CREATION OF
3D DIGITAL PRINTED FASHION
PROTOTYPE WITH
INNOVATIVE SURFACE TEXTURE

CHAN HIU SEN

PhD

The Hong Kong Polytechnic University

2019

The Hong Kong Polytechnic University

Institute of Textiles and Clothing

CREATION OF 3D DIGITAL PRINTED FASHION PROTOTYPE WITH INNOVATIVE SURFACE TEXTURE

CHAN HIU SEN

A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy

June 2018

CERTIFICATE OF ORIGINALITY

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written, nor material that has been accepted for the award of any other degree or diploma, except where due acknowledgement has been made in the text.

CHAN Hiu Sen

ABSTRACT

Recent studies have indicated that three-dimensional printing technology benefits the design process and is defined as a breakthrough in the manufacturing process. Three-dimensional printing has come into wide use in different industries as well as fashion industry. Fashion or textile designers adopt 3D printing technology as their creative design tools, such as creating 3D printed garments, 3D printed fabrics or fashion accessories. 3D printers can practically create anything, hence they give designers wide imaginary space and produce creative products. It can be predicted that 3D printing technology will be rapidly applied and play an important role in fashion industries in the future.

This research study is practice-based, which combines the theories of 3D printing technologies, practical concept and physical prototype development of 3D printed fashion with innovative surface texture that could be able to apply in current fashion market. The aim of this study is to develop a high-value fashion prototype with an innovative coloured surface texture by using 3D printing technology, based on a theoretical design process model.

The research was mainly divided into four stages: research stage, development of the design process model, development and evaluation of the initial prototypes, and detailed design stage. A final 3D printed fashion prototype with innovative texture was then created according to the developed design process model. The knowledge of aesthetic and technical aspects of

3D printing technology and a specific design process model were integrated in this study; thus, both theoretical and practical contribute to the field of 3D printed fashion design to illustrate the innovative design process for 3D printed fashion. The developed theoretical design process model for 3D-printing-based fashion with innovative surface texture can be implemented to contemporary fashion and the high value 3D printed prototype can enhance novelty in high fashion and inspire fashion designers to create successful 3D printed designs for the market.

PUBLICATIONS GENERATED FROM THIS STUDY

Conference Paper

Chan, I., Au, J., Ho, C.P. & Lam, J. Development of Theoretical Process Model for 3D Printed Fashion Prototypes with Innovative Surface Texture. *Proceedings of the 14th Asian Textile Conference, The Hong Kong Polytechnic University, Hong Kong.* Date: 27 – 30 Jun 2017.

Chan, I., Au, J., Ho, C.P. & Lam, J. Design and Development of Multi-coloured 3D Printed Fashion Garment with Innovative Surface Texture. *Proceedings of the International Conference on Clothing and Textiles 2018, Seoul*. Date: 26 May 2018. *Remark: Winner of 2018 ICCT Graduate Student Research Competition.*

Exhibition

Chan, I., Au, J., Ho, C.P. & Lam, J. Creation of 3D Digital Printed Prototype with Innovative Surface Texture. *Opening Ceremony of the University Research Facility in 3D Printing, The Hong Kong Polytechnic University, Hong Kong.* Date: 19 Apr 2017.

Chan, I., Au, J., Ho, C.P. & Lam, J. 3D Multi-coloured Printed Fashion. *PolyU 80th Anniversary Open Day: PolyU Research Showcase: Human-centered Innovation (Design & Textile), The Hong Kong Polytechnic University, Hong Kong.* Date: 2 – 3 Dec 2017.

Chan, I., Au, J., Ho, C.P. & Lam, J. 3D Multi-coloured Printed Bottom Dress. *PolyU 80th Anniversary Open Day: PolyU IC 3D Printing Lab Tour Guide Showcase, The Hong Kong Polytechnic University, Hong Kong.* Date: 2 – 3 Dec 2017.

Invited Speech

Chan, I., Au, J., Ho, C.P. & Lam, J. Development of 3D Printed Fashion Prototype with Innovative Surface Texture. *Fashion Business Seminar Series 2018: Introduction to 3D Printing - Future of the Fashion Industry? The Hong Kong Polytechnic University, Hong Kong.* Date: 6 Feb 2018.

ACKNOWLEDGEMENTS

I would like to express my appreciation to my chief supervisor Dr. Joe Au for his valuable guidance and suggestions throughout the research. Without his expertise and support, I would not have been able to complete this thesis.

