. outside border was seen...
as four identical side border modules rotated 90° around the centre point of the bandana. The rosette module was seen as symmetrical or asymmetrical sector modules, similarly rotated around the centre point. Each side border was further deconstructed into symmetrical corner modules and border bands connecting the corners. The border band was made out of repeating symmetrical modules. The process of deconstruction for another template would therefore depend on the template’s shape and required details. One dynamic template was created based on four placeholder modules with copies of placeholder modules generated by sequences of symmetry operations. The dynamic nature of the template allowed for immediate visual verification of symmetry operations sequences when a precisely tessellated template was formed. The template then was used to generate two different engineered repeating prints by substituting placeholder modules with art modules.

The MD method presented many advantages as a method for engineered repeating prints. The workflow was broken into easily manageable steps of template development, template set-up, art design, generation of art prototypes, and further prototypes editing for variations of design. The symmetry operations sequences were built during the template set-up with regularly shaped placeholder modules, which facilitated construction of a print structure. The boundaries of the placeholder modules also acted as guides when art modules were created. Successful application of the method though required exact sizing of all geometrically different placeholder modules and creating art to the exact dimensions of placeholder modules.

Although it is possible to use proprietary plug-ins to achieve similar results, for example, Artlandia’s SymmetryWorks, this research utilised Adobe programs that are readily available to the users. Additional plug-ins are not readily available to the users and can be expensive. In addition, the techniques, demonstrated in Experiment One, can be used to construct engineered repeating prints to fit into diverse geometrical shapes including garment patterns. The method can also be used for transformations required when preserving the design intent of complex repeating prints between graded garment sizes by allowing for independent scaling and relative positioning of the repeating print modules.

This exploration also identified the need for better understanding of the theories behind the underlying geometrical symmetry of nested repeat structures and symmetry operations required to construct nested repeating print. Still, the use of interchangeable symbols as modules and dynamic effects as appearances facilitated editing both at the template and prototype stages and also required less computing power. In addition, parts of different templates could be used as higher level modules and combined to create new template configurations. Multiple templates could be updated simultaneously to visualise print versions built from the same art modules. Also, successful templates could be shared among multiple users, if versions of engineered repeating print were required, or distributed to the less advanced CAD users as a starting point.
7. Experiment Two: Flexible Tiling of a Repeating Print Formation

7.1. Methods

7.1.1 Introduction

This study evaluated Flexible Tiling (FT) as a potential direction for engineering of repeating prints and examined attributes such as repeat size and foreground to background elements ratio as factors affecting repeating print adaptability for the engineered printing (EP) method. To implement the FT method, a repeating print formation was proposed to be manipulated to fit within a garment pattern through a programming solution. The repeating print could be generated without the limitation of a fixed repeat size, with the formation achieved by small variations of background elements while preserving and dynamically fitting foreground elements inside a pattern piece. Nonetheless, not all repeating prints would be suitable for such manipulation, as a clear separation between foreground and background elements would be required. Also, the method would be more suitable for repeating prints that can tolerate irregularities in motifs’ placement within a repeat. For evaluation of the FT method’s validity, existing computer-aided design (CAD) tools of Adobe Illustrator and InDesign were used, and Adobe Paragraph Composer was selected as an existing programming solution to allow for the simulation of the required functionality.

7.1.2 Experiment Two objectives and hypotheses

This experimental study aimed to evaluate the FT method as a direction for engineering of repeating prints. The attributes such as repeat size and foreground to background ratio were examined as factors affecting the adaptability of repeating print for the EP method. The study had the objectives to:

- establish procedures and instruments;
- establish independent and dependent variables and measurement levels;
- establish measurements’ validity and reliability;
- describe variables in terms of operations or measuring techniques;
- establish possible effect size for the main study experiments;
- calculate the sample size for the main study experiments.

Research Hypotheses were made prior to the experiments in relation to principles of the FT method and repeating print attributes:

Hypothesis One: The FT method can reduce the areas of print repeats falling outside of the garment pattern shape compared to the traditional Mainstream (MS) method.

Hypothesis Two: The FT method can preserve more important foreground elements of a print by fitting them inside of a garment pattern shape. Therefore, the proportion of background in a repeat area falling outside garment pattern shape would be higher for larger repeat sizes.

Hypothesis Three: As the FT programming solution can contain foreground elements within pattern shapes, it might result in the foreground to background ratio inside garment pattern
shape being higher in the FT method compared to the MS, which could create a difference in the visual appearance of a print. However, for the FT solution to work as a direction for engineering of repeating prints, the visual appearance has to be maintained, and so the foreground to background inside ratio has to be kept as per the MS method.

7.1.3 Research design
The study included two independent groups of equal allocation:

- baseline group simulated repeating print matching procedures employed in the MS printing method;
- treatment group used the FT method, through adjustment of repeat formation by a programming solution.

Experiments were set up in an Adobe CAD environment with repeating prints as vector graphics for both groups to ensure precise construction and consistent measurements. The MS model was set-up in Adobe Illustrator due to the necessity for the Patterns Fill tool. Vector art for a single type character was used to represent a motif inside a rectangular repeat. The FT model was set-up in Adobe InDesign to utilise its superior Type tools, specifically Adobe Paragraph Composer, as precise control over multiple character and paragraph formatting attributes was required.

Print repeats used Red, Green, Blue (RGB) Black (0, 0, 0) for foreground colour and RGB Grey (128, 128, 128) for background colour. The Front pattern shape was selected from available dress garment patterns and set on an RGB White (255, 255, 255) rectangle of a known size, and filled with a repeating print. The repeats were allowed to extend outside of the pattern shape. The result was exported as a raster 72dpi JPG file with the maximum quality and no anti-aliasing to reduce possible rasterisation noise artefacts.

In the next stage of the experiments, the areas of repeating print’s foreground and background falling inside and outside of the garment pattern shape were measured with the Photoshop Histogram tool as the number of pixels corresponding to specific intensity levels of 0, 128 or 255 across three channels.

7.1.4 Population and sample
A priori statistical power analysis was conducted to determine a possible sample size to achieve 80% power in an independent equal allocation research design and the two-tailed 0.05 level of significance for future hypothesis testing. The sample size calculation was performed using G*Power 3.1.9.2 (Faul et al. 2009) with large and medium effect sizes used for the estimation. The total required sample size was found to be 128 (64 in each group) for d=0.5 or 52 (26 in each group) for d=0.8. Therefore, for this pilot study the sample size of 90 (15 fonts by 3 repeat sizes resulting in 45 cases in each group) was chosen, as a medium to large effect was anticipated. The study design allowed for scaling up to 120, 150.

The one-directional arrangement of a single motif inside a repeat was selected for this study. Three common repeat sizes of 4 cm, 8 cm and 16 cm were chosen as the vertical repeat size (RSV) categorical variable. To randomise horizontal repeat dimensions, the repeats were established as a distance between the same capital letters (asymmetrical letter F in this study) of an unconstrained paragraph typed within a rectangular text frame in 15 different typefaces at 113pt, 226pt and 452pt with 100% leading to match the selected vertical repeat dimensions of 4 cm, 8 cm and 16 cm.
To minimise artefacts from intended rasterisation of vector graphics, Sans Serif fonts were chosen. The typefaces were selected from four Sans Serif font groups (Arial, Calibri, Compacta and Futura) that had diverse Narrow, Regular, Bold, Black and Condensed formatting options available. The second important consideration for the font selection was the availability of these typefaces for replication of the study by other researchers – all of the selected fonts are supplied as part of computer operating systems or the Adobe CC package. The selected fonts are listed in Table 6. The capital letter characters from all 15 fonts were analysed for inner symmetry characteristic (asymmetrical, X and Y reflection, rotation), and unique characters for these inner symmetry categories were selected. The asymmetrical letter ‘F’ then was nominated for this study. The fifteen used F characters are demonstrated in Figure 17.

7.1.5 Variables and measures

Measured variables are presented in Table 5 and the list of initially collected variables for the FT direction, the code sheet for the selected fonts in Table 6.

7.1.6 Experimental procedures

Paragraph styles were established in Adobe CC InDesign for all the 15 typefaces at 113 pt, 226 pt and 452 pt respectively, with 100% leading, baseline alignment to 1cm grid and Justified Centre alignment. The characters’ colour was set to RGB Black (0, 0, 0). Underline attributes were set to simulate RGB Grey (128, 128, 128) background. The unconstrained rectangular text frame in Adobe InDesign was filled with a string of ‘F’ characters, and then the text was converted to vector shapes and copied to Adobe Illustrator where exact matching Pattern Fill swatches were generated, Figure 18.

The MS group had a separate artboard (measuring 2268 by 2551 pixels at 72dpi) for each typeface/repeat size case with the garment pattern shape centred. The pattern shape was first filled with the corresponding repeating print with Pattern Fill alignment matching the first line of the FT group’s equivalent case at a Centre Front upper edge location (the location marked with a red dot). Then, fills were expanded and all outside tiles that did not intersect with the pattern shape were removed, shown in Figure 19(a).

The FT model, which was set-up in Adobe InDesign, had a separate page (measuring 2268x2551 pixels at 72dpi) for each typeface/repeat size case with a centred text frame constrained by
Table 5: List of initially collected variables for Flexible Tiling direction

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Type of variable</th>
<th>Description</th>
<th>Measurement level</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID</td>
<td>ID number</td>
<td>Unique identification number</td>
<td></td>
</tr>
<tr>
<td>Group</td>
<td>Independent</td>
<td>Mainstream print (MS) – baseline group, repeat’s horizontal size is static</td>
<td>Category</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Flexible Tiling (FT) – treatment group, repeat’s horizontal size is dynamic</td>
<td></td>
</tr>
<tr>
<td>Font</td>
<td>Independent</td>
<td>Font typeface – 15 Sans Serif fonts from 4 common font groups</td>
<td>Category</td>
</tr>
<tr>
<td>Repeat size vertical</td>
<td>Independent</td>
<td>Repeat size, vertical, mm – were used as grouping variable – ‘40’, ‘80’, ‘160’ in this study</td>
<td>Ordinal</td>
</tr>
<tr>
<td>Black foreground outside garment shape</td>
<td>Dependent</td>
<td>Black foreground area, intensity level 0 with pattern overlay, total count in 3 channels (RGB)</td>
<td>Ratio</td>
</tr>
<tr>
<td>Grey background outside garment shape</td>
<td>Dependent</td>
<td>Grey background area, intensity level 128 with pattern overlay, total count in 3 channels (RGB)</td>
<td>Ratio</td>
</tr>
<tr>
<td>White background outside + white pattern shape</td>
<td>Dependent</td>
<td>White intensity level 255 area, with pattern overlay, total count in 3 channels (RGB)</td>
<td>Ratio</td>
</tr>
<tr>
<td>Black foreground total</td>
<td>Dependent</td>
<td>Black foreground intensity level 0 area, no pattern overlay, total count in 3 channels (RGB)</td>
<td>Ratio</td>
</tr>
<tr>
<td>Grey background total</td>
<td>Dependent</td>
<td>Grey background intensity level 128 area, no pattern overlay, total count in 3 channels (RGB)</td>
<td>Ratio</td>
</tr>
<tr>
<td>White background outside only</td>
<td>Dependent</td>
<td>White intensity level 255 area, no pattern overlay, total count in 3 channels (RGB)</td>
<td>Ratio</td>
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</table>

Table 6: List of selected fonts

<table>
<thead>
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<th>Code</th>
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<tr>
<td>Arial Regular</td>
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<td>10</td>
</tr>
<tr>
<td>Arial Bold</td>
<td>3</td>
<td>11</td>
</tr>
<tr>
<td>Arial Black</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>Calibri Light</td>
<td>5</td>
<td>13</td>
</tr>
<tr>
<td>Calibri Regular</td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td>Calibri Bold</td>
<td>7</td>
<td>15</td>
</tr>
<tr>
<td>Compacta Light BT</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>
the selected garment pattern shape, indicated by the magenta line in Figure 19(b). A string of repeating capital F characters was used to fill that text frame and paragraph styles applied to the text. In each case, the text was over-set (i.e. a string too long to fit inside text frame) to force Adobe Paragraph Composer to redistribute the characters on all lines.

The results were exported as raster 72dpi JPG files with maximum quality and no anti-aliasing to reduce artefacts noise. JPGs were collected in Adobe Photoshop files for each group as layers. A top layer was added, containing white garment pattern vector shape positioned in the exact location. Visibility of this pattern shape layer was turned off and on to display each measured case, Figure 20 (a) and (b). In the next stage, the areas of print’s foreground and background elements in relation to the garment pattern shape were measured as a precise, consistent number of pixels corresponding to a particular intensity level (0, 128 or 255 across three channels) using Histogram Panel.

All recorded data was entered into an Excel spreadsheet, screened and cleaned. Additional variables were calculated in SPSS v.22 to determine foreground and background areas of print meas-
ured in pixels falling inside and outside the garment pattern shape. The sums of these areas were calculated to derive the total print areas outside and inside, and foreground/background ratio for these areas, as shown in Figure 21 (a) to (c). Conversion from three intensity levels for each pixel to pixel was incorporated into the calculations.

7.1.7 Statistical analyses procedures

Descriptive statistics analyses were performed on all main variables in SPSS v.22 to determine measures of central tendency and variation. Data was also examined visually with plots to establish the groups’ distribution type and identify any outliers that had to be investigated further.

Group comparisons analyses were performed to examine the differences between two groups. Following normality testing, two-sample t-test in SPSS was used to test for a significant difference between the mean scores of the FT and MS group for foreground and background areas inside, outside and total, and foreground to background ratio for these areas with the significance level $\alpha =0.05$. The Levene’s test of homogeneity of variance was used to verify the assumption of equal variance.

7.2. Results and Analyses

In this study, the FT method was evaluated as a potential direction for the engineering of repeating prints. The print attributes such as repeat size and foreground to background ratio were also examined as factors affecting the adaptability of repeating prints for the EP method. The study was also employed to develop procedures and instruments, and to establish measurements validity and reliability. Post hoc analyses were conducted to determine achieved Cohen’s $d$ effect and power level and to generate a plot of required sample size for the subsequent research.

7.2.1 Descriptive analyses

Descriptive statistics analyses were performed on all main variables in SPSS v.22 to determine measures of central tendency and variation and visually with plots to establish their distribution type and identify any outliers that have to be investigated further. Cases were examined based on group and repeat size vertical categories. Descriptive statistics for groups are presented in Table 7 and Table 8.

For the FT group, the foreground outside area measured lower on average by 89,414 pixels, and the background outside area lower on average by 127,088 pixels. Total print areas outside was lower for the FT group by 209,174 pixels. These differences between groups could be explained by a predicted impact of the FT method causing a reduction in the print’s areas falling outside of the garment pattern shape (Hypothesis One).

For the inside of the garment pattern shape, foreground elements for the FT group were measured lower on average by 29,249 pixels, and background elements higher on average by 11,745 pixels. The total print area inside for the FT group was lower by 17,505 pixels, and that difference needed to be investigated further as it indicated a possible measurement error.

Box-plots for foreground and background areas falling inside and outside of the garment pattern shape were also compared, shown in Figure 22. Foreground and background areas of print inside the pattern shape showed distribution similarity between the FT and MS groups. Background
areas inside were negatively skewed, while foreground areas were positively skewed for both groups. There were no outliers for both groups.

Outside foreground and background areas demonstrated some differences: all were positively skewed, and distributions for the FT group visually appeared tighter. Outliers for cases 40 and 41 were shown for the FT group on foreground areas outside, and the MS group had outliers in both foreground (cases 86 and 90, extreme outlier case 85) and background (case 80) areas. All outliers were investigated and explained as cases using heavy Black formatting of type characters (Compacta Black BT and Futura Extra Black BT).