Secondly, I would like to acknowledge a studentship received from The Hong Kong Polytechnic University Postgraduate Research Grant and offer my thanks to the material sponsorship from Stratasys AP Limited.

I would also like to thank Ir. Sidney Wong and Mr. Frankie Chan of Industrial Centre of The Hong Kong Polytechnic University for their technical assistances.

Last but not least, I would like to express my thanks to my mom for her support and encouragement throughout my study.

TABLE OF CONTENTS

CERTIFICATE OF ORIGINALITY i

ABSTRACT ii

PUBLICATIONS GENERATED FROM THIS STUDY iv

ACKNOWLEDGEMENTS vi

TABLE OF CONTENTS vii

LIST OF FIGURES xvi

LIST OF TABLES xx

CHAPTER 1: INTRODUCTION 1

1.1 Background of Study 1

1.1.1 Importance of 3D Printed Fashion and Textile Design 2

1.1.2 Definition of 3D Printing 3

1.1.3 Definition of Surface Texture 3

1.2 Problem Statement 4

1.3 Objectives 5

1.4 Research Methodology 6

1.4.1 Research Review 6

1.4.2 Development of Design Process Model 7

1.4.3 Development and Evaluation of Initial Prototypes 7

1.4.4 Development of Final Prototype 7

1.5 Significance of Study 8

CHAPTER 2: LITERATURE REVIEW..10

2.1 Introduction 10

2.2 Introduction to 3D Printing 10

2.2.1 Historical Background of 3D Printing 11

2.2.2 Significance of 3D Printing Technologies................................. 12

2.2.2.1 Customisation 12

2.2.2.2 Energy Savings.. 13

2.3 Three-Dimensional Printing Methods... 13

2.3.1 Photopolymerisation 13

2.3.1.1 Stereolithography 14

2.3.2 Extrusion Deposition... 14

2.3.3 Material Jetting 15

2.3.4 Granular Material Binding 15

2.3.5 Binder Jetting.. 16

2.3.6 Directed Energy Deposition 16

2.3.7 Sheet Lamination 17

2.3.8 Three-Dimensional Printing Pen... 17

2.3.9 Summary of 3D Printing Methods.. 18

2.4 Three-Dimensional Printing Technologies....................................... 19

2.4.1 Three-Dimensional Printing Materials...................................... 19

2.4.2 Software.. 20

2.4.2.1 Three-dimensional Modelling.. 21

2.4.2.2 Texturing in 3D Modelling 22

2.4.2.3 Rendering... 23

2.4.3 Post-processing 23

2.4.4 Colour Printing Methods for 3D Objects 23
2.4.4.1 Direct Colour Printing Using 3D Printers 23
2.4.4.1.1 Powder-Binder 3D Printers 24
2.4.4.1.2 Layer-laminated Printers.. 25
2.4.4.1.3 PolyJet 3D Printers 25
2.4.4.2 Dyeing 26
2.4.4.3 Electroplating or Anodising 26
2.4.4.4 Hydrographic Transfer Printing 27
2.5 Current 3D Printed Products with Coloured or Texturised Surfaces. 28
2.5.1 Fashion Garments and Textiles 28
2.5.1.1 Black Drape Dress... 28
2.5.1.2 N12 Bikini 29
2.5.1.3 Stained Glass Corset.. 29
2.5.1.4 Hard Copy.. 30
2.5.1.5 Three-Dimensional Printed Swimwear 30
2.5.1.6 Dita's Gown 31
2.5.1.7 Designer Iris van Herpen... 31
2.5.1.8 Wearable Skins... 33
2.5.2.9 3D Printed Fashion Collection at Home............................. 33
2.5.2.10 Multi-material 3D Printed Oscillation Dress 34
2.5.1.11 3Doodled Seashell Lace Dress.. 34
2.5.2.12 Three-Dimensional Printed Textiles................................. 35
2.5.2.13 Three-Dimensional Printed Fabrics on the Runway 35
2.5.2.14 Metallic Space Fabric 36
2.5.3 Product Design.. 36

2.5.3.1 Molecular Shoes 36
2.5.3.2 Adhesive Joint Development 37
2.5.3.3 Three-Dimensional Printed Furniture 37
2.5.3.4 3D Printed Dazzle Lighting 38
2.5.3.5 Petfig: Creating 3D Printed Sculptures 38
2.5.3.6 3D Printed Replica Based on 3D Body Scanning 39
2.5.3.7 MirrorMe3D 39
2.6 Use of Three-Dimensional Printing for Creating a Fashion Prototype 40
2.6.1 Three-Dimensional Body Scanning 40
2.6.1.1 Background of 3D Body Scanning 40
2.6.1.2 Principle of 3D Body Scanner 41
2.6.2 Ergonomics 41
2.6.2.1 Definition of Ergonomics 41
2.6.2.2 Ease Allowance 42
2.7 Research Gaps 46
2.8 Conclusion 47