Further examinations were made for foreground and background areas inside and outside based on vertical repeat size and group categories. Only one outlier for the case 85 for fore-
Chapter 7 Experiment Two: Flexible Tiling

Figure 22
Boxplots for foreground and background elements

Figure 23
Distributions for foreground elements of print: (a) outside of garment pattern shape and (b) inside of garment pattern shape
Chapter 7 Experiment Two: Flexible Tiling

ground outside areas (Compacta Black BT font) in the MS group was observed. Distributions of foreground elements for both groups inside of the garment pattern shape demonstrated very similar positively skewed scores across all repeat sizes, Figure 23 b. Similarity of results were also demonstrated for distributions of background elements for both groups inside of the garment pattern shape with negatively skewed scores across all repeat sizes, Figure 24 b. These results indicated that visual appearance for inside areas of print remained very similar, which can be explained by the predicted impact of the FT method (Hypothesis Three).

However, the outside garment pattern shape distributions for foreground and background elements showed a different behaviour. For foreground elements outside garment pattern shapes, the scores were also positively skewed, but quite visually different between groups and repeat sizes, Figure 23 a. The difference between the various repeat sizes became even more pronounced for background elements outside the garment pattern shapes, Figure 24 a. The scores for background elements outside the garment pattern shapes were mostly positively skewed and visually different between the groups. Also, with the increase of repeat size, both foreground and background areas of print falling outside of the pattern shape were increasing, but at the higher rate for background areas. These results can be explained by the predicted impact of the FT method (Hypothesis Two).

7.2.2 Group comparisons

The differences between the groups were further examined with t-tests. Following normality testing, independent-samples t-test in SPSS were used to test for a significant difference between the mean scores of the FT and MS groups inside and outside of garment pattern shape with the significance level \( \alpha = 0.05 \), shown in Table 9. The Levene’s test of homogeneity of variance was used to verify the assumption of equal variance for the variables. Displayed in Table 9 results were filtered by Levene’s test to include only relevant results.
In order to test the first and the second hypotheses, a two-sample t-test was used to test for a significant difference between the means for the foreground, background and total print areas falling outside of garment shape for the FT and MS groups.

Total print outside garment shape area for the FT group exhibited evidence of non-normality while the MS group appeared normal. The CLT ensured that the t-test that can be carried on if the normality assumption is violated for at least one group when the sample sizes in each group are greater than 30. The Levene’s test of homogeneity of variance indicated that equal variance could not be assumed. The results of the two-sample t-test not assuming equal variance found statistically significant evidence of a difference between the mean scores of the FT and MS groups, t(df = 64.254) = -5.075, p<0.001, 95% CI for the difference in means [-291504, -126845]. The

Table 9: t-test results for Flexible Tiling experiment

<table>
<thead>
<tr>
<th>Variables</th>
<th>F</th>
<th>Levene’s test for equality of variances</th>
<th>t-test for equality of means</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Sig. t df Std. Error Mean difference</td>
<td>95% Confidence Interval</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Equal variances assumed</td>
<td></td>
</tr>
<tr>
<td>Foreground elements inside shape</td>
<td>.037 .849 -.364 88 .717 -29249 80402 -189031 130533</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Background elements inside shape</td>
<td>.006 .940 .146 88 .884 11745 80596 -148422 171911</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foreground elements outside shape</td>
<td>Equal variances not assumed</td>
<td>-4.472 61.541 .000 -82087 18354 -118782 -45392</td>
<td></td>
</tr>
<tr>
<td>Background elements outside shape</td>
<td>Equal variances not assumed</td>
<td>-3.803 69.466 .000 -127088 33418 -193748 -60428</td>
<td></td>
</tr>
<tr>
<td>Total print inside shape</td>
<td>Equal variances not assumed</td>
<td>-2.981 71.030 .004 -17505 5872 -29214 -5796</td>
<td></td>
</tr>
<tr>
<td>Total print outside shape</td>
<td>Equal variances not assumed</td>
<td>-5.075 64.254 .000 -209174. 41215 -291504 -126845</td>
<td></td>
</tr>
<tr>
<td>Ratio F to B inside</td>
<td>Equal variances assumed</td>
<td>.109 .743 -.281 88 .780 -.023758 .084662 -.192006 .144490</td>
<td></td>
</tr>
<tr>
<td>Ratio F to B outside</td>
<td>Equal variances assumed</td>
<td>1.812 .182 -1.480 88 .142 -.110247 .074501 -.258303 .037808</td>
<td></td>
</tr>
<tr>
<td>Ratio F to B total</td>
<td>Equal variances assumed</td>
<td>.239 .626 -.403 88 .688 -.032902 .081606 -.195076 .129272</td>
<td></td>
</tr>
</tbody>
</table>
results of the study found statistically significant evidence that Total print outside areas for the FT group were smaller than for the MS group (Hypothesis One).

Foreground outside garment shape areas for both groups exhibited evidence of normality. The Levene’s test of homogeneity of variance indicated that equal variance could not be assumed. The results of the two-sample t-test not assuming equal variance found statistically significant evidence of a difference between the mean scores of the FT and MS groups, t(df = 61.541) = -4.472, p<0.001, 95% CI for the difference in means [-118782, -45392]. The results of the study found statistically significant evidence that foreground areas falling outside garment shape means for the FT group were smaller than for the MS group (Hypothesis One).

Background outside garment shape areas scores for both groups exhibited evidence of normality. The Levene’s test of homogeneity of variance indicated that equal variance could not be assumed. The results of the two-sample t-test not assuming equal variance found statistically significant evidence of a difference between the mean scores of the FT and MS groups, t(df = 69.466) = -3.803, p<0.001, 95% CI for the difference in means [-193748, -60428]. The results of the study found statistically significant evidence that background areas outside garment shape means were, for the FT group, were smaller than for the MS group (Hypothesis One).

This significant difference is visually confirmed in Figure 25 (a) and (b). The 95% CI error bar plots showed an increase in the total area falling outside with the increase in repeat size vertical for both groups and also the tendency for the increase of the means’ difference between groups in both foreground and background areas for larger repeat sizes within the tested vertical repeat size range (Hypothesis Two).

Both the foreground and background elements areas falling outside of the garment pattern shape were statistically significantly lower for the FT group and, with the increase in repeat size, the effect became more evident especially for background elements of the prints. The study found evidence in support of Hypotheses One and Two.

![Figure 25](image.png)

*Figure 25* Error Bar plots for 95% CI: (a) background elements outside garment pattern shape and (b) foreground elements outside garment pattern shape
In order to test Hypothesis Three, a two-sample t-test was used to test for a significant difference between the means for the foreground to background ratio for elements falling outside and inside of garment shape for the FT and MS groups. The scores for the MS group exhibited evidence of non-normality, however, the CLT ensured that t-test could be applied as the sample sizes in each group was high. The Levene’s test of homogeneity of variance was employed for testing of the equal variance assumption. In both cases of inside and outside areas, the results of the study failed to find statistically significant evidence that foreground to background ratio means were different, shown in Table 9. Visually the results were confirmed by error bar plots of 95% CI for the different vertical repeat sizes, shown in Figure 26 (a) and (b).

The results of the study found no statistically significant difference between foreground to background ratio of repeating print in garment pattern shapes filled with either MS or FT methods. This suggests that the FT method was able to maintain the visual appearance of the print, and, therefore, the study found evidence in support of Hypothesis Three. However, the study was limited to using a single asymmetrical motif that had a clear separation from the background. It was also assumed that the resulting print can tolerate irregularities in motifs’ placement within a repeat formation.

7.2.3 Additional statistical analyses

One of the objectives of this study was to examine the procedure for the evaluation of adaptability of repeating prints for EP. The method included conversion from vector to raster graphics that could introduce noise and generate measurement error. A two-tailed, one-sample t-test was used to determine whether the mean total print inside area measurements were significantly different from the known pattern shape population mean area of 2662063 pixels. For this experiment a 0.05 level of significance was applied. The mean for the sample’s total print inside was $M = 2623496$ pixels, $SD = 29063$ pixels. The results of the one-sample t-test found the mean Total print inside to be statistically significantly lower than the population mean area, $t(89) = -12.589$, 

Figure 26
Error Bar plots for 95% CI: (a) foreground to background ratio outside garment pattern shape and (b) foreground to background ratio inside garment pattern shape
t-tests - Means: difference between two independent means (two groups)
Tail(s) = Two. Effect size \( d = 1.06995 \). Allocation ratio \( N2/N1 = 1 \), \( \alpha \) err prob = 0.05

\[ \begin{array}{cccccccc}
10 & 20 & 30 & 40 & 50 & 60 & 70 & 80 & 90 & 100 \\
0.32 & 0.482 & 0.619 & 0.726 & 0.807 & 0.867 & 0.909 & 0.939 & 0.96 & 1.0 \\
\end{array} \]

**Figure 27**
Plot for future sample size determination

\( p < .001 \), 95% CI for the difference \([-44654, -32480]\). It was decided to employ an alternative method for the future experiments with RGB space replaced by Greyscale space. Also, the lossy JPG format of raster files was to be replaced by a lossless TIFF format. Another source of error was explained by the magenta outline for the garment pattern shape used for the alignment of the overlaying pattern shape and printed areas. For similar future experiments, it was decided to replace the line with dots to minimise noise.

A post hoc power analysis was conducted with G*Power 3.1.9.2 to determine the achieved Cohen’s \( d \) effect and power level and to generate a plot of required sample size for the subsequent research. The Cohen’s \( d \) was found to be 1.06995, calculated for the difference between two independent groups (45 cases each group) using the means and standard deviations of print outside the garment pattern shape reported in the study, at the 0.05 level of significance for future hypothesis testing. Power level \((1-\beta)\) was found to be 0.999. A plot for future sample size determinations was generated, shown in **Figure 27**.

### 7.2.4 Conclusion

This study evaluated Flexible Tiling as a potential direction for engineering of repeating prints and examined attributes such as repeat size and foreground to background elements ratio as factors affecting the adaptability of repeating prints for the EP method. The Flexible Tiling method was demonstrated with existing CAD tools by the introduction of small variations in repeat formation in order to fit more important foreground elements of the repeat within a garment pattern shape by manipulating the background elements. The study showed that foreground repeat elements can be preserved by redistributing them inside of a pattern piece and minimising foreground parts of the repeat falling outside. The method at the same time allowed maintaining the overall appearance of a repeating print. The impact of the method became more evident when the repeat size was increased, and even more so for background elements of the repeating print. The method could be employed for repeating prints with a clear separation between background and foreground elements. The suitable repeating designs should also tolerate irregularities in motifs’ placement within a repeat.
8. Experiment Three: Dynamic Manipulation of a Repeating Print Formation with a Distortion Mesh

8.1. Methods

8.1.1 Introduction
This experiment evaluated distortion as a potential direction for engineering of repeating prints. The direction would be applied when affine transformations alone are not sufficient to engineer repeating print within garment patterns. The direction though should be used with caution as visual appearance might suffer from noticeable distortions.

This experiment also examined print attributes such as repeat size, colours number and edge length as factors affecting the adaptability of repeating prints for the engineered printing (EP) method. Envelope distortion with an orthogonal deformation mesh was selected as a computer-aided design (CAD) technique to allow for alignment in both horizontal and vertical directions for continuity of the repeating print across seams. Using a TIFF format for raster images and conducting the experiment in Greyscale colour space allowed the reduction of rasterisation noise and limiting of measurement error. It was demonstrated that it is possible through dynamic distortion to achieve continuity of print between repeats at garment seams with a lot higher accuracy than by traditional print matching methods.

8.1.2 Experiment Three objectives and hypotheses
This study had objectives to:

- evaluate validity of the Distortion method as a direction for engineering of repeating prints;
- examine a limited number of attributes as factors affecting the adaptability of repeating prints for the EP method. Repeat size, colours number and edge length were examined in this study;
- describe variables in terms of operations or measuring techniques;
- establish independent and dependent variables and measurement levels;
- establish measurements validity and reliability;
- refine previously established procedures and instruments.

It was proposed that dynamic distortion could achieve continuity of repeating prints across garment seams with a lot higher accuracy than through traditional methods. Use of orthogonal deformation mesh would provide for alignment on both axes and continuity of repeating prints across seams. Research Hypotheses were made prior to the experiment:

Hypothesis One: Distortion method can allow significantly more accurate continuity of repeating prints at garment seams compared with traditional matching techniques.

Hypothesis Two: repeat size can affect continuity of print between repeats.

Hypothesis Three: complexity (operationalised as edge length) and colours number of a repeat will have a negative correlation with continuity of print between repeats.
Continuity of print between repeats was operationalised as the grey value mean of the remainder of Difference operation between images of the side seam area of a dress (where repeating prints in Front and Back garment patterns were meant to continue across seam) and an ‘ideal’ sample of the same repeating prints. When repeats were correctly aligned and continued, the difference was 0 and the resulting image was black. In areas of a partial match, the resulting image would have various shades of grey. The closer grey value mean was to zero, the better was the achieved continuity.

### 8.1.3 Research design

This study included two independent groups of equal allocation (120 cases in each group):

- **Distortion Group (DG)–** treatment group, measuring the difference between the side seam areas of garment pattern shapes filled with a distortion mesh and ideal repeating prints;
- **Control Group (CG)–** baseline group, measuring the difference between side seam areas of garment pattern shapes filled in the traditional way and ideal repeating print.

<table>
<thead>
<tr>
<th>Design Code</th>
<th>Design Code</th>
<th>Design Code</th>
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<tbody>
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<tr>
<td>9</td>
<td>19</td>
<td>29</td>
</tr>
<tr>
<td>10</td>
<td>20</td>
<td>30</td>
</tr>
</tbody>
</table>
Models for both groups were set-up in Adobe Illustrator CC to use its Pattern Fill and Distortion tools. Models were simulated at actual size as vector graphics allowing for precise construction and consistent measurements, using pixels for base units and with raster settings of 100 ppi. Following the previous work on Flexible Tiling, stated in Chapter Seven, the colour space was switched to Greyscale and raster file format to lossless TIFF to limit possible measurement error.

### 8.1.4 Population and sample

Attributes of repeat size, the number of distinctive colours and edge length for elements of the repeat were examined in this study. Thirty repeats were generated that contained single or multiple identical motifs, or different motifs, geometrical or free-form motifs, single or multiple colours, flat colour or gradual colour, repeats with distinctive foreground-background separation and repeats with a continuous flow of elements, see Table 10. Four repeat sizes were tested for each repeat. Square repeats had dimensions of 100 pixels, 200 pixels, 400 pixels and 800 pixels. Thus, the research design allowed for the sample size of 120 for each group.

### 8.1.5 Variables and measures

Descriptive statistics for the difference between images of seam areas of garment pattern shapes, filled with ideal repeating print and distortion mesh print for DG or the traditional way for CG, were measured using the Adobe Photoshop Histogram panel and recorded with the Measurement Log panel. The experiment’s variables are presented in Table 11, the code sheet in Table 12.