CHAPTER 3: RESEARCH METHODOLOGY 48

3.1 Introduction 48
3.2 Definition of Practice-Based Research Methodology 49
3.3 Background of Practice-Based Research Methodology 50
3.4 Development of Theoretical Design Process Model 50
3.4.1 Problem Identification 51

3.4.2 Defining the Problem 51
3.4.3 Studying the Problem and Searching for Alternative Solutions. 52
3.4.4 Evaluation 52
3.4.5 Specification of Solutions 53
3.4.6 Communication of Solution 53
3.5 Review of Theoretical Design Process Model 53
3.5.1 Design Process Model in Fashion and Textile Design 54
3.5.1.1 Orlando's (1949) Design Process Model 54
3.5.1.2 DeJonge's (1984) Design Process Model 54
3.5.1.3 Watkins's (1988) Design Process Model 55
3.5.1.4 Lamb and Kallal's (1981) Design Process Model 55
3.5.1.5 Regan, Kincade and Shelden's (1998) Design Process Model 55
3.5.1.6 LaBat and Sokolowski's (1999) Design Process Model 56
3.5.1.7 Summary of the Design Process Model used in Fashion and Textile design 56
3.5.2 Design Process Model in Architecture and Environment Design 58
3.5.2.1 Koberg and Bagnall's (1973) Design Process Model 58
3.5.2.2 Broadbent's (1984) Design Process Model 58
3.5.2.3 Zeisel's (1984) Design Process Model 59
3.5.2.4 Summary of the Design Process Model used in Architecture and Environmental design 59
3.5.3 Design Process Model in Engineering and Industrial Design 61
3.5.3.1 Asimow's (1962) Design Process Model 61

3.5.3.2 Jones's (1970) Design Process Model 62

3.5.3.3 Lawson's (1980) Design Process Model 62

3.5.3.4 Archer's (1984) Design Process Model 62

3.5.1.5 Cross and Roy's (1989) Design Process Model 63

3.5.1.6 Hollins and Pugh's (1990) Design Process Model 63

3.5.1.7 Ehrlenspiel and Dylla's (1993) Design Process Model 63

3.5.1.8 French's (1999) Design Process Model 63

3.5.2.9 Takala, Keinonen and Mantere's (2006) Design Process Model 64

3.5.3.10 Pahl, Beitz, Feldhusen & Grot's (2007) Design Process Model 64

3.5.2.11 Summary of the Design Process Model used in Engineering and Industrial design 64

3.6 Development of Theoretical Design Process Model for 3D Digital Printed Fashion with Innovative Surface Texture 67

3.6.1 Analysis 67

3.6.1.1 Problem Definition 68

3.6.1.2 Identification of Sub-problems 68

3.6.2 Synthesis 68

3.6.2.1 Investigation of the Problem 69

3.6.2.2 Conceptual Design 69

3.6.2.3 Determination of Solutions 70

3.6.2.4 Searching for Alternatives 71

3.6.2.5 Development of Prototypes 71

3.6.3 Evaluation 71

3.6.3.1 Evaluation of Initial Prototypes and Decisions................... 71

3.6.3.2 Detailed Design with Specifications 72

3.7 Conclusion... 73

CHAPTER 4: DEVELOPMENT AND EVALUATION OF INITIAL PROTOTYPES...74

4.1 Introduction 74

4.2 Design Inspiration of the Colour Theory 75

4.2.1 Colour Wheel.. 77

4.2.2 Colour Harmony and Colour Schemes 78

4.3 Creation of Colour Patterns.. 80

4.4 Design Creation in 3D Modelling 83

4.5 Texture Mapping on Meshes 84

4.6 Development of Initial 3D Printed Prototypes................................. 85

4.6.1 Three-dimensional Printing Materials....................................... 85

4.6.1.1 Assessment of 3D Printing Materials................................. 87

4.6.1.1.1 Colour Performance of Plaster and Resin Prototypes87

4.6.1.1.2 Tactile Sensation of Plaster and Resin Prototypes.... 88

4.6.1.1.3 Mechanical Properties of Plaster and Resin Prototypes 89

4.6.1.1.4 Weight Comparison of Plaster and Resin Prototypes 91

4.6.1.2 Summary of 3D Printing Materials.................................... 91

4.6.2 Pattern Density Design.. 92

4.6.2.1 Assessment of Pattern Density Design............................... 93

4.6.2.2 Summary of Pattern Density Design 94

4.6.3 Colours 95

4.6.3.1 Colour Assessment 99

4.6.3.2 Summary for Colours 102

4.6.4 Initial 3D Printed Prototypes of Interlocks and Joints 102

4.6.4.1 Initial 3D Printed Interlock Prototypes............................ 102

4.6.4.1.1 Interlock Design Concepts 103

4.6.4.1.2 Interlock Assessments... 105

4.6.4.2 Initial 3D Printed Joint Prototypes.................................. 106

4.6.4.2.1 Joints Assessments.. 107

4.6.4.3 Alternative Interlock Solutions 110

4.6.4.4 Summary for Interlocks and Joints...................................110

4.7 Conclusion...111

CHAPTER 5: CREATION OF A 3D PRINTED FASHION PROTOTYPE WITH INNOVATIVE SURFACE TEXTURE............112

5.1 Introduction 112

5.2 Preparation for 3D Modelling of the Final Prototype......................112

5.2.1 Ease Allowance Through 3D Body Scanning 114

5.3 Detailed Design with Specifications..115

5.3.1 Design Considerations for the Final 3D Printed Prototype.......115

5.3.2 Panel Cutting 118

5.3.3 Silhouette and Texture Density... 123

5.3.4 Shell Thickness 125

5.3.5 Joints and Interlocks 129
5.3.6 Colouration and Texture Mapping 130
5.3.7 Materials and 3D Printing Process 133
5.4 Presentation of the Garment 135

CHAPTER 6: CONCLUSION 138

6.1 Introduction 138
6.2 Conclusions Regarding Research Problems 138
6.3 Contributions 139
6.3.1 Contributions to Theoretical Research 139
6.3.2 Contributions to Practical Research 142
6.4 Study Limitations 144
6.5 Implications for Future Research 146

APPENDICES 149
Appendix I Colour variations generated by Colour Wheel Pro 149
Appendix II Data sheet of Vero and plaster 151
Appendix III Data sheet of tough PLA and material performance of ABS, PLA and tough PLA 153
Appendix IV Details of the 3D modelling process 154
Appendix V Safety data sheet of Vero 157

REFERENCES 159

LIST OF FIGURES

Figure 1.1 Categorisation of Texture 3

Figure 2.1 Three-dimensional printed colour charts 24

Figure 2.2 Colour objects produced by MCor IRSI HD 3D printer.............25

Figure 2.3 3D PolyJet printing process 25

Figure 2.4 Hydrographic printing process..27

Figure 2.5 Black Drape Dress..28

Figure 2.6 N12 Bikini..29

Figure 2.7 Stained Glass Corset..29

Figure 2.8 Hard Copy...30

Figure 2.9 3D Printed Swimwear...30

Figure 2.10 Dita's Gown...31

Figure 2.11 Crystallisation Collection..31

Figure 2.12 Escapism Collection 31

Figure 2.13a Skeleton Dress Figure 2.13b Cathedral Dress........................32

Figure 2.14 Liquid Dress..32

Figure 2.15 (a) Voltage Collection, (b) Biopiracy Collection, and (c) Magnetic Motion Collection...32

Figure 2.16 Wearable skins..33

Figure 2.17 3D printed fashion collection by Peleg...................................33

Figure 2.18 Oscillation Dress 34

Figure 2.19 3Doodled Seashell Lace Dress..34

Figure 2.20 3D printed weave structure 35

Figure 2.21 3D printed knitwear 35

Figure 2.22 Metallic space fabric..36
Figure 2.23 Molecular Shoes...36
Figure 2.24 3D printed foldable form..37
Figure 2.25 Puzzle Chair 37
Figure 2.26 Dazzle Lamps..38
Figure 2.27 Process of Petfigs..38
Figure 2.28 3D printed replica 39
Figure 2.29 MirrorMe3D...39
Figure 3.1 Theoretical design process model for 3D digital printed fashion with an innovative surface texture 73
Figure 4.1 Electromagnetic spectrum...75
Figure 4.2 CYMK and RGB 76
Figure 4.3 Munsell's colour system 76
Figure 4.4 Colour hue code in NCS system..77
Figure 4.5 Colour values and shades proportion in NCS system................77
Figure 4.6 Primary colour chosen in NCS system 81
Figure 4.7 Segmentation of the design pattern and after filling in colours in triadic colour scheme..81
Figure 4.8 Creation of basic object 83
Figure 4.9 Creation of 3D object by Para 3D 83
Figure 4.10 a) Star shape design, b) rectangular based design, c) triangular based design 83
Figure 4.11 Texture mapping by UVW map..84
Figure 4.12 UVW unwrapping and render to texture process 84
Figure 4.13 The light reflection on matte and gloss surfaces 87