### Table 11: List of Distortion experiment variables

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Type of variable</th>
<th>Description</th>
<th>Measurement level</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID</td>
<td>ID number</td>
<td>Unique identification number</td>
<td></td>
</tr>
<tr>
<td>Group</td>
<td>Independent</td>
<td>Distortion group (DG) – treatment group, difference between distortion mesh repeating print and ideal repeating print</td>
<td>Category</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control group (CG) – baseline group, difference between garment pattern shapes filled in traditional way and ideal repeating print</td>
<td>Category</td>
</tr>
<tr>
<td>Design</td>
<td>Independent</td>
<td>30 various repeating prints, see code sheet for the list</td>
<td>Category</td>
</tr>
<tr>
<td>Repeat size</td>
<td>Independent</td>
<td>Repeat size, pixels</td>
<td>Ordinal</td>
</tr>
<tr>
<td>Colours</td>
<td>Independent</td>
<td>Number of distinctive colours in a repeat</td>
<td>Ratio</td>
</tr>
<tr>
<td>Grey value mean</td>
<td>Dependent</td>
<td>Grey value mean, intensity level of remainder of Difference operation</td>
<td>Ratio</td>
</tr>
<tr>
<td>Edge length</td>
<td>Dependent</td>
<td>Edge length of elements in a repeat, pixels</td>
<td>Ratio</td>
</tr>
</tbody>
</table>

### Table 12: Distortion study code sheet

<table>
<thead>
<tr>
<th>Group</th>
<th>Code</th>
<th>Repeat size</th>
<th>Code</th>
<th>Repeat size</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distortion group</td>
<td>1</td>
<td>100x100 pixels</td>
<td>1</td>
<td>400x400 pixels</td>
<td>4</td>
</tr>
<tr>
<td>Control group</td>
<td>2</td>
<td>200x200 pixels</td>
<td>2</td>
<td>800x800 pixels</td>
<td>8</td>
</tr>
</tbody>
</table>
8.1.6 Experimental procedures

A rectangular shape representing a fabric piece was generated to match vertical and horizontal dimensions of a garment’s patterns, and the template Pattern Fill was applied to the shape for DG. A distortion mesh was created with fabric pieces inside the envelope, using garment Front and Back symbols as guides. For CG, the same template pattern fill was applied as an appearance to another instance of the Front and Back symbols. A rectangular shape measuring 100x1540 pixels was filled with the same ‘template’ Pattern Fill for a sample of an uninterrupted and undistorted ‘ideal’ repeating print imitating the area of the ideal side seam. Alignment of the template repeating print within pattern shapes was set to match the edge of the repeat to the Centre Front and Centre Back, and to start from the centre hem point. Finished templates were converted to symbols as shown in Figure 28. Three artboards measuring 100x1540 pixels were set-up. Front and Back symbols for both groups were rotated and positioned to have the left side seam closed and aligned to the vertical axis at the centre of the artboard, shown in Figure 29 (a) and (b).

The use of dynamic CAD elements such as symbols, distortion envelopes and appearances combined with separate artboards set-up ensured consistency in the alignment of repeating prints during the subsequent replacement of the template Pattern Fill with repeating prints #1-30 in four different repeat sizes. The routine operations for the replacement were recorded as custom actions and replayed for all cases using the Actions panel.
The results were exported as raster Greyscale 100dpi TIFF files and collected as layers in separate Adobe Photoshop files for DG, CG and as ideal repeating print. Then stacks of corresponding layers were created for both DG and CG with ideal repeating prints, with DG and CG layers Blending mode set to Difference. Images were cropped to 50 pixels wide to isolate an area approximately 0.75cm to both sides of the seam line. Descriptive statistics for remaining pixels were measured using the Adobe Photoshop Histogram panel and recorded with the Measurement Log panel. The data was exported as CSV files for initial processing in Excel.

The complexity of each print was assessed using Wolfram Mathematica, where the edge length for elements of each repeat was measured as a number of pixels. An example of the routine is shown in Figure 30. The second routine was used to establish the number of colours for each repeat design, shown in Figure 31. All recorded data was entered into an Excel spreadsheet, screened and cleaned.
8.1.7 Statistical analyses procedures

Statistical analyses were performed on all main variables using SPSS v.22 to determine measures of central tendency and variation. Data was also examined visually with plots to establish the groups’ distribution type and identify any outliers that needed to be investigated further.

Group comparisons analyses were performed to examine the differences between two groups. Following normality testing, a two-sample t-test in SPSS was used to test for a significant difference between the mean scores of the DG and CG for Grey value mean with the significance level $\alpha = 0.05$. The Levene’s test of homogeneity of variance was used to verify the assumption of equal variance. Correlation and linear regression analyses were performed to establish relationships between independent and dependent variables.

8.2. Results, Analyses and Discussion

In this study, the Distortion method was evaluated as a direction for engineering of repeating prints within garment patterns. The print attributes such as repeat size, colours number and design complexity were also examined as factors affecting the adaptability of repeating prints for engineered printing method. The study was also employed to improve further procedures and instruments.

8.2.1 Descriptive analyses

Statistical analyses were performed in SPSS for grey value means to determine measures of central tendency and variation, the results are shown in Table 13.

The distributions were also examined visually with plots. Box-plots for grey value mean were compared based on repeat size category, shown in Figure 32. Grey value mean CG distributions appeared to be more symmetrical than DG with a lot of similarity between different repeat sizes. No outliers were displayed. Grey value mean measured at 59.3 intensity level and appeared to be fairly consistent across different repeat sizes. Grey value mean distributions for DG were positively skewed, with outliers related to repeat #19 across all three repeat sizes and extreme outliers in 200px and 800px repeat size. Three other repeats were displayed as outliers on 800px repeat size for designs #23, #20 and #17 – all four of these repeats had a large number of colours and higher edge length values. For DG, the grey value mean measured at 14.8 intensity level, which was 44.5 intensity levels lower than CG. This difference between groups could be explained by the predicted impact of the Distortion method causing more accurate continuity of repeats (Hypothesis One).

The differences in frequency distributions between DG and CG were further examined visually and by Kurtosis and Skewness values, shown in Figure 33 and Table 14. CG distribution was visually approximately normal. DG distribution was asymmetrical, exhibiting a pile-up of scores on the left of the distribution, with a pointy shape and heavy right tail.

Table 13: Descriptive statistics for grey value mean

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean</th>
<th>N</th>
<th>Std. Deviation</th>
<th>Std. Error</th>
<th>Kurtosis</th>
<th>Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distortion</td>
<td>14.7678</td>
<td>120</td>
<td>15.83747</td>
<td>1.44576</td>
<td>2.291</td>
<td>1.632</td>
</tr>
<tr>
<td>Control</td>
<td>59.2532</td>
<td>120</td>
<td>23.39502</td>
<td>2.13566</td>
<td>-.342</td>
<td>.299</td>
</tr>
<tr>
<td>Total</td>
<td>37.0105</td>
<td>240</td>
<td>29.90342</td>
<td>1.93026</td>
<td>-.656</td>
<td>.562</td>
</tr>
</tbody>
</table>
Further normality testing with Kolmogorov-Smirnov and Shapiro-Wilk tests confirmed normality for CG across all repeat sizes, see Table 14. The same tests for DG showed statistically significant deviations from normality, see Table 15.

### 8.2.2 Group comparisons

A two-sample t-test was used to test for a significant difference between the grey value mean scores of the DG and CG, see Table 16. Scores for CG were approximately normal, and while the scores for DG exhibited evidence of non-normality, the CLT ensured that the t-test could be applied as the sample sizes in each group was high. The Levene’s test of homogeneity of variance indicated that equal variance could not be assumed. The results of the two-sample t-test not assuming equal variance found statistically significant evidence of a difference between the mean scores of the DG and CG, $t(\text{df}=209.139)=-17.249$, $p<0.001$, CI for the difference in means $[-49.57, -39.40]$. Based on the statistical evidence it could be stated that the Distortion method could be
Table 14: Tests of normality for Control group

<table>
<thead>
<tr>
<th>Grey value mean</th>
<th>Repeat size</th>
<th>Kolmogorov-Smirnov&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Shapiro-Wilk</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Statistic</td>
<td>df</td>
<td>Sig.</td>
</tr>
<tr>
<td></td>
<td>100x100px</td>
<td>.107</td>
<td>30</td>
<td>.200*</td>
</tr>
<tr>
<td></td>
<td>200x200px</td>
<td>.116</td>
<td>30</td>
<td>.200*</td>
</tr>
<tr>
<td></td>
<td>400x400px</td>
<td>.162</td>
<td>30</td>
<td>.044</td>
</tr>
<tr>
<td></td>
<td>800x800px</td>
<td>.113</td>
<td>30</td>
<td>.200*</td>
</tr>
</tbody>
</table>

* This is a lower bound of the true significance.

b. Lilliefors Significance correction

Table 15: Tests of normality for Distortion group

<table>
<thead>
<tr>
<th>Grey value mean</th>
<th>Repeat size</th>
<th>Kolmogorov-Smirnov&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Shapiro-Wilk</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Statistic</td>
<td>df</td>
<td>Sig.</td>
</tr>
<tr>
<td></td>
<td>100x100px</td>
<td>.259</td>
<td>30</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>200x200px</td>
<td>.222</td>
<td>30</td>
<td>.001</td>
</tr>
<tr>
<td></td>
<td>400x400px</td>
<td>.195</td>
<td>30</td>
<td>.005</td>
</tr>
<tr>
<td></td>
<td>800x800px</td>
<td>.250</td>
<td>30</td>
<td>.000</td>
</tr>
</tbody>
</table>

* This is a lower bound of the true significance.

b. Lilliefors Significance correction

Table 16: Independent samples t-test for grey value mean

<table>
<thead>
<tr>
<th>Grey value mean</th>
<th>Levene’s Test for Equality of Variances</th>
<th>t-test for equality of means</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F</td>
<td>Sig.</td>
<td>t</td>
</tr>
<tr>
<td>Equal variances assumed</td>
<td>17.827</td>
<td>.000</td>
<td>-17.249</td>
</tr>
<tr>
<td>Equal variances not assumed</td>
<td>-17.249</td>
<td>209.139</td>
<td>.000</td>
</tr>
</tbody>
</table>

applied to improve continuity of print between repeats across garment seams (Hypothesis One). Visual comparison of 95% Confidence Intervals with error bar plot had confirmed the results of the t-test, see Figure 34. DG performed significantly better in all tested repeat sizes.

8.2.3 Correlations

Correlation between independent variables such as edge length, repeat size, colours number and dependent variable grey value mean were explored. All CI for the correlation coefficient r were calculated with the online tool The Confidence Interval of rho (http://vassarstats.net/rho.html?).

For Hypothesis Two, a Pearson’s correlation was calculated to measure the strength of the linear relationship between repeat size and grey value mean, see Table 17. For both groups, no statistically significant linear relationship was detected.
Figure 34
95%CI for grey value mean for two groups

Table 17: Correlations between repeat size and grey value mean.

<table>
<thead>
<tr>
<th>Repeat size</th>
<th>Grey value mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control group</td>
</tr>
<tr>
<td>Pearson correlation</td>
<td>.081</td>
</tr>
<tr>
<td>Sig. (2-tailed)</td>
<td>.379</td>
</tr>
<tr>
<td>N</td>
<td>120</td>
</tr>
</tbody>
</table>

**Correlation is significant at the 0.01 level (2-tailed).**

Table 18: Correlations between edge length and grey value mean

<table>
<thead>
<tr>
<th>Edge length</th>
<th>Grey value mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control group</td>
</tr>
<tr>
<td>Pearson correlation</td>
<td>.291**</td>
</tr>
<tr>
<td>Sig. (2-tailed)</td>
<td>.001</td>
</tr>
<tr>
<td>N</td>
<td>120</td>
</tr>
</tbody>
</table>

**Correlation is significant at the 0.01 level (2-tailed).**

Table 19: Correlations between colours and grey value mean

<table>
<thead>
<tr>
<th>Colours</th>
<th>Grey value mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control group</td>
</tr>
<tr>
<td>Pearson correlation</td>
<td>-.057</td>
</tr>
<tr>
<td>Sig. (2-tailed)</td>
<td>.534</td>
</tr>
<tr>
<td>N</td>
<td>120</td>
</tr>
</tbody>
</table>

**Correlation is significant at the 0.01 level (2-tailed).**
A Pearson’s correlation was calculated to measure the strength of the linear relationship between edge length and grey value mean for CG and DG, see Table 18. The positive correlation was statistically significant for CG, $r = .291$, $p = .001$, 95% CI [0.118, 0.446]. The positive correlation was statistically significant for DG, $r = .852$, $p < .001$, 95% CI [0.795, 0.894]. The current study found evidence in support of Hypothesis Three, which stated that edge length of repeating print has a negative impact on the continuity of print between repeats.

A Pearson’s correlation was calculated to measure the strength of the linear relationship between colours number and grey value mean. In the CG, no statistically significant correlation was detected, see Table 19. In DG, the positive correlation was statistically significant, $r = .361$, $p < .001$, 95% CI [0.195, 0.507]. Further investigation into the colours attribute of repeating prints was planned during the following study.

**8.2.4 Linear regression**

The relationship between edge length and grey value mean for both groups was further examined in linear regression analyses, shown in Table 20.

For CG, a linear regression model was fitted to predict the dependent variable, grey value mean, using measures of edge length as a single predictor. Prior to fitting the regression, a scatterplot

<table>
<thead>
<tr>
<th>Table 20: Linear regression analyses between grey value mean and edge length</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dependent variable: grey value mean, model summary</strong></td>
</tr>
<tr>
<td>Group</td>
</tr>
<tr>
<td>Control</td>
</tr>
<tr>
<td>Distortion</td>
</tr>
<tr>
<td>b. Predictors: (Constant), Edge length</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group</td>
</tr>
<tr>
<td>Control</td>
</tr>
<tr>
<td>Control</td>
</tr>
<tr>
<td>Control</td>
</tr>
<tr>
<td>Distortion</td>
</tr>
<tr>
<td>Distortion</td>
</tr>
<tr>
<td>Distortion</td>
</tr>
<tr>
<td>c. Predictors: (Constant), Edge length</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group</td>
</tr>
<tr>
<td>Control</td>
</tr>
<tr>
<td>Control</td>
</tr>
<tr>
<td>Distortion</td>
</tr>
<tr>
<td>Distortion</td>
</tr>
</tbody>
</table>
assessing the bivariate relationship between grey value mean and edge length was inspected. The scatterplot demonstrated evidence of a positive linear relationship. Other non-linear trends were ruled out. The overall regression model was statistically significant, $F(1, 118) = 10.955, p = .001$, and explained 8.5% of the variability in grey value mean, $R^2 = .085$. The estimated regression equation was grey value mean = $51.393 + 0.001 \times \text{EL}$.

The positive slope for edge length was statistically significant, $b = 0.001, t(118) = 3.310, p = .001, 95\% \text{ CI } [0.000, 0.001]$. Final inspection of the residuals supported normality and homoscedasticity.

For DG, a linear regression model was fitted to predict the dependent variable, grey value mean, using measures of edge length as a single predictor. Prior to fitting the regression, a scatterplot assessing the bivariate relationship between grey value mean and edge length was inspected. The scatterplot demonstrated evidence of a positive linear relationship. Other non-linear trends were ruled out. The overall regression model was statistically significant, $F(1, 118) = 312.568, p < .001$, and explained 72.6% of the variability in grey value mean, $R^2 = .726$. The estimated regression equation was grey value mean = $0.002 \times \text{EL}$. The constant for edge length was not statistically significant $p=0.5$ and was removed from the regression model. The positive slope for edge length was statistically significant, $b = 0.002, t(118) = 17.680, p < .001, 95\% \text{ CI } [0.002, 0.002]$. Final inspection of the residuals supported normality and homoscedasticity. Visually the results of assessment of bivariate relationship between grey value mean and edge length and fitted models are demonstrated in Figure 35.