Figure 4.14 Tensile strength..89

Figure 4.15 Elongation at break...89

Figure 4.16 Flexural strength...89

Figure 4.17 Flexural modulus...90

Figure 4.18 Connecting method of the spire dress...................................103

Figure 4.19 Interlock designs of 3DTi...103

Figure 4.20 The design and measurement of interlock 104

Figure 4.21 Deformation of the 1-mm prototype......................................105

Figure 4.22 Method of assessment a) slipping upwards and downwards, b) twisting 107

Figure 4.23 a) Long jaw digital calliper b) point jaw digital calliper 107

Figure 4.24 The position of twisting angle..107

Figure 4.25 The breakage on resin joint..110

Figure 4.26 Neoprene Interlock and after joining with joints....................110

Figure 4.27 Summary of Chapter 4...111

Figure 5.1 Scanning a size 10 dummy by 3D body scanner......................112

Figure 5.2 A 3D mesh of a size 10 dummy scanned by 3D body scanner .113

Figure 5.3 Before and after repairing meshes on the size 10 dummy’s 3D model 113

Figure 5.4 The original size 10 dummy and 3D model after adding ease..114

Figure 5.5 Body map of affordable load values for different body parts...116

Figure 5.6 The panels’ design draft on the size 10 dummy 121

Figure 5.7 Fashion illustration and production drawings of the final fashion prototype...122

Figure 5.8 Dummy’s 3D model with reference template 123

Figure 5.9 The creation process of panels by PolyDraw tool....................124

Figure 5.10 Texture created by Para 3D..124

Figure 5.11 Defects on the shell thickness 2-3 mm on hollow area...........127

Figure 5.12 Position marking of the joints 129

Figure 5.13 Texture mapping by materials editor 130

Figure 5.14 A UV map of one of the small segments................................130

Figure 5.15 The render pictures of the final 3D model 132

Figure 5.16 The working screen print picture of PolyJet Studio 133

Figure 5.17 Different views of the final 3D printed fashion prototype......136

Figure 5.18 Details of the final 3D printed fashion prototype...................137

Figure 6.1 Combination of rigid and soft resin prototype 147

LIST OF TABLES

Table 2.1 Summary of 3D printing methods..18

Table 2.2 Suggested ease allowances 44

Table 2.3 Ease allowance for different clothing positioning 45

Table 3.1 Summary of the design process model used in fashion and textile design...57

Table 3.2 Summary of the design process model used in architecture and environmental design...60

Table 3.3 Summary of the design process model used in engineering and industrial design 65

Table 4.1 Summary of Colour Schemes 79

Table 4.2 Colours involved in each colour scheme.....................................82

Table 4.3 Plaster and resin prototypes..86

Table 4.4 Mechanical properties specification of plaster and resin 91

Table 4.5 Summary of plaster and resin prototypes 92

Table 4.6 Pattern density design of prototypes 93

Table 4.7 Summary of pattern density design...94

Table 4.8 Initial 3D printed prototypes with monochromatic colour scheme 96

Table 4.9 Initial 3D printed prototypes with analogous colour scheme 96

Table 4.10 Initial 3D printed prototypes with complementary colour scheme 97

Table 4.11 Initial 3D printed prototypes with split complementary colour scheme 97

Table 4.12 Initial 3D printed prototypes with triadic colour scheme...........98

Table 4.13 Initial 3D printed prototypes with tetrad colour scheme............98

Table 4.14 Interlock assessments 106

Table 4.15 Joint design renderings...106

Table 4.16 Joint assessment of slipping upwards and downwards 109

Table 4.17 Joint assessment of twisting..109

Table 5.1 Size 10 dummy measurements before and after ease allowances

....114

Table 5.2 Comparative material consumption of an integrated panel and a

panel divided into four...120

Table 5.3 Number of rows (1D) and columns (2D) in each panel 125

Table 5.4 Panel weights 128

Table 5.5 Estimated consumption of materials and time...........................134

CHAPTER 1: INTRODUCTION

1.1 Background of Study

Recently, businesses of all sizes and across a wide range of industries such as the footwear, jewellery, automotive, aerospace, and defence industries have started using 3D printing technologies, and the fields in which these technologies are being used include industrial design, fashion design, medicine, and architecture. Furthermore, research is being conducted on the use of these technologies for the production of products such as human bones, nanoscale machines, and aircraft parts (Iancu, Iancu & Stăncioiu, 2010; Taylor & Unver, 2014). Three-dimensional printing technologies help improve the design and manufacturing process of industries by the application of different aspects and simplifying different operations of industries, such as the replacement of assembly lines of production with a single-step process for minimising complicated manufacturing steps, digitalising designs for eliminating the process of transforming information into materials, customising products of different types and in a range of sizes for minimising additional costs, and reducing labour requirements (Campbell, Williams, Ivanova & Garrett, 2011). The technologies impact the environment as well as the socioeconomic status, demographic data, geopolitics, and home security; moreover, they have implications for creative industries, designers, and artists (Campbell et al., 2011; Ratto & Ree, 2012). It can be predicted that applications of 3D printing will continue to increase rapidly in the future.

1.1.1 Importance of 3D Printed Fashion and Textile Design

The Economist (2011) identified 3D printing as 'the manufacturing technology that will change the world', and recently, 3D printing was defined as one of the transformative technologies in history. Three-dimensional printing technologies have facilitated breakthroughs and influenced various fields, with their influence extending from the design process to the manufacturing process and the production of finished products. In particular, 3D printing has revolutionised the process of design; while traditionally, design and manufacturing processes have been clearly defined and demarcated, the use of 3D printing in designing has resulted in designers being involved in the determination of ways to transform 2D concepts (computer-aided design (CAD)/computer-aided manufacturing (CAM) processes) into 3D objects (real products), and participating in manufacturing processes (Petrick & Simpson, 2013). Specifically, 3D technologies modify the initial steps in the design of a product, and they may be said to reverse the concept of *designing for manufacturing* to *manufacturing for designing* (Beaman, 2015). Rifkin (2012), an American economic and social theorist, labelled 3D printing technology as 'the third Industrial Revolution'. Some innovative companies already provide support to commercial businesses for rapid prototyping and offer an online sharing platform for designers to easily generate and share ideas. Three-dimensional printing technologies have become popular in not only the manufacturing industry but also the fashion industry, and they are now an integral part of the fashion industry, being employed by many fashion and textile designers. Lipson and Kuman (2013) defined a 3D printer as a machine that can produce almost anything. Recently, in the fashion and textile industries, 3D printing has been used to produce fabrics that evoke various human sensations upon being worn by a person; it has also been used to produce products such as fashion lifestyle products and accessories. Designers use 3D printing as a creative tool in clothing production.

1.1.2 Definition of 3D Printing

Three-dimensional printing is an additive basic manufacturing technique. During the manufacturing process of a product, materials are successively assembled on one cross-sectional layer at a time, with the final product comprising of many layers (Campbell et al., 2011).

1.1.3 Definition of Surface Texture

If 3D objects are to be highly reflective, they should have appropriate surface spatial organisation, which is qualitatively described using terms such as fine, coarse, linear, and irregular. These terms represent the surface texture. A rough surface texture is characterised by a surface pattern deviating from the pattern of a plane surface and showing irregularities. A pattern can be formed and periodically repeated for realising rough, wavy, and lay textures or identifying flaws (Brosheer, 1948; Haralick, 1979).