The relationship between colours number and grey value mean for both groups were further examined in linear regression analyses, shown in Table 21. For CG the test indicated no statistically significant correlation with constant equal to 59.741 across all tested 30 repeats. For DG, a linear regression model was fitted to predict the dependent variable, grey value mean, using measures of colours number as a single predictor. Prior to fitting the regression, a scatterplot assessing the bivariate relationship between grey value mean and colours number was inspected.
### Table 21: Linear regression analyses between grey value mean and colours number

<table>
<thead>
<tr>
<th>Group</th>
<th>Model</th>
<th>R</th>
<th>R square</th>
<th>Adjusted R square</th>
<th>Std. Error of the estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>1</td>
<td>.057*</td>
<td>.003</td>
<td>-.005</td>
<td>23.45523</td>
</tr>
<tr>
<td>Distortion</td>
<td>1</td>
<td>.361*</td>
<td>.130</td>
<td>.123</td>
<td>14.83253</td>
</tr>
</tbody>
</table>

b. Predictors: (Constant), Colours number

### ANOVA

<table>
<thead>
<tr>
<th>Group</th>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>1</td>
<td>214.493</td>
<td>1</td>
<td>214.493</td>
<td>.390</td>
<td>.534°</td>
</tr>
<tr>
<td>Residual</td>
<td></td>
<td>64917.441</td>
<td>118</td>
<td>550.148</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>65131.934</td>
<td>119</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Distortion 1 Regression 3887.764 1 3887.764 17.671 .000°
Residual 25960.471 118 220.004
Total 29848.236 119

c. Predictors: (Constant), Colours number

### Coefficients

<table>
<thead>
<tr>
<th>Group</th>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
<th>t</th>
<th>Sig. Lower Bound</th>
<th>95.0% Confidence Interval for B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Std. Error</td>
<td>Beta</td>
<td></td>
<td></td>
<td>Upper Bound</td>
</tr>
<tr>
<td>Control</td>
<td>1</td>
<td>(Constant)</td>
<td>59.741</td>
<td>2.280</td>
<td>26.208</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Colours number</td>
<td>-.034</td>
<td>.054</td>
<td>-.057</td>
<td>-.624</td>
</tr>
<tr>
<td>Distortion</td>
<td>1</td>
<td>(Constant)</td>
<td>12.689</td>
<td>1.442</td>
<td>8.802</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Colours number</td>
<td>.145</td>
<td>.034</td>
<td>.361</td>
<td>4.204</td>
</tr>
</tbody>
</table>

Figure 36
Fitted linear regression model for colours number for Distortion group
The scatterplot demonstrated evidence of a positive linear relationship. Other non-linear trends were ruled out. The overall regression model was statistically significant, $F(1, 118) = 17.761$, $p < 0.001$, and explained 36.1% of the variability in grey value mean, $R^2 = .361$. The estimated regression equation was grey value mean = 12.689 + 0.145*colour. The positive slope for colour number was statistically significant, $b = 12.689$, $t(118) = 8.802$, $p < .001$, 95% CI 9.834, 15.543]. Final inspection of the residuals supported normality and homoscedasticity. Visually the results are demonstrated in Figure 36.

8.2.5 Conclusion

The study has confirmed the validity of Distortion direction as a method for engineering of repeating prints. The limited number of attributes such as repeat size, colours number and edge length of elements in the repeat were examined as factors affecting the adaptability of repeating prints for the EP method. The experiment was conducted in Greyscale colour space that allowed limiting of measurement error for intensity level values. The TIFF format for raster images also allowed for the reduction in generated due to rasterisation artefact noise.

It was demonstrated that it is possible through dynamic distortion to achieve continuity of print between repeats at garment seams with a lot higher accuracy than by traditional methods. Use of a single orthogonal deformation mesh, which was generated for the specific garment patterns, allowed for alignment on both axes and for the continuity of repeating prints across the seam in a variety of repeats (30) and repeat sizes (4).

The study didn’t find any statistically significant relationship between repeat size and continuity of print between repeats in both traditional and Distortion methods. For colours number, the traditional method indicated no significant correlation with a constant measuring 59.741 across all tested 30 repeats. For the Distortion method, negative correlation between the number of colours and continuity has been confirmed.

The edge length of repeating prints elements had a statistically significant correlation with continuity of print between repeats in both traditional and Distortion methods. However, the Distortion method demonstrated better results in the tested edge length range when linear regression models were compared.
9. Experiment Four: Dynamic Manipulation of a Repeating Print Formation for Engineered Printing of Graded Garments

9.1. Methods

This experimental study proposed a dynamic method for engineering of repeating print formation inside garment patterns by combining all three previously validated directions. The dynamic method aimed to achieve print continuity across garment seams and was contrasted with traditional print matching techniques that can only achieve limited print alignment at the main seams. Also following the grading of the garment, the dynamic method achieved the preservation of the design intent between garments of different sizes by allowing the repeating print elements to retain position and relative proportion to overall garment proportion. The previous Experiment Three demonstrated the correlation between continuity of print and number of colours and edge length of repeat elements when the Distortion method was used. To minimise the visual impact of Distortion, in this experiment it was applied gradually: during fitting of repeat formations inside garment pattern shapes and during grading when the base size patterns were distorted to the other sizes.

9.1.1 Experiment Four objectives and hypotheses

The study had the following objectives:

- evaluate validity of the dynamic method for engineering of repeating print formation;
- develop new measures and instruments;
- establish independent and dependent variables and measurement levels;
- describe variables in terms of operations or measuring techniques;
- examine limited number of attributes as factors affecting the adaptability of repeating prints for the engineered printing (EP) method. Garment size, colours number, motifs number and edge length of elements in repeat were examined in this study;
- establish new measurements’ validity and reliability;
- test the main hypotheses in order to advance engineered printing theory;
- contribute to the adaptability of EP as a mainstream manufacturing method.

Hypotheses were made prior to the experiments in relation to the dynamic method’s principles and repeating print attributes as factors affecting the adaptability of repeating prints for engineered printing method:

Hypothesis One: Dynamic method can preserve the design intent during the grading process better than the traditional method;

Hypothesis Two: Dynamic method can allow preservation of print continuity across garment seams better than the traditional method.

9.1.2 Research design

Study included two independent groups of equal allocation:

- Dynamic group (DG) method, using a combination of three previously validated directions;
- Yardage group (YG) method – simulating traditional repeating print matching techniques.
### Table 22: Experiment Four, list of variables

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Type of variable</th>
<th>Description</th>
<th>Measurement level</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID</td>
<td>ID number</td>
<td>Unique identification number</td>
<td></td>
</tr>
<tr>
<td><strong>Group</strong></td>
<td>Independent</td>
<td>Dynamic Group – garment pattern shapes filled by application of dynamic methods</td>
<td>Category</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Yardage Group – garment pattern shapes filled in traditional way by yardage</td>
<td></td>
</tr>
<tr>
<td>Repeat #</td>
<td>Independent</td>
<td>10 various repeating prints, see Table 23</td>
<td>Category</td>
</tr>
<tr>
<td>Colours #</td>
<td>Independent</td>
<td>Number of distinctive colours in repeat</td>
<td>Ratio</td>
</tr>
<tr>
<td>Motifs #</td>
<td>Independent</td>
<td>Number of distinctive motifs in repeat</td>
<td>Ratio</td>
</tr>
<tr>
<td>Size</td>
<td>Independent</td>
<td>Garment size, 8, 10 and 12 in this study</td>
<td>Category</td>
</tr>
<tr>
<td>Edge length</td>
<td>Independent</td>
<td>Complexity of a printed design, operationalised as edge length of elements of repeat</td>
<td>Ratio</td>
</tr>
<tr>
<td>R1-01</td>
<td>Dependent</td>
<td>Shoulder seam</td>
<td>Ordinal</td>
</tr>
<tr>
<td>R1-02</td>
<td>Dependent</td>
<td>Left hand side front dart</td>
<td>Ordinal</td>
</tr>
<tr>
<td>R1-03</td>
<td>Dependent</td>
<td>Right hand side front dart</td>
<td>Ordinal</td>
</tr>
<tr>
<td>R1-04</td>
<td>Dependent</td>
<td>Left hand side seam above waist</td>
<td>Ordinal</td>
</tr>
<tr>
<td>R1-05</td>
<td>Dependent</td>
<td>Rh side seam above waist</td>
<td>Ordinal</td>
</tr>
<tr>
<td>R1-06</td>
<td>Dependent</td>
<td>Left hand side seam below waist</td>
<td>Ordinal</td>
</tr>
<tr>
<td>R1-07</td>
<td>Dependent</td>
<td>Right hand side seam below waist</td>
<td>Ordinal</td>
</tr>
<tr>
<td>R1-08</td>
<td>Dependent</td>
<td>Back seam</td>
<td>Ordinal</td>
</tr>
<tr>
<td>R1-09</td>
<td>Dependent</td>
<td>Hemline</td>
<td>Ordinal</td>
</tr>
<tr>
<td>R2-01</td>
<td>Dependent</td>
<td>Flow of repeating print across seams in 3D, evaluated as Horizontal match</td>
<td>Ordinal</td>
</tr>
<tr>
<td>R2-02</td>
<td>Dependent</td>
<td>Vertical match</td>
<td>Ordinal</td>
</tr>
<tr>
<td>R2-03</td>
<td>Dependent</td>
<td>Diagonal match</td>
<td>Ordinal</td>
</tr>
<tr>
<td>R3-01</td>
<td>Dependent</td>
<td>Accuracy of registration in 3D – placement of the same repeats at the same location on garments of different sizes, evaluated at Camera view 01—front</td>
<td>Ordinal</td>
</tr>
<tr>
<td>R3-02</td>
<td>Dependent</td>
<td>Camera view 02—right side</td>
<td>Ordinal</td>
</tr>
<tr>
<td>R3-03</td>
<td>Dependent</td>
<td>Camera view 03—back</td>
<td>Ordinal</td>
</tr>
<tr>
<td>R3-04</td>
<td>Dependent</td>
<td>Camera view 04—left side</td>
<td>Ordinal</td>
</tr>
<tr>
<td>R4</td>
<td>Dependent</td>
<td>Fidelity of repeat</td>
<td>Ordinal</td>
</tr>
<tr>
<td>R5-01</td>
<td>Dependent</td>
<td>Visual perception of garment proportions between sizes, evaluated at Camera view 01—front</td>
<td>Ordinal</td>
</tr>
<tr>
<td>R5-02</td>
<td>Dependent</td>
<td>Camera view 02—right side</td>
<td>Ordinal</td>
</tr>
<tr>
<td>R5-03</td>
<td>Dependent</td>
<td>Camera view 03—back</td>
<td>Ordinal</td>
</tr>
<tr>
<td>R5-04</td>
<td>Dependent</td>
<td>Camera view 04—left side</td>
<td>Ordinal</td>
</tr>
<tr>
<td>R6-01</td>
<td>Dependent</td>
<td>Ready-to-Print images flow of repeating print across seams in 2D, evaluated as Horizontal match</td>
<td>Ordinal</td>
</tr>
<tr>
<td>R6-02</td>
<td>Dependent</td>
<td>Vertical match</td>
<td>Ordinal</td>
</tr>
<tr>
<td>R6-03</td>
<td>Dependent</td>
<td>Diagonal match</td>
<td>Ordinal</td>
</tr>
<tr>
<td>R7-01</td>
<td>Dependent</td>
<td>Front</td>
<td>Ordinal</td>
</tr>
<tr>
<td>R7-02</td>
<td>Dependent</td>
<td>Left hand side back</td>
<td>Ordinal</td>
</tr>
<tr>
<td>R7-03</td>
<td>Dependent</td>
<td>Right hand side back</td>
<td>Ordinal</td>
</tr>
</tbody>
</table>
Both models were set up in Adobe Illustrator to use the Patterns Fill and Pattern Brush tools. Models were simulated at actual size as vector graphics allowing for precise construction and consistent measurements, using pixels for base units.

Placeholder repeat was created for the template setup, and replaced during the experiment with design repeats. Front, Right Hand Side (RHS) and Left Hand Side (LHS) Back garment pattern pieces in size 10 for a straight ladies’ dress were imported from Pattern Design System at actual size and filled with the placeholder repeating print using the YG and DG methods. Filled copies of Front and LHS, RHS Backs were positioned to join along side seams and back seam on a separate artboard for each group. Boards were then exported as JPG images for the subsequent rating. Additional copies of Front and LHS and RHS Backs for DG were also set up on separate artboards individually. Boards were exported as JPG images for the following grading in Photoshop and importing into VStitcher as attachments. Single Pattern Swatch for YG was set on a separate 400x400px artboard and exported as a JPG file to use as fabric texture in VStitcher. Garments in three sizes and ten repeating prints were simulated in the VStitcher 3D environment for both groups, and snapshots taken for the following rating.

9.1.3 Population and sample

In this study, attributes of garment size, the number of distinctive colours, motifs and edge length of repeat elements were examined as factors affecting the adaptability of repeating prints for the EP method. Ten repeats were generated that contained multiple different motifs, geometrical or free-form, single or multiple flat colours, repeats with distinctive foreground-background separation and repeats with a continuous flow of elements, demonstrated in Table 23. Thus, the research design allowed for the sample size of 30 for each group.

9.1.4 Variables and measures

The experiment’s variables are presented in Table 22, the code sheet in Table 23.

Attributes of each repeat were assessed using Wolfram Mathematica environment, where edge length for elements of each repeat were measured as a number of pixels, as shown in Figure 37. The motifs number for each repeat was measured as the length of a string in the same routine. The second routine measured the number of colours for each repeat, shown in Figure 38.
Figure 38
Number of colours calculations

Table 23: Code sheet for Experiment Four

<table>
<thead>
<tr>
<th>Print design repeat</th>
<th>Code</th>
<th>Print design repeat</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Design P01" /></td>
<td>P01</td>
<td><img src="image2" alt="Design P06" /></td>
<td>P06</td>
</tr>
<tr>
<td><img src="image3" alt="Design P02" /></td>
<td>P02</td>
<td><img src="image4" alt="Design P07" /></td>
<td>P07</td>
</tr>
<tr>
<td><img src="image5" alt="Design P03" /></td>
<td>P03</td>
<td><img src="image6" alt="Design P08" /></td>
<td>P08</td>
</tr>
<tr>
<td><img src="image7" alt="Design P04" /></td>
<td>P04</td>
<td><img src="image8" alt="Design P09" /></td>
<td>P09</td>
</tr>
<tr>
<td><img src="image9" alt="Design P05" /></td>
<td>P05</td>
<td><img src="image10" alt="Design P10" /></td>
<td>P10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Group</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic group</td>
<td>1</td>
</tr>
<tr>
<td>Yardage group</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Size</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>08</td>
<td>S08</td>
</tr>
<tr>
<td>10</td>
<td>S10</td>
</tr>
<tr>
<td>12</td>
<td>S12</td>
</tr>
</tbody>
</table>
Table 24: Collected ratings

<table>
<thead>
<tr>
<th>Construct</th>
<th>Rating</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Print matching and continuity across garment seams</td>
<td>R1</td>
<td>Accuracy of matching repeat elements at location, evaluated in 9 specific locations</td>
</tr>
<tr>
<td></td>
<td>R2</td>
<td>Flow of repeating prints across seams in 3D, evaluated horizontally, vertically and diagonally</td>
</tr>
<tr>
<td></td>
<td>R6</td>
<td>Ready-to-Print images flow of repeating print across seams in 2D, evaluated horizontally and diagonally</td>
</tr>
<tr>
<td>Preservation of the design intent between garment sizes</td>
<td>R3</td>
<td>Accuracy of print registration in 3D – placement of the same repeats at the same location on garments of different sizes, evaluated at front, back, left and right side views</td>
</tr>
<tr>
<td></td>
<td>R5</td>
<td>Visual perception of garment proportions between sizes, evaluated at front, back, left and right side views</td>
</tr>
<tr>
<td></td>
<td>R7</td>
<td>Ready-to-Print images registration in 2D, three garment patterns, evaluated for each pattern piece</td>
</tr>
<tr>
<td>Fidelity</td>
<td>R4</td>
<td>Fidelity of repeat</td>
</tr>
</tbody>
</table>

9.1.5 Rating protocol instrument

A rating protocol was setup to assess achieved preservation of design intent and print continuity across the seams of a garment. An additional construct for fidelity of repeat tile was also explored. Collected ratings are shown in Table 24. For the rating procedure, JPG images from Illustrator, Ready-to-Print (RTP) images and snapshots from VStitcher were sorted and organized in Adobe Bridge by applying meta-data to allow viewing them in specific combinations, shown in Figures 39-44. Viewed images were rated by the author for R1 to R7 on a Likert-type scale, with rating values from 1 to 5, where 1 meant ‘Excellent’, 2 was ‘Good’, 3 was ‘Satisfactory’, 4 was ‘Below satisfactory’ and 5 was ‘Poor’.

All recorded data was entered into an Excel spreadsheet, screened and cleaned. Data was then imported into SPSS v. 22. Additional variables for average ratings for R1, R2, R3, R5, R6 and R7 were calculated in SPSS.

9.1.6 Experimental procedures

The following section demonstrates Adobe Illustrator set up of templates for both groups, followed by populating the template with sample repeats.

Garment pattern shapes for size 10 ladies’ straight dress were imported from VStitcher into Illustrator and traced. Outlines were saved as symbols and used as guides for the DG method and as a shape for the application of Pattern swatch fills in the YG method. A placeholder Pattern swatch was created for the template. Ten print repeats were generated and saved as Pattern swatches, shown in Figure 45. All swatches were 400 px square. Placeholder Pattern Brush was created for the template set up from scaled placeholder Pattern swatch, measuring 10px square. The size was chosen to facilitate outline scaling. 10 Pattern Brushes were generated from scaled Pattern swatches, shown in Figure 46 (a). Properties of the brushes were set to ‘Stretch to Fit’, demonstrated in Figure 46 (b).
Figure 39
Snapshots from VStitcher in the same size without avatar for ratings 1 and 2, camera views 05-09. Demonstrated for print 01 (a) yardage group and (b) dynamic group.

Figure 40
Snapshots from VStitcher all three sizes together without avatar for rating 3, sorted by camera view. Demonstrated for print 05, camera view 05 (a) yardage group and (b) dynamic group.
Figure 41
Snapshots from VStitcher in the same size with avatar for rating 4, camera views 01-04. Demonstrated for print 07 (a) yardage group and (b) dynamic group.

Figure 42
Snapshots from VStitcher with avatar for rating 5 all three sizes together sorted by camera view. Demonstrated for print 02 camera view 06 (a) yardage group and (b) dynamic group.
Figure 43
Ready-to-print images with seams joined and all sizes together for rating 6. Demonstrated for print 06 (a) yardage group and (b) dynamic group.

Figure 44
Ready-to-print images sorted by garment pattern piece for all three sizes together for rating 7. Demonstrated for print 04 front pattern piece (a) yardage group and (b) dynamic group.
For YG, symbols for pattern pieces for Front, LHS and RHS Back were set up with the hemline side points aligned, shown in Video 1 on the right. Placeholder Pattern fill was applied as an appearance, positioned to align at hemline side seams horizontally, and centred at the Centre Front and Back vertically. This was done to simulate traditional techniques for matching repeating prints at seams. Artboard was then created with symbols garment pattern pieces laid out to join at the side and back seams, shown in Video 1 on the left. Pattern pieces were rotated and duplicated. Only skirt areas of the dress could be unwrapped flat due to the 3D nature of the garment. The unwrapped area was indicated with red overlay. All text was on a separate layer, and visibility of this layer was turned off for exporting of JPG images. Placeholder Pattern swatch was replaced with specific repeat prints and each time artboards were exported.

For DG, artboard was created with garment pattern pieces laid out to join at side and back seams. Pattern pieces were rotated and duplicated to create an area for blending Pattern Brush lines, shown in Video 2 on the left. Brush lines were drawn along the hem and waistline, and blended to fit the specified number of steps in between. Placeholder Brush was applied to the lines. The weight value of the lines was adjusted to fit the equal number of brush tiles on each line of the Blend, and to distribute the lines to eliminate space between brush lines. Copies of the Blend template for Front, LHS and RHS Back pattern pieces with 20px seam allowance were created on
**Video 1**
Template set-up for yardage group, demonstrating how artboards were populated with sample repeats

**Video 2**
Template set-up for dynamic group, demonstrating how artboards were populated with sample repeats
Figure 47
Distorting size 10 JPGs to match sizes 8 and 12 outlines in Photoshop, demonstrated with print 01

Figure 48
Creating size 8 and 12 avatar bodies.
additional art boards. Template brush was replaced with repeat brush, and each time artboards were exported as JPGs.

Photoshop files were set up to grade DG images from the base size 10 to sizes 8 and 12, demonstrated in Figure 47. Nested pattern pieces imported from VStitcher. Front, LHS and RHS Back JPGs of DG in size 10 were imported as layers in Photoshop PSD files and saved as stacks. Stacks were imported into a separate PSD file as Smart Objects layers and duplicated for three sizes. Stacks for size 8 and 12 were distorted to match relevant nest pattern outlines. Visibility of Smart Objects layers was edited to display different layers and layers were exported as JPGs for sizes 8, 10, 12 for following 3D simulation in VStitcher.

3D virtual simulations of the garment were generated in the next VStitcher stage. Size 10 avatar dimensions were modified for body sizes 8 and 12, as shown in Figure 48. A dress with base size 10 was simulated in the balanced pose. Fabric properties were verified. Sizes 8 and 12 were added, and patterns were graded, as shown in Figure 49. Initial colourway for the dress was ‘White’.

Nine camera positions were set-up to capture the full height of the avatar from the front, back, left and right side, the full length of the garment in the camera view, and to show shoulder seams shot. Camera positions were numbered and given descriptive labels, as shown in Figure 50.

VStitcher file copies were saved for YG and DG. For DG, working with size 10 as the base size, colourway 01 was added and attachments for Front, LHS and RHS Back pattern pieces for print 01 imported into VStitcher and positioned over the pattern pieces. Colourway 02 was cloned from colourway 01, and attachments
were replaced with corresponding files. The rest of the colourways were generated in the same manner.

For YG, working with size 10 as the base size, colourway 01 was added and print 01 applied to dress. Colourway 02 was cloned from colourway 01, the repeating print was replaced with corresponding files. The rest of the colourways were generated in the same manner.

Camera images were generated for all colourways in 9 camera positions, with and without the avatar body for both groups’ size 10 garments. Then size 8 patterns were nominated as base patterns, avatar size 10 body was replaced for size 8 body, and the dress simulated for size 8. Size 12 patterns were nominated as base patterns, avatar size 10 body was replaced with size 12 body and the dress simulated for size 12.

Camera snapshots and RTP images were generated for all colourways and sizes and exported as PNGs and JPGs files from VStitcher.

9.1.7 Statistical analyses procedures
Statistical analyses were performed on all main variables using SPSS v.22 to determine measures of central tendency and variation. Data were also examined visually with plots to establish the groups’ distribution type and identify any outliers that have to be investigated further.

Group comparisons analyses were performed to examine the differences between the two groups. Following normality testing, a two-sample t-test in SPSS was used to test for a significant difference between the mean scores of the DG and CG with the significance level $\alpha = 0.05$. The Levene’s test of homogeneity of variance was used to test the assumption of equal variance.

Correlation and linear regression analyses were performed to establish relationships between independent and dependent variables.

Principal components analyses were performed on the results of rating. Additional factor analysis package, Factor v9.2 (Lorenzo-Seva & Ferrando 2006), was used to re-analyse the data as SPSS has limited options in regards to rotation. Also, 95% CI for the statistically significant correlation coefficients $r$ were calculated with on-line tool The Confidence Interval of Rho (http://vassarstats.net/rho.html?).

9.2. Results, Analyses and Discussion
This study focused on the evaluation of an engineered method for dynamic manipulation of a repeating print formation. The method was applied to create engineered repeating prints for a dress with the garment graded into three sizes. The print attributes such as garment size, colours number, motifs number and edge length of print elements were also examined as factors affecting the adaptability of repeating print for the EP method. The study was also employed to develop new procedures and instruments.

9.2.1 Descriptive analyses
Statistical analyses were performed on all main variables in SPSS to determine measures of central tendency and variation, the results are shown in Table 25 and compared visually with plots to establish variables distribution type, shown in Figures 51-57. Normality assumptions for distributions of all main variables were nominated to be verified further with testing.
Means distributions for accuracy of matching R1 for both groups were visually approximately normal and symmetrical, shown in Figure 51. However, the differences in mean, 2.6333 for DG and 3.4222 for YG were visually confirmed by the comparison graph. On average, DG scored higher than YG for accuracy of matching R1 by 0.7889.

Means distributions for print flow R2 for both groups were visually asymmetrical, with means 1.9000 for DG and 2.7889 for YG. The DG group scored on average higher than YG by 0.8889. The difference between DG and YG also was also explored by looking at the comparison graph for frequency distribution and kurtosis and skewness values. YG distribution was visually approxi-

**Table 25: Measures of central tendency and variation**

<table>
<thead>
<tr>
<th>Group</th>
<th>Variable</th>
<th>N</th>
<th>Range</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Variance</th>
<th>Skewness</th>
<th>Kurtosis</th>
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<tbody>
<tr>
<td>Dynamic</td>
<td>Accuracy of matching R1</td>
<td>30</td>
<td>1.22</td>
<td>2.11</td>
<td>3.33</td>
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<td></td>
<td>Print flow in 3D R2</td>
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<td>3.00</td>
<td>1.00</td>
<td>4.00</td>
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<td>.561</td>
<td>1.361</td>
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<td>Garment registration in 3D R3</td>
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<td>Tile fidelity R4</td>
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<td>.490</td>
<td>.240</td>
<td>.583</td>
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<tr>
<td></td>
<td>Visual proportion in 3D R5</td>
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<td>1.25</td>
<td>2.50</td>
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<td>.380</td>
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<td></td>
<td>RTP flow in 2D R6</td>
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<td>1.00</td>
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<td>.48857</td>
<td>.239</td>
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<td>RTP registration in 2D R7</td>
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<td>2.33</td>
<td>2.1000</td>
<td>.15536</td>
<td>.024</td>
<td>.920</td>
<td>-1.242</td>
</tr>
<tr>
<td>Valid N (listwise)</td>
<td></td>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 51**
Frequency for accuracy of matching R1

**Figure 52**
Frequency for print flow R2
mately normal. DG distribution exhibited a pile-up of scores on the left of the distribution, with a pointy shape and heavy right tail, shown in Figure 52.

Means distributions for garment registration 3D R3 for both groups were bimodal, with means of 1.9250 for DG and 3.1500 for YG. The DG group scored on average higher than YG by 1.225. Kurtosis values for both groups were negative, and visually the graph confirms that distributions are platykurtic, shown in Figure 53.

Tile fidelity R4 means comparison showed YG scoring higher than DG by 0.3 on average (1.07 and 1.37 respectively), shown in Figure 54. The result could be explained by differences in methods and chosen base woven fabric properties for this experiment (i.e. with a very stretchy fabric the distortion of the surface print is likely to occur with a mainstream method, and can be actually reduced with the dynamic method).

Means distributions for visual proportion in 3D R5 for both groups were visually asymmetrical, with means 1.8500 for DG and 2.7755 for YG. The DG group scored on average higher than YG by 0.9255. The differences between DG and YG were also explored by looking at a comparison graph for frequency distribution, shown in Figure 55, and kurtosis (both negative, with higher negative value for DG) and skewness (both positive) values.

Means distributions for RTP flow in 2D R6 for both groups were visually asymmetrical, with means 1.4333 for DG and 2.7111 for YG. The DG group scored on average higher than YG by
Means distributions for RTP registration in 2D R7 for both groups were visually asymmetrical, with means 1.4667 for DG and 2.1000 for YG. The DG group scored on average higher than YG by 0.6333. The differences between DG and YG were also explored by looking at a comparison graph for frequency distribution, shown in Figure 57, and kurtosis and skewness values. DG distribution exhibited a pile-up of scores on the left of the distribution, with a pointy shape and heavy right tail. YG distribution exhibited a pile-up of scores on the right of the distribution, with a pointy shape and heavy right tail.

Kolmogorov-Smirnov and Shapiro-Wilk tests confirmed normality for DG and YG for accuracy of matching R1 and visual proportion in 3D R5 for YG, shown in Table 26. The rest of the variables showed statistically significant deviations from normality, but as the sample size for each group was high, and CLT ensures that sampling distribution of the mean is approximately normal regardless of the variable underlying population distribution when the sample size is large, the analysis proceeded with t-tests.

Table 26: Tests of normality for experiment four variables

<table>
<thead>
<tr>
<th>Group</th>
<th>Kolmogorov-Smirnov</th>
<th>Shapiro-Wilk</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Statistic</td>
<td>df</td>
</tr>
<tr>
<td><strong>Accuracy of matching R1</strong></td>
<td>Dynamic</td>
<td>.098</td>
</tr>
<tr>
<td></td>
<td>Yardage</td>
<td>.133</td>
</tr>
<tr>
<td><strong>Pint flow in 3D R2</strong></td>
<td>Dynamic</td>
<td>.256</td>
</tr>
<tr>
<td></td>
<td>Yardage</td>
<td>.161</td>
</tr>
<tr>
<td><strong>Garment registration in 3D R3</strong></td>
<td>Dynamic</td>
<td>.296</td>
</tr>
<tr>
<td></td>
<td>Yardage</td>
<td>.215</td>
</tr>
<tr>
<td><strong>Tile fidelity R4</strong></td>
<td>Dynamic</td>
<td>.406</td>
</tr>
<tr>
<td></td>
<td>Yardage</td>
<td>.537</td>
</tr>
<tr>
<td><strong>Visual proportion in 3D R5</strong></td>
<td>Dynamic</td>
<td>.193</td>
</tr>
<tr>
<td></td>
<td>Yardage</td>
<td>.123</td>
</tr>
<tr>
<td><strong>RTP flow in 2D R6</strong></td>
<td>Dynamic</td>
<td>.248</td>
</tr>
<tr>
<td></td>
<td>Yardage</td>
<td>.257</td>
</tr>
<tr>
<td><strong>RTP registration in 2D R7</strong></td>
<td>Dynamic</td>
<td>.250</td>
</tr>
<tr>
<td></td>
<td>Yardage</td>
<td>.440</td>
</tr>
</tbody>
</table>

* This is a lower bound of the true significance.

a Lilliefors Significance Correction
9.2.2 Group comparison tests

A two-sample t-test was used to test for a significant difference between the mean scores of the ratings for DG and YG, shown in Table 27. The Levene’s test of homogeneity of variance was used to verify the assumption of equal variance for the variables, and displayed results were filtered by Levene’s test to include relevant results only.

For accuracy of matching R1, the Levene’s test for homogeneity of variance indicated that equal variance could be assumed. The results of the two-sample t-test assuming equal variance found statistically significant evidence of a difference between the mean scores of the DG and YG, $t(df=58)=-10.589$, $p<0.001$, 95% CI for the difference in means [-.93801, -.63977]. The results of the study found statistically significant evidence in support of Hypothesis Two. The Dynamic method improved the accuracy of matching for repeating print across garment seams and, therefore, improved continuity of repeating print for the 3D shape of the garment. The results of the t-test were confirmed visually with error bar plot for 95% Confidence Intervals, shown in Figure 58.