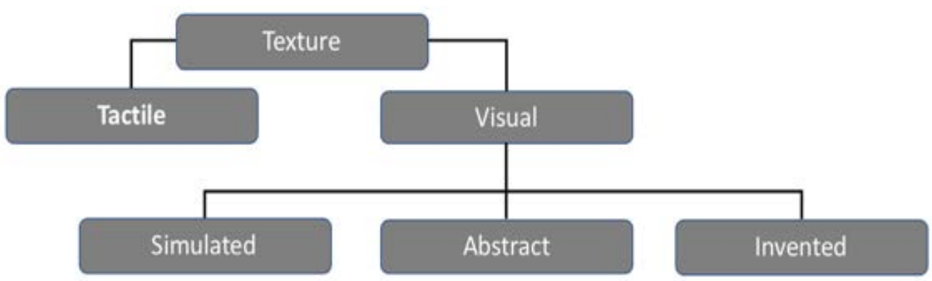


Figure 1.1 Categorisation of Texture

Texture can be categorised into tactile and visual textures (Figure 1.1). Tactile is defined as tangible surface texture of the original object that can be sensed, felt and seen by touching and seeing (Ocvirk, Stinson, Wigg, Bone & Cayton, 2002; Pipes, 2004). Visual texture is defined as sensation perception of the surface that the texture sensed by imagination. It can be sorted into simulated texture, abstracted texture, and invented texture. Simulated texture is unreal, but it can trigger one's memories and feeling of the real object without sense of touch, such as texture presented in photography. Abstracted texture is developed by modification from the real object's texture with associations, such as the texture of leopard print. Invented texture is created without any associations with reality (Pipes, 2004).

1.2 Problem Statement

This practice-based study used the theories of 3D printing technologies to develop a practical concept of fashion designing and produce a physical prototype of a high-value fashion design. The technologies and their applications were comprehensively investigated for the possible use of identify technologies appropriate for designing fashion garments with innovative surface textures. A practical 3D-printed prototype was finally produced. The latest 3D printed products in the fashion, textile, and product design markets were reviewed, together with the 3D printing technologies and their applications. Such a review was necessary to acquire conceptual knowledge for identifying problems and initiating a problem-solving process; the review was also crucial for integrating 3D printing technologies with fashion designing for producing 3D fashion garments with specific innovative surface textures considering the aesthetic and ergonomic requirements of high-value contemporary fashion garments.

1.3 Objectives

The main objectives of this study were to develop a fashion prototype with an innovative coloured surface texture by using a 3D printing technology, and to apply ergonomics to the design and development of high-value fashion prototypes, on the basis of a theoretical design process model developed in the present study. The objectives of the present study were as follows:

a) to review relevant theoretical design process models;
b) to study the latest 3D printing technologies and related CAD/CAM process;
c) to explore colour 3D printing methods that can be used to create an innovative texture;
d) to examine the latest 3D-printed fashion products in the market;
e) to investigate the ergonomic factors related to 3D-printed fashion prototypes;
f) to study the 3D body scanning technologies suitable for developing 3D printed fashion prototypes;
g) to develop a theoretical design process model for developing 3D printed fashion prototypes with an innovative surface texture;
h) to create and assess initial 3D printed prototypes on the basis of the theoretical design process model developed in this study; and
i) to create a final fashion prototype with an innovative surface texture.

1.4 Research Methodology

A practice-based research methodology was adopted in this study, and the main focus was the design practice. A self-reflective evaluation should be included in a practice-based methodology, and it is required to prepare assessable reports or evaluate artefacts for improving decision-making and enhancing technical knowledge (Murray & Lawrence, 2000; Winter, Griffiths & Green, 2000). The evaluation 'would provide a much needed insider's perspective to the existing knowledge on creativity' (McIntyre, 2006, p.4). Accordingly, in this study, the research design was divided into four stages: research, development of the design process model, development and evaluation of the initial prototypes, and development of the final prototype.

1.4.1 Research Review

The first stage of this study involved a comprehensive literature review, which helped identify and focus on relevant studies, theoretical design process models, 3D printing technologies (including materials used), the CAD/CAM process (including 3D modelling and texture mapping in creating 3D virtual object), and colouring technology. Furthermore, ergonomic factors, 3D body scanning technology, and the latest 3D printed fashion and textile products in the market were examined. These reviews helped generate ideas for developing designs.

1.4.2 Development of Design Process Model

The theoretical design process model developed in this study for designing 3D printed fashion with an innovative surface texture was structured on the basis of the 'analysis–synthesis–evaluation' concept. The procedural steps in the analysis part were defining the problem and identifying sub-problems, and those in the synthesis part were investigating the problem, developing a conceptual design, determining solutions, searching for alternatives, and developing prototypes; the steps in the evaluation part were evaluating the initial prototypes and decisions and developing a detailed design and providing its specifications. The design process model developed was finally used for producing a 3D printed fashion prototype.

1.4.3 Development and Evaluation of Initial Prototypes

On the basis of the framework of the design process model, suitable materials and production methods were identified and other technical specifications were prepared. The design statement and concept of the prototype could be inspired by aesthetic and technological factors in this stage. The colouration, graphic patterns, materials, and silhouette of the prototype were determined and technical methods were developed. Possible physical initial prototypes were produced and assessed.

1.4.4 Development of Final Prototype

After assessing the initial fashion prototypes produced in the previous stage, appropriate changes were made to them, and a final 3D printed fashion prototype with an innovative surface texture was produced.