The visual difference in means of the R1 rating was also examined in the error bar plot that displayed R1 components separately, shown in Figure 59. Due to the execution of dynamic processing in the 2D Adobe Illustrator environment, where the 3D form of the garment could be only partially flattened in the skirt area from waist to hem, the matching in the areas above the

Table 27: t-test results for experiment four ratings

<table>
<thead>
<tr>
<th></th>
<th>Levene’s test for equality of variances</th>
<th>t-test for equality of means</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F</td>
<td>Sig.</td>
</tr>
<tr>
<td>Accuracy of matching R1</td>
<td>1.473</td>
<td>.230</td>
</tr>
<tr>
<td>Print flow in 3D R2</td>
<td>-5.687</td>
<td>.000</td>
</tr>
<tr>
<td>Garment registration in 3D R3</td>
<td>-11.090</td>
<td>.000</td>
</tr>
<tr>
<td>Tile fidelity R4</td>
<td>2.977</td>
<td>.005</td>
</tr>
<tr>
<td>Visual proportion in 3D R5</td>
<td>.023</td>
<td>.880</td>
</tr>
<tr>
<td>RTP flow in 2D R6</td>
<td>3.097</td>
<td>.084</td>
</tr>
<tr>
<td>RTP registration in 2D R7</td>
<td>-9.152</td>
<td>.000</td>
</tr>
</tbody>
</table>
Figure 58
95% CI for experiment four ratings

Figure 59
95% CI error bar plots for accuracy of matching R1 components separately

Figure 60
95% CI for dynamic and yardage groups by R1 components and garment sizes
waist was not controlled. Consequently, the 95% CI of values for ratings for evaluated areas above waist were very close or overlapping on R1-01, R1-02, R1-03, R1-04 and R1-05 for both groups. The Back seam matching R1-08 covered both above and below waist regions and in DG it was reflected in a longer bar. However R1-06, R1-07 and R1-09 areas, where dynamic matching was applied for the entire length of seam/hem, presented much higher scores compared to YG.

Further examination of the R1 components for the two groups split by the garment sizes as shown in Figure 60, demonstrated similar behaviour, with not much difference between sizes within each group. Dynamically manipulated R1-06, R1-07 and R1-09 components outperformed traditionally matched ones, with base size 10 exhibiting the best performance as expected, and slightly decreased scores for sizes 12 and 8 due to additional errors acquired during the distortion process.

For print flow in 3D R2, the Levene’s test for homogeneity of variance indicated that equal variance could not be assumed. The results of the two-sample t-test not assuming equal variance found statistically significant evidence of a difference between the mean scores of the DG and YG, t(df=45.288)= - 5.687, p<0.001, 95% CI for the difference in means [-1.20362, -.57415]. The results of the study found statistically significant evidence in support of Hypothesis Two. The Dynamic method improved the print flow of repeating print across garment seams and, therefore, improved continuity of repeating print for the 3D shape of the garment. The results of the t-test were confirmed visually with the error bar plot for 95% CI for Print Flow R2, see Figure 58.

For garment registration in 3D R3, the Levene’s test for homogeneity of variance indicated that equal variance could not be assumed. The results of the two-sample t-test not assuming equal variance found statistically significant evidence of a difference between the mean scores of the DG and YG, t(df=50.641)= - 10.910, p<0.001, 95% CI for the difference in means [-1.45046, -.99954]. The results of the study found statistically significant evidence in support of Hypothesis One. The Dynamic method improved garment registration in 3D for repeating print and improved preservation of the design intent between garment sizes. Visual comparison of 95% CI with error bar plot had confirmed the results of the t-test for garment registration in 3D R3, see Figure 58.

For tile fidelity R4, the Levene’s test for homogeneity of variance indicated that equal variance could not be assumed. The results of the two-sample t-test not assuming equal variance found statistically significant evidence of a difference between the mean scores of the DG and YG, t(df=43.500)=2.977, p=0.005, 95% CI for the difference in means [.097, .503]. The results of the study found statistically significant evidence that tile fidelity of a decorative repeating print design, when woven fabric is used for a semi-fitted garment, is retained better in the mainstream method. Still, for close-fitting garments and stretchy fabrics, the distortion of surface print might be more pronounced for the mainstream method. The dynamic method might be able to take fabric stretching into account and provide visually more even appearance. Visual comparison of 95% CI with the error bar plot had confirmed the results of the t-test for tile fidelity R4, see Figure 58.

For visual proportion in 3D R5, the Levene’s test for homogeneity of variance indicated that equal variance could be assumed. The results of the two-sample t-test assuming equal variance found statistically significant evidence of a difference between the mean scores of the DG and YG, t(df=58)= - 7.797, p<0.001, 95% CI for the difference in means [-1.16247, -.68753]. The results
of the study found statistically significant evidence in support of Hypothesis One. The dynamic method retained visual proportions of the garment and improved preservation of the design intent between garment sizes. Visual comparison of 95% CI with error bar plot had confirmed the results of the t-test for visual proportion in 3D R5, see Figure 58.

For RTP flow in 2D R6, the Levene’s test for homogeneity of variance indicated that equal variance could be assumed. The results of the two-sample t-test assuming equal variance found statistically significant evidence of a difference between the mean scores of the DG and YG, \( t(\text{df}=58)=-11.554, p<0.001, 95\% \text{ CI for the difference in means } [-1.49915, -1.05640] \). The results of the study found statistically significant evidence in support of Hypothesis Two. The dynamic method improved repeating print flow for RTP images and, therefore, improved continuity of repeating print for the 3D shape of the garment. Visual comparison of 95% CI with error bar plot had confirmed the results of the t-test for visual proportion in 3D R5, see Figure 58.

For RTP registration in 2D R7, the Levene’s test for homogeneity of variance indicated that equal variance could not be assumed. The results of the two-sample t-test not assuming equal variance found statistically significant evidence of a difference between the mean scores of the DG and YG, \( t(\text{df}=40.253)=-9.152, p<0.001, 95\% \text{ CI for the difference in means } [-0.77317, -0.49349] \). The results of the study found statistically significant evidence in support of Hypothesis One. The dynamic method improved repeating print registration for RTP images in 2D across garment seams and improved preservation of the design intent between garment sizes. Visual comparison of 95% CI with error bar plot had confirmed the results of the t-test for RTP flow in 2D R6, see Figure 58.

Table 28: Correlations analyses for experiment four

<table>
<thead>
<tr>
<th>Independent variable</th>
<th>Statistic</th>
<th>Dynamic Group</th>
<th>Yardage Group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R1 accuracy of matching</td>
<td>R3 garment registration</td>
<td>R5 visual proportion</td>
</tr>
<tr>
<td>Motifs number</td>
<td>Pearson correlation</td>
<td>.162</td>
<td>-.068</td>
</tr>
<tr>
<td>Sig. (2-tailed)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td></td>
<td>.021</td>
<td></td>
</tr>
<tr>
<td>95% CI Lower</td>
<td></td>
<td>.145</td>
<td></td>
</tr>
<tr>
<td>95% CI Upper</td>
<td></td>
<td>.649</td>
<td></td>
</tr>
<tr>
<td>Colours number</td>
<td>Pearson correlation</td>
<td>.175</td>
<td>-.005</td>
</tr>
<tr>
<td>Sig. (2-tailed)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td></td>
<td>.048</td>
<td></td>
</tr>
<tr>
<td>95% CI Lower</td>
<td></td>
<td>.048</td>
<td></td>
</tr>
<tr>
<td>95% CI Upper</td>
<td></td>
<td>.665</td>
<td></td>
</tr>
<tr>
<td>Edge length</td>
<td>Pearson correlation</td>
<td>.169</td>
<td>.076</td>
</tr>
<tr>
<td>Sig. (2-tailed)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>N</td>
<td></td>
<td>.311</td>
<td></td>
</tr>
<tr>
<td>95% CI Lower</td>
<td></td>
<td>.311</td>
<td></td>
</tr>
<tr>
<td>95% CI Upper</td>
<td></td>
<td>.791</td>
<td></td>
</tr>
</tbody>
</table>

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).
**9.2.3 Correlations**

Correlation between independent variables such as colours number, motifs number and edge length and dependent ratings variables were explored, shown in Table 28. All 95% CI for the statistically significant correlation coefficients $r$ were calculated with the on-line tool The Confidence Interval of Rho (http://vassarstats.net/rho.html?).

Accuracy of matching R1 was not affected by either motifs number, colours number or edge length in DG while R1 in YG has a positive correlation with motifs and colours number.

Garment registration R3 and RTP flow R6 were similarly not affected by either motifs number, colours number or edge length in DG while the same variables for YG had a significant negative correlation.

Significant negative correlations were also demonstrated between motifs number, colours number and edge length and RTP registration R7 in the YG group while, in the DG group, colours number showed significant positive correlation. Visual proportion R5 in DG was significantly affected by motifs number and edge length while YG was not affected significantly.

Overall DG group ratings have appeared to be much less affected by attributes of a specific repeating print compared to YG, with only visual proportion R5 reflecting the change in repeating prints on motifs number and edge length, and RTP registration R7 on colours number.

**9.2.4 Principal components analysis**

Next, the rating protocol instrument was examined for validity and reliability (Baglin 2014).

A new measurement instrument, the rating protocol, was built for this study with the aim of measuring ‘3D print design continuity’ and ‘Preservation of the design intent’ constructs. The protocol had 27 items rated on a 5 point Likert-type scale. The ratings were assigned values of 1 to 5, where 1 meant ‘Excellent’, 2 was ‘Good’, 3 was ‘Satisfactory’, 4 was ‘Below satisfactory’ and 5 was ‘Poor’.

Data was analysed in SPSS with the Principal components analysis (PCA) method selected to verify the construct validity of the protocol and investigate the reduction of a large number of interrelated variables into a smaller set of components with minimal loss of information.

Pearson correlation with a Promax oblique rotation method with Kaiser Normalisation was used. Small loadings below 0.39 were suppressed. KMO and Bartlett’s Test, Table 29, confirmed the suitability of the sample for PCA, with a Kaiser-Meyer-Olkin Measure of sampling adequacy of 0.774 and a statistically significant result of Bartlett’s Test of Sphericity, $p<0.001$.

Six components were retained as a result of the PCA, explaining 75.81% of the total variability for all variables. However, the 44.89% of total variability was explained by the first component.

<table>
<thead>
<tr>
<th>Table 29: KMO and Bartlett’s test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaiser-Meyer-Olkin measure of sampling adequacy</td>
</tr>
<tr>
<td>Bartlett’s test of sphericity</td>
</tr>
<tr>
<td>Approx. Chi-Square</td>
</tr>
<tr>
<td>df</td>
</tr>
<tr>
<td>Sig.</td>
</tr>
</tbody>
</table>
Table 30: Component matrix

<table>
<thead>
<tr>
<th>Dimension Component</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>R3, LHS view</td>
<td>.898</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R7, Front</td>
<td>.896</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R6, vertical flow</td>
<td>.880</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1, RHS seam below waist matching</td>
<td>.878</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1, LHS seam below waist matching</td>
<td>.868</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R6, horizontal flow</td>
<td>.863</td>
<td></td>
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</tr>
<tr>
<td>R3, Front view</td>
<td>.847</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>R5, LHS view</td>
<td>.829</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>R3, RHS view</td>
<td>.825</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R6, diagonal flow</td>
<td>.815</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>R5, RHS view</td>
<td>.755</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1, Along hemline matching</td>
<td>.708</td>
<td>-.422</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R2, vertical flow</td>
<td>.698</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R5, Front view</td>
<td>.682</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R2, diagonal flow</td>
<td>.673</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R7, RHS Back</td>
<td>.652</td>
<td>.390</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1, Back seam matching</td>
<td>.632</td>
<td>.497</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R5, Back view</td>
<td>.574</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R2, horizontal flow</td>
<td>.568</td>
<td>.451</td>
<td>-.419</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R3, Back View</td>
<td>.535</td>
<td>-.480</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1, RHS seam above waist matching</td>
<td>.758</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1, LHS Seam above waist matching</td>
<td>.552</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>R1, RHS Front dart matching</td>
<td>.551</td>
<td>.411</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R4, Tile fidelity</td>
<td></td>
<td>.545</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1, Shoulder seam matching</td>
<td>-.439</td>
<td>.700</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1, LHS Front dart matching</td>
<td>.442</td>
<td>-.554</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R7, LHS Back</td>
<td></td>
<td>.406</td>
<td>-.624</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Extraction Method: Principal Component Analysis.
a. 6 components extracted.

Table 31: Reliability statistics

<table>
<thead>
<tr>
<th>Analysed items</th>
<th>Cronbach’s Alpha</th>
<th>N of Items</th>
</tr>
</thead>
<tbody>
<tr>
<td>All 27 items</td>
<td>.927</td>
<td>27</td>
</tr>
<tr>
<td>Factor 1 items</td>
<td>.958</td>
<td>20</td>
</tr>
<tr>
<td>Factor 2 items</td>
<td>.547</td>
<td>3</td>
</tr>
</tbody>
</table>
scree plot was examined to consider if the components number was overestimated in the PCA based on the Kaiser criteria, Figure 61. Visually the point of inflection can be considered after the first or fourth component, so Parallel Analysis (PA) results were further examined in the component matrix, shown in Table 30.

Component 1 had the highest number of loadings on a single dimension (total of 20, three of them cross-loaded), followed by component 2 (total of three, one cross-loaded), component 5 (total of two, one cross-loaded), component 3 (single loading) and component 6 (total of two, one cross-loaded). Component 4 had three cross-loadings. Most of the components, loading on the multiple dimensions, were for R1 above waist measurements.

Reliability of the rating protocol was confirmed by calculating Cronbach’s alpha (Field 2009), which indicated a high level of internal consistency of 0.927. For this, the internal consistency of the items on the scale and selected factors was calculated, results shown in Table 31. Cronbach’s alpha indicated a high level of internal consistency with 0.927 statistic on all 27 items. On the other hand, when only factor 1 items were analysed (20 items), Cronbach’s alpha statistic improved to 0.958. Factor 2 items, when analysed separately, showed lower Cronbach’s alpha of 0.547, but the number of items was only three, which could be contributing to the lower score. Therefore, consideration should be given when designing the future studies to dropping low loading items and reducing the dimensions of the rating protocol, or re-designing it to provide more balanced components loading.

An additional factor analysis package, Factor (Lorenzo-Seva & Ferrando 2006), was used to re-analyse the data as SPSS has limited options in regards to the rotation. As polychoric correlations could not be estimated, the PA was conducted using Pearson correlation and oblique Promin rotation method. The Kaiser-Meyer-Olkin (KMO) test indicated 0.75464 (fair) statistic, and Bartlett’s
test of specificity was significant, 1554.4 (df = 351; P < 0.01). The results of PA are presented in Table 32. The PA recommended retaining one factor.

A communality report, shown in Table 33, was also examined to reflect the degree of an item’s variance by factor 1. Typically, all communalities below 0.4 should be considered for removal. The results should be taken into consideration for refinement of the rating protocol instrument.

### 9.2.5 Conclusion

This study demonstrated a dynamic manipulation method for adjustment of engineered repeating print formation with existing computer-aided design tools. Experimental testing of the method in comparison with mainstream production methods has proved its validity for
addressing key challenges of continuity of repeating print at seams and preservation of the design intent between graded sizes.

Non-destructive tools in Adobe CC software were used to generate a dynamic template for a base set of garment patterns and re-populate the template with repeating prints to generate RTP images. RTP images were then graded into three sizes, and garments were 3D simulated both for traditional matching techniques and the dynamic method. A performance rating protocol instrument was created for the study. Achieved performance in 3D garment simulations was rated on a Likert-type scale and statistically analysed.

For the dynamic method, 3D simulation of garments demonstrated improved matching of repeating print elements at garment seams with a significantly higher accuracy of matching compared to traditional method and, therefore, improved print continuity across seams. The dynamic method also allowed for the grading into three garment sizes with significantly improved preservation of the design intent between garment sizes by allowing repeats to retain position and relative proportion to the overall garment proportion. However, setting up a dynamic template in a 2D environment for the complex 3D shape might be challenging and would require separating the template into more manageable sections. Such separation might be a source of errors.

A limited number of attributes such as motifs number, colours number, edge length of print design and garment size were examined as factors affecting the adaptability of repeating prints for engineered printing method. Overall the DG group appeared to be much less affected by attributes of a specific repeating print compared to YG, with only Visual Proportion R5 reflecting the change in repeating prints on motifs number and edge length, and RTP Registration R7 on colours number.
Chapter 10 Stage Three

10. Stage Three

10.1. Discussion

The need for engineering of repeating prints comes from the realisation of the wastefulness of current practices used for matching of repeating print fabrics and cost-savings potentials from the adoption of the *engineered printing* (EP) method. The annual worldwide market for printed fashion fabrics is over $33 Billion and up to 30% is wasted due to print matching requirements (Geršak 2013; Ujiie 2012). EP offers more cost-effective use of materials and more sustainable manufacturing. Adoption of the EP approach as a mainstream manufacturing method is also important because it can allow for mass customisation of a fashion product and improved visual appearance of a printed garment.

One of the main goals of this research was to investigate opportunities for mass customisation fashion business to take advantage of progress in digital technologies and adopt the EP approach that supports integration of repeating prints with garments. Outcomes of this investigation are (a) the taxonomy model of repeating print attributes, (b) potential design directions for engineered repeating prints, (c) computer-aided design techniques, based on accessible software tools, for integration of repeating prints with garment patterns and (d) findings in relation to repeating print attributes as factors affecting their adaptability for the EP method.

As the result of this research, *computer-aided design* (CAD) techniques were developed for integration of repeating prints with garment patterns that can work with mainstream digital production. Textile designers can exploit proposed directions for development of engineered repeating prints or repeating prints more readily adaptable for EP. Fashion designers can integrate existing repeating prints with garment patterns or implement an integrated product development process for innovative fashion apparel. Software developers can use information on repeating print attributes in the development of dedicated programming solutions for EP or to upgrade the existing CAD applications. Mass customisation fashion business can increase differentiation and competitive edge of their product by improving the visual aesthetics, and implementing *Just-in-Time* (JIT) solutions and more sustainable manufacturing. Also, fashion and textile design educational institutions can expand their curriculum to support technical expertise required from modern practitioners to take full advantage of available digital technologies.

The engineered printing approach is not new, and is a form of engineered design process that has been widely accepted for apparel development. Examples of engineered design approach can be seen in the development of decorative elements such as placement prints and embroideries for mass-produced apparel, where design is composed to fit within a particular garment pattern. One-off fashion show garments often have surface decoration integrated with the whole shape of a garment. Knit garments often achieve shaping of the garment through integrated surface texture. The aesthetic advantages of such engineered approach for fashion applications are clear, but the engineered print design for the whole garment is still limited outside of the high-end market and mostly done for non-repeating prints. The main reasons for this limited application are that all of these methods could be technically difficult and usually require collaboration.
between designers and technicians. Also, often the application of engineered design is restricted by access to specialist software, as well as limitations in functionality or difficulties in the use of such software. In contrast, CAD techniques developed in this research intentionally utilised universal Adobe software. Popularity and familiarity of the users with Adobe applications are expected to facilitate implementation and further evolution of the suggested techniques.

Engineering of repeating prints with garment patterns is even more complex. In a typical apparel supply chain, textile prints are designed separately and printed well before a garment’s design. Repeating prints are constructed from elements organised in a systematic manner, which can make any deviation from it or interruptions in the flow of repeating print more easily noticeable. Furthermore, repeats could be composed of many motifs, and consistently engineering that many elements can be overwhelming as garment patterns are typically irregularly shaped. Nonetheless, once repeating prints have been integrated with garment patterns, *digital textile printing* (DTP) allows for printing of *Ready-to-Print* (RTP) images.

However, mass-produced garments are graded into a range of sizes. The grading changes pattern pieces to accommodate changes in body sizes, which are not proportional. This process results in different parts of a pattern changing at different rates, so re-engineering of print is needed for each size pattern. As the result, the technical aspect of required engineering in the absence of dedicated programming solutions has made the task impractical for mass fashion. However, this research attempted to investigate if recent developments in digital technologies such as DTP, CAD and the 3D virtual environment have opened up a possibility to change this situation.

Technological developments in manufacturing have been historically impacting textile design methods. Each technological stage introduced new textile print styles that reflected capabilities and limitations of this stage. EP is said to be one of the potential textile print styles that are particularly enabled by digital printing technology. The upsurge of the EP style is reflected in the popularity of digitally printed engineered garments in many fashion collections with non-repeating designs. This popularity and advantages of EP called for expanding the style to repeating prints. However, the technical complexity of the task justified a more analytical approach. This research had set out to apply such an analytical approach to facilitate engineering of repeating prints.

Stage One of this research started with the exploratory qualitative investigation into issues that are currently hindering the adoption of EP. The investigation began with a literature review on digital and mainstream technologies used for textile print design and manufacturing, which separated these issues into processing methods and attributes of repeating prints. An Applied Thematic Analysis (ATA) approach was then employed to compile a visual model of a code-tree of repeating print attributes by examining current practices and terminology for mainstream and digital pre-printing and printing processes (Guest, MacQueen & Namey 2012a). Subsequent interpretation of the code-tree allowed it to be refined into the repeating print attributes taxonomy.

Even though the diversity of the terminology was expected, the data collected through ATA demonstrated that, as a result of rich traditions and modern practices in textile and fashion design, often several meanings were assigned to the same word depending on the context, for example, *pattern* could mean *garment pattern* or *decorative pattern*. For this research, the use of the word *pattern* had been reserved for the former. Similarly, different words were used to represent the same concepts, for example, the words *yardage, motif, layout, grid* and *pattern* were
often placed together with repeat or used to replace repeat. Also, differences emerged between textile design and scientific or graphic software terminology for types of repeating prints. For example, common textile print repeat layouts such as block, drop and brick were based on the same symmetry operation, and in the case of graphic software they were referred to as Grid, Brick by Row and Brick by Column. All of these types were converted to a block layout swatch by the Pattern Fill tool (naming of the tool in Adobe Illustrator further demonstrated the previous point about pattern).

The code-tree facilitated the differentiation of these concepts and establishment of clear definitions for the attributes of repeating prints. The taxonomy hierarchy emerged, and the model was extracted. The quantifiable attributes of repeating prints were classified as belonging to one of three levels. Repeat system and repeat size (horizontal and vertical) were placed on a superordinate surface level. Foreground/background ratio, direction and motifs number were recognised as attributes at a basic repeat level. Inner symmetry, complexity (operationalised as edge length) and colours number were the attributes at a subordinate motif level. Experiments in Stage Two were proposed to investigate specific sets of repeating print attributes.

The literature review and code-tree development also led to the aggregation of information on potential design directions for engineering of repeating prints. Examination of this information allowed for the proposed three directions:

Modularity Design, in which a print is formed from repeating interchangeable modules. Modules can be used to construct higher level modules. Transformations can include finite, linear and planar symmetry operations or combinations of operations;

Flexible Tiling, in which a print repeat formation can be dynamically manipulated to fit within a garment pattern with a programming solution. Flexible Tiling programming solutions for adjustment of repeat formation should mostly change background elements while preserving and dynamically fitting foreground elements inside pattern pieces;

Distortion, which can be used to fine-tune fitting of a repeating print to a garment pattern, but should be used with caution as visual appearance might suffer from noticeable distortions.

The first Modularity Design direction proposed building the complete print design out of simpler parts that can be created separately, interchanged and combined as required to produce several variations of the final design. The application of the modularity concept for engineered design was suggested by Hann (2013) based on the application of the principle in the natural environment and man-made fields such as art, architecture or industrial sectors. This concept could be similarly applied to engineered repeating prints, where garment patterns become containers for complex configurations of repeating modules constructed out of a few simpler modules. The concept of a container is employed in Adobe applications in Symbol or Smart Object (Illustrator and Photoshop respectively) to indicate reusable self-contained objects, instances of which can be added to a document multiple times. The use of self-containing objects for a recurring module provides consistency, ease of editing and can significantly reduce file size for the complex prints. The objects can also be saved as external files or libraries, which facilitates distribution and reuse of such objects as templates. Instances of objects in a document are linked to a specific ‘master’
object. Any edits inside the container are instantly propagated to all instances of the object in a document.

Use of the Modularity Design method also relies on an understanding of the theories behind geometrical symmetry. There is a considerable amount of literature on the application of geometrical symmetry for the construction of repeating designs (Hann & Thomson 1992; Washburn & Crowe 1988). Four types of symmetry operations can be applied to modules: translation, rotation, reflection and glide-reflection.

Modules for engineered repeating prints can be constructed on all three levels of taxonomy. On a superordinate surface level, each garment pattern piece becomes a module that contains a combination of geometrically different and identical modules that each represent a basic level of repeats. Each repeat module can be constructed out of smaller modules that represent a subordinate level of motifs. The construction method then defines an overall composition. The same modules can be used in different structures resulting in visually different compositions. A similar approach was explored by Drudi and Haworth (2008) for the construction of repeating prints for one-piece garments such as wraps, shawls, scarves and sarongs, but with manual techniques demonstrated for the construction of repeating designs. The authors used reflection and rotation to compose a symmetrical rectangular block repeat from motifs, and applied translation and reflection to fill the garment shapes. Reflection was also applied to generate new symmetrical block repeats from arbitrary rectangular and triangular sections of completed designs.

Some programming solutions have been already suggested. Zamani, Amani-Tehran and Latifi (2009) developed a method to generate designs for a rectangular carpet shape out of design elements by an interactive genetic algorithm. Offered by the algorithm alternatives were then evaluated by the human participant and the ‘fittest’ combination evolved after a few generations. Proprietary plug-ins, for example, Artlandia’s SymmetryWorks, can facilitate visualisation of a rectangular shape filled with repeating designs. However, the intention of this research was to use readily available CAD software rather than proprietary plug-ins, as they might not be accessible to a wider community of users and require additional cost. Besides, even though plug-ins provide a user-friendly interface, they work by utilising the functionality of a host application. Additionally, garment patterns are mostly irregularly shaped. Furthermore, some garment patterns could be too complex to allow seamless tiling of modules, and further manipulation might be required to provide continuity of repeating print over garment seams and to accommodate grading of garments.

The second Flexible Tiling direction proposed that a print repeat formation can be manipulated to fit within a garment pattern. To optimise the fitting process, the elements of each repeat were prioritised on their importance to the overall print appearance. The appearance of more important elements was then preserved to maintain print appearance while less important elements were manipulated to fit repeat formations inside garment patterns. For example, repeating prints often have distinctive background and foreground elements that are disconnected. Repeats for such prints can be separated into foreground and background. Foreground elements can then be redistributed within the combined surface of pattern shapes.

Some approaches for manipulation of print formation have been reported. Briggs-Goode and Russell (2011) informed that research has started on a programming solution that can intro-
duce small random variations in the repeat formation. A generative software was used to place elements of print into a fabric-wide infinite non-repeating design (Russell 2014). This research however examined existing accessible Adobe applications for tools that are sensitive to and can accommodate variation in the repeat formation to optimise the fit. The tools that offered such functionality were Brushes and Blends. They are set to distribute an integer number of object’s instances over a path or space respectively. Brushes can be restricted to add additional space between objects or to subtract from that space without distorting the object. Blends can be restricted to generate a specified integer number of objects between the start and end of the blend, or place the intermediate objects at a specified distance. Both tools can control scale and, to a degree, the colouration of generated objects. The initial blend objects and brush definition work as self-contained objects, i.e. replacing them with an alternative replaces the objects in a brush stroke or a blend.

The third direction, Distortion, proposed to fine-tune the fitting of a repeat formation where regular or irregular repeat formation is not sufficient to fit a print into boundaries of garment patterns. It could work by applying small irregularities to each repeat shape. For example, the boundaries fitting method can grade RTP images from a base size into the full graded set. For printed textiles, similar irregularities in repeat shape are inevitably introduced when flexible fabrics are draped over the 3D body form. Various levels of distortion to surface print can occur in different parts of a garment depending on fabric properties and garment style. Some control over the draping of surface print is possible through the pattern design. However, repeating prints are not designed to accommodate flexibility of fabric, as mainstream printing methods require regular repeat formation. Also, prints are often designed before the specific fabric is selected, or the same design might be printed on a different substrate, which can have different draping properties.

In contrast, engineered printing and 3D simulation technology allow designing a print with a view of incorporating the draping of fabric over the body into the finished look of a garment. The method has been applied with highly elastic fabrics used for custom-made body-tight garments or for one-off fashion garments that were designed to accommodate draping fabrics (Parrillo-Chapman & Little 2012; Townsend 2004). However, the research was limited to non-repeating prints and the required manipulations were applied manually and individually to each design.

Adobe tools allow for both polynomial warping, done by mapping key points from the source to the destination image, and piecewise warping, done with a control mesh. The available tools in Illustrator and Photoshop were assessed based on the type of underlying approach. The choice of a tool then determined the use of vector or raster graphics. Also, the preference was given to tools that allow for non-destructive dynamic editing. Distortion is supported by both Adobe Illustrator and Photoshop though different tools employ different approaches discussed above. The polynomial warping can be done, for example, with Puppet Warp in Photoshop. Mesh warping is employed in Liquefy filter and Warp transformation in Photoshop and Envelope tool in Illustrator. The polynomial approach can work well with uniform grids, which define the structure behind repeating prints. While the grids can be formed from 3, 4 or 6-edged polygons, 4-edged polygons are most commonly used in uniform textile grids (popular block, brick and half-drop repeats are examples of such grids). If polynomial warping is selected as the Distortion method, and
supposing that a repeat tile corresponds to a polygon shape, when the image is warped, the edges of polygons get distorted. For distortions occurring on a pixel level, this fact can be ignored as the error, introduced by approximation of straight edges of initial polygons to possibly curved edges of resulting polygons, is small. During distortion of repeats to fit inside an irregular garment pattern shape, each rectangular pixel is transformed into a quadrilateral shape. Then the reconstruction process recalculates the resulting pixel colour, and a continuous image is displayed. Such an approach would require raster image and can be undertaken with the Puppet Warp tool in Photoshop. The tool though uses a visual triangular grid and more suitable for drastic but localised distortions. Fitting of a repeating print inside the garment pattern shape requires better precision control.

On the other hand, distortion with a control mesh transforms a uniform repeat structure by dragging the control points on the mesh or, if pre-defined warp style is selected, parametrically. Mesh is based on a quadrilateral grid and visually is easier to relate to a rectangular based uniform grid of repeating print. Liquefy filter in Photoshop uses a more free-form approach similar to painting and is better suited to retouching images or creating artwork. The Warp tool in Photoshop provides parametric control, but only for pre-defined warp styles, and the mesh resolution is limited to 3x3 grid with control handles at outside corners only, which is not sufficient for fitting repeating prints inside more complex garment pattern shapes. On the other hand, the Envelope tool in Mesh mode in Illustrator allows the creation of meshes with necessary grid resolution. Control handles are present at all anchor points, and additional control points can be created on mesh lines for extra fine adjustments. The tool also has an option of applying the distortion to Pattern Fill of the inside object. Envelope itself works as a container and will apply pre-set distortion to any content placed inside.

The experimental procedures were then designed to test and validate proposed potential directions as suitable for engineering of repeating prints. Stage Two was broken into four consecutive studies: one for each of the directions and the final study combining all three directions to engineer repeating prints for a graded garment. CAD techniques, based on existing tools of universal, accessible Adobe software, were suggested for each experiment. For each study, specific sets of repeating print attributes were nominated to be examined as factors affecting the adaptability of repeating prints for the EP method. The experiments then validated all three directions as suitable for engineering of repeating prints and data was collected for the subsequent statistical analyses.

Even though a substantial amount of literature can be found about manual and CAD techniques for repeating prints design or placement print design, not much is published about engineered prints. Also, available CAD-oriented literature mostly focuses on basic techniques for construction that are analogous to traditional manual techniques. For any automation of the repeating process, authors point towards proprietary plug-ins, such as Artlandia’s SymmetryWorks that work well for regular repeating prints. However, the decision was made not to use any additional software tools for the reasons discussed earlier. Engineered repeating prints are usually mentioned as a potentially superior method of manufacturing, but techniques are deemed too technically complex and practical application is limited to one-off fashion pieces. This research
aimed to suggest practical CAD techniques for mass-customised application of engineered repeating prints.

Although specific tools were selected to engineer repeating prints for each experiment, similar results could have been achieved with different combinations of tools. It was surprising to find that the range of available functionality in universal software, not specifically intended for textile print design, was diverse and provided many pathways to solve print engineering problems posed in experiments. This research found that, with the current level of accessible universal CAD technology, a fashion business should be able to develop design procedures to take advantage of more innovative and sustainable EP methods. The methods define boundaries of the domain practice (Li 1997; Moxey 1998), and CAD methods have progressed to allow expansion of the textile domain to the engineering of repeating prints.

10.2. Limitations of the Research

This research was based only on the tools of Adobe applications. Further limitations were noticed for each of these experiments:

- The Modularity Design demonstration was limited to a bandana repeating print contained in a single square shape. However, a similar approach can be taken with more complex shapes or surfaces constructed from shapes with adjoining boundaries as long as the required transformations are affine (i.e. preserve collinearity and ratios of distances).
- Flexible Tiling was demonstrated for a single garment pattern shape, with foreground elements of repeats pushed to fit inside boundaries of that shape. For a garment surface, constructed from multiple patterns, the boundaries of the entire surface move to the edges not connected to other edges. The seams of a garment, which connect edges of patterns, are therefore located within the boundaries of this surface. Repeating prints can flow over the seams, and adjustment in the repeat formation can be distributed over the entire surface. That effect was demonstrated in Experiment Four, where the Flexible Tiling method was employed for distribution of repeats.
- The second limitation of the Flexible Tiling experiment was related to the use of a repeat with a single asymmetrical motif. That drawback was imposed by the use of Adobe Paragraph Composer as a software solution to the presented design problem. The tool works by considering all breakpoints for a paragraph text and optimising spacing between characters and words in the lines of text to produce a visually balanced block of text. This tool’s functionality satisfied many desired characteristics. Ideally, the Flexible Tiling tool would be able to fill the available surface of a garment between boundaries by optimising the distances between foreground elements while placing them in a mostly regular grid and filling the remaining surface with background elements.
- The third shortfall, which was overcome in the following Distortion experiment, was related to a measurement error acquired during conversion from vector to raster graphics. The Flexible Tiling experiment used RGB colour space and JPG conversion. As the result, excessive noise was generated and detected in one-sample t-test that lead to the use of Greyscale colour space and TIFF conversion in the Distortion experiment.
• The Distortion experiment was restricted to assessing distortion in the narrow area along a side seam of a garment. The rationale for this decision was based on the understanding that draping of fabric over a 3D body naturally introduces distortion to any surface decoration. The experiment was designed to separate this naturally occurring distortion from the distortion resulting from engineering of repeat formations. The second limitation of the study was related to one of the variables - complexity of a repeating print. It was operationalised in this and the next experiment as edge length of elements in a repeat. However, the complexity of a repeat needs to be addressed more thoroughly in the future studies, as other dimensions might apply.

• The fourth and final experiment used a dress garment with the Front pattern with bust darts and Left and Right Back patterns. The garment had a semi-fitted waistline and A-line skirt. Due to the shaping of garment patterns, only partial flattening was possible when side and back seams were joined. The engineering of a repeating print was controlled in the below waist area and not controlled above the waist. To achieve control over the entire surface of the dress, the flattening could have been done in separate sections, and the sections assembled in an RTP image. Alternatively, a different combination of tools could have been employed for the Flexible Tiling part of the study. The engineering could also have been done to achieve a different final look, for example with lesser scaling of repeats. The repeats design, however, would have to be altered to reconstruct the elements that are trimmed along the repeat’s perimeter. The repeat then would have an irregular boundary.

• The rating protocol was developed for the fourth experiment with the aim of measuring two main ‘3D print design continuity’ and ‘Preservation of the design intent’ constructs. Each of the two constructs had three dimensions, with a few measurements taken for each dimension. The third construct, ‘Tile fidelity’ was also explored. The protocol had 27 items in total, which were rated on a 5 point Likert-type scale. A principal components analysis was conducted to verify the construct validity of the protocol. Six components were retained as a result of the analysis, explaining 75.81% of the total variability for all variables. However, 44.89% of total variability was explained by the first component. Component 1 had the highest number of loadings on a single dimension (total of 20, three of them cross-loaded), followed by component 2 (total of three, one cross-loaded), component 5 (total of two, one cross-loaded), component 3 (single loading) and component 6 (total of two, one cross-loaded). Component 4 had three cross-loadings. Most of the components, loading on the multiple dimensions, were for R1 above waist measurements.

• Reliability of the rating protocol was confirmed by calculating Cronbach’s alpha (Field 2009), which indicated a high level of internal consistency of 0.927 on all 27 items. On the other hand, when only factor 1 items were analysed (20 items), Cronbach’s alpha statistic improved to 0.958. Therefore, consideration should be given when designing the future studies to dropping low loading items and reducing the dimensions of the rating protocol, or re-designing it to provide more balanced components loading.

• The CAD techniques, demonstrated in this research, assume that engineered repeating prints are printed on fabric with stable dimensions. In reality, textiles can change dimen-
sions as a result of a printing or fixing stage or some other processing involved. This dimensional change is however outside of the scope of this research. As a suggestion, it can be handled with calibration of the printer for a specific fabric.

10.3. Findings in Relation to Repeating Print Attributes

The experimental stage, apart from validating potential directions for engineering of repeating prints and suggesting practical CAD techniques, aimed at collecting empirical data about relationships between repeating print attributes and their impact on the adaptability of repeating prints for the EP method. Each of the experiments focused on specific variables. The following relationships were observed:

Repeat size was observed to have a negative impact on the fitting of more important foreground elements of a repeat inside a garment pattern in the Flexible Tiling experiment. Both traditional and dynamic methods were affected. However, dynamic methods demonstrated significantly improved performance compared to traditional matching methods. In the Distortion experiment, no significant linear relationship was detected between repeat size and continuity of print between repeats across a seam. This result was explained for the distortion group by the used CAD method: distortion mesh was generated to map a rectangular shape to garment pattern boundaries. The various repeat sizes then became a texture of this rectangular shape that had no significant effect on continuity of print across the garment seam. For the control group, where only the alignment of repeats was possible across the garment seam, the continuity appears to be randomised due to differences in repeat designs.

Foreground and background distributions were examined in the Flexible Tiling experiment. In both groups distributions exhibited evidence of normality, however, outliers were observed that were explained by cases with heavy foreground elements. Repeats with more background and lighter foreground elements performed better when fitted to a garment pattern shape. The repeating prints with clear separation between background and foreground elements and lower foreground to background ratio are expected to be more adaptable for print engineering.

The complexity of repeat, which was operationalised as edge length of the repeat’s elements, negatively affected continuity of print between repeats in the Distortion experiment for both groups. Fitted linear regression models demonstrated better performance by the dynamic group in the tested range. However, as the complexity of repeats increased, the performance between groups became more similar, and for very complex repeats the linear models projected better performance by the control group. This result was explained for the control group by the lower probability of continuity of print between repeats for more complex repeats in general. For the dynamic group, the results could be explained by the obtainable precision of generated distortion mesh. The dynamic group results can be improved with the ability to control mesh points with more precision, for example through parametric input for specific points. In the final experiment, edge length had no significant correlation with accuracy of matching R1 for both groups. Even though the dynamic group had significantly better performance, the distributions of the means for both groups were approximately normal. In the yardage group, that could be explained by a randomly occurring match between elements of repeats as they are aligned at garment seams. In the dynamic group, even though the method provided for continuity of repeating print across
seams rather than alignment, accuracy of matching R1 had limitations imposed by the obtained precision of the method.

Motifs number was also assessed in the final experiment and showed no significant effect on accuracy of matching R1 for the dynamic group while in the yardage group it had a significant negative effect. Also, negative correlations were observed between RTP registration R7 and motifs number, colours number and edge length in the yardage group. As repeats were becoming more diverse and complex, it was becoming more difficult for the observer to notice differences in the registration of repeat’s elements between garments of different sizes. These results were however for Greyscale repeats, and repeats with the full range of colours might produce a different result. Opposite positive correlation in the dynamic group was observed for RTP registration R7 and colours, with no significant correlations between motifs number or edge length. Because the dynamic method allowed for identical repeat elements and relatively precise positioning of these elements in relation to garment patterns between different sizes, the only noticeable differences for RTP registration R7 came from the difference in colours.

For the dynamic group, negative correlation was also observed in Distortion experiment between continuity of print and the number of colours in repeat. With the increase in the number of colours, less precision was observed. Again, improvement could be attempted with better control over the distortion mesh. In the control group, the number of colours had no statistically significant correlation with continuity of print between repeats, performance was similar between different repeat designs and was comparable with the worse performance by the dynamic group. For traditional methods, it can be argued that apart from the registration issues that can affect the quality of repeating prints in mainstream printing methods, the number of colours has no significant effect on print alignment between repeats. In the final experiment, where continuity of print was assessed, the Flexible Tiling and the Distortion methods were combined to create a continuous repeating print across seams. Minimising the application of the Distortion method improved achieved continuity of print and colours number had no effect on accuracy of matching R1 for the dynamic group.

10.4. Recommendations and Future Research Directions

The suggested techniques require a certain familiarity with more advanced tools of Adobe and as such might present difficulties for beginners. Education more targeted towards technological aspects of textile design for practicing textile and fashion designers would be beneficial. This would include practical skills in the application of CAD and DTP technologies, and a better understanding of the capabilities and limitations of these technologies. The opportunities to use computer technology as design and analytical tools should be systematically presented to students and form part of regular activities.

The research highlighted the need for dedicated software solutions. As universal and proprietary software packages develop, the improvements of functionality will allow achievable outcomes to expand. Software developers though need to understand the required functionality of the tools to support the textile domain methods, rules and standards.

The future studies might address testing of similar techniques with more complex garments, in full colour and with a wider range of repeat designs. Other directions for development of engi-
 CHAPTER 10  STAGE THREE

Chapter 10 Stage Three

neered repeating prints or techniques may emerge with improvements in CAD tools and understanding of engineered design potential.

10.5. Conclusion

This research investigated the opportunities allowing mass customisation fashion business to implement the EP approach for repeating prints. The opportunities were identified in the development of innovative CAD techniques that employ advanced dynamic tools of universally available, popular and accessible software. With the techniques, RTP images can be generated and then printed with DTP technology.

First, this investigation consolidated terminology used in relation to repeating prints and provided the taxonomy of repeating print attributes organised by the surface, repeat and motif levels. The taxonomy allowed refinement of repeating print attributes into the concise set of quantitative variables.

Secondly, potential design directions for engineering of repeating prints were suggested and tested. The directions provided diverse approaches to finding design solutions for engineering of repeating prints that could also be combined.

Thirdly, practical CAD techniques, based on Adobe software tools, for integration of repeating prints with garment patterns were developed and tested. The techniques were demonstrated with specific tools, but could be expanded to a different combination of tools. The deficiencies of existing CAD tools were also highlighted. Exposed deficiencies can inform decisions by software professionals for the development of dedicated programming solutions for engineered repeating prints. Fashion designers can use suggested or similar techniques for integration of repeating prints with garments.

Finally, attributes of repeating prints were examined as factors affecting prints’ adaptability for the EP method. Relationships between the attributes and their impact on the adaptability of repeating prints for the EP method were statistically evaluated. These findings could assist textile designers in creating repeating prints that are more adaptable to the EP method. Fashion designers could assess existing repeating prints in regards to their adaptability. The findings can also help in the development of dedicated software.
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## Glossary and abbreviations

| **Action Panel** | Panel in Illustrator and Photoshop to record, play, edit, and delete individual actions |
| **Adobe Composer** | A tool that works by considering all breakpoints for a paragraph text and optimising spacing between characters and words in the lines of text to produce visually balanced block of text |
| **Adobe® CC** | Universal graphics software package. Illustrator, Photoshop and InDesign applications from the package were used in this research |
| **Appearance Panel** | Panel in Adobe Illustrator that allows application of fills, strokes, transparency and dynamic effects to any object, group or layer in a document in order to change their appearance without altering their underlying structure |
| **Blend tool** | Blend tool creates transitional objects and distributes them between two original objects, including two open paths with Brush stroke attribute applied, or two instances of Symbols. If original objects are edited or replaced, the Blend updates accordingly |
| **CAD** | Computer-aided design |
| **DTP** | Digital textile printing |
| **Distortion** | The third direction in this research |
| **Envelope tool** | A container, which can be made out of an object, a preset warp shape or a mesh grid. Anything placed inside such envelope is distorted in identical way. Envelopes can be edited independently from the contained inside objects |
| **EP** | Engineered printing |
| **Factor v9.2** | Factor analysis package software |
| **FT** | Flexible Tiling - the second direction in this research |
| **G*Power 3.1.9.2** | A general stand-alone power analysis program for statistical tests |
| **Histogram Panel** | A tool in Photoshop that provides tonal and colour information about images |
| **Illustrator** | A vector graphics application from Adobe CC package |
| **InDesign** | A desktop publishing software application from Adobe CC package |
| **JIT** | Just-in-Time |
| **KWIC** | Key-Word-in-Context |
| **MTM** | Made-to-Measure |
| **MS** | Mainstream printing methods, such as rotary and flatbed screen printing |
| **Measurement Log Panel** | The tool in Photoshop that records the measurements from Histogram panel |
| **Microsoft Excel** | A spreadsheet software |
| **MD** | Modularity Design - the first direction in this research |
| **PA** | Parallel analysis |
| **PDS** | Pattern Design Systems |
| **Pattern Brush tool** | Pattern Brush tool applies a repeat design along the path, and any updates to the definition of brush can be propagated to existing objects carrying that attribute. |
| **Pattern Fill tool** | Repeating fill tool in Illustrator |
| **Photoshop** | A raster graphics software from Adobe CC package |
| **PCA** | Principal components analysis |
| **PD** | Product Development |
| **RIP** | Raster Image Processing |
| **RTP** | Ready-to-Print |
| **RGB** | Red, Green, Blue |
| **Smart Filters** | Non-destructive effects in Photoshop |
| **Smart Objects** | Reusable self-contained objects in Photoshop, instances of which can be added to a document multiple times |
| **SPSS** | A software package used for statistical analysis |
| **Symbol** | Reusable self-contained objects in Illustrator, instances of which can be added to a document multiple times |
| **Transform Effect** | Transform effect allows application of affine transformations as appearances to a source object or to the required number of copies of the source object. |
| **VStitcher v.6.0** | 3D virtual prototyping software |
| **Warp tool** | Type of distortion used in Photoshop and Illustrator |
| **Wolfram Mathematica** | A symbolic mathematical computation program, used in many scientific, engineering, mathematical, and computing fields. |