1.5 Significance of Study

This study contributes to existing knowledge of the aesthetic and technical aspects of 3D printed fashion, thereby facilitating the development of novel contemporary fashion designs. In this study, a theoretical design process model and innovative fashion prototype were developed; thus, this study makes both theoretical and practical contributions to the field of 3D-printing-based fashion design. The theoretical design process model could be used by the high fashion industry for designing contemporary fashion, as well as in fashion education. The final fashion prototype could be used to produce attractive and high-quality 3D printed fashion garments. Furthermore, it can enhance the capability of designers to provide an element of novelty in high fashion and, therefore, to develop successful designs for the market. In addition, the prototype can be used for designing the clothes of performers of stage shows, to enhance the ambience of the performance space. As the prototype was designed by considering ergonomic factors and with suitable cutting and ease allowance, it can be used for producing well-fitting contemporary fashion garments that facilitate the easy movement and that are comfortable to wear.

The salient features of this study are as follows:

a) Both aesthetic and technical aspects of 3D printing were integrated for use in the contemporary fashion design industry.

b) A new theoretical design process model for producing 3D printed fashion with an innovative surface texture was developed, and it is expected to be useful to the fashion industry and in fashion education.

c) The final prototype developed can be used for producing 3D fashion garments with high performance in terms of colouration and texture.
d) The final prototype can be used for designing the clothes of performers of certain stage shows to provide entertainment to the audience.
e) The final prototype involved the integration of ergonomics and 3D printed fashion, and it can be used to produce well-fitting fashion garments that facilitate easy movement and that are comfortable to wear.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

In this chapter, 3D printed fashion, 3D printed textiles, 3D printed fashion accessories, and product design are reviewed, together with 3D printing technologies and their applications. The following topics are covered: a) introduction to 3D printing technologies (historical background and significance of 3D printing), b) 3D printing methods, c) 3D printing technologies, 3D printing materials, software, and post-processing, d) colour printing methods for 3D objects, e) 3D printed products in different design fields (fashion garments and fashion products, textile products, and product design), and f) use of 3D printing for creating a fashion prototype (3D body scanning and ergonomics). Subsequently, research gaps that were identified for this study are discussed.

2.2 Introduction to 3D Printing

Three-dimensional printing technology is a type of assembling technology, and it addictively stacks layers in a manufacturing process; such a manufacturing process is termed an addictive manufacturing process (Campbell et al., 2011). The process starts with a 3D digital model that is generated on a computer by using different types of 3D drawing software programs; such a computer-based generation of a model is referred to as CAD. Another model generation method involves the use of a 3D scanner to directly and fully scan an object and record the image on a computer. A software program slices the model into layers and converts the layers into readable files for a 3D printer; subsequently, materials are added layerwise by the printer to form a 3D object.

Today, there are over 100 types of 3D printers available (Gebhardt, 2012). The 3D printing process comprises computer modelling, printing, and the use of a finishing process for obtaining the final product. In general, the layer addition process of 3D printing involves the use of a CAD digital file, which is in a stereolithography (STL) format or other readable formats, in the pre-processing stage. Information on each layer, which is called a slice, originates from the 3D CAD file and is saved as a slice file, and the slice file is then sent to a 3D printer for printing (Iancu et al., 2010; Petrovic et al., 2011). The basic steps in 3D printing are coating and fusing. Coating refers to the laying of a layer of a designed object, and fusing refers to the binding of existing layers together. A 3D product is produced by repeating these two steps. Post-processing techniques such as sanding and polishing may be required after the completion of printing, depending on the types of 3D printing methods (France, 2014; Iancu et al., 2010; Petrovic et al., 2011).

2.2.1 Historical Background of 3D Printing

In 1984, the concept of 3D printing, which is also referred to as additive manufacturing, rapid prototyping, and solid-freeform technology, was developed by Charles Hull. Hull started studying photopolymer devices in the early 1980s, and the performance of 3D printed prototypes was unsatisfactory. Hull strove to make improvements to the prototypes. In 1986, he developed the first 3D printing system and the STL file format, which can be read by

CAD software and printers (Hull, 1986; Hull, 1990; Hull, 1993). The first 3D printer, named a 'Stereolithography Apparatus', and it was commercially manufactured. In 1990, Scott Crump of Stratasys extended the work of Hull and examined the use of 3D printing for manufacturing (Crump, 1992). In 1993, Michael Cima and Emanuel Sachs developed the first '3D printer' that could successfully print plastic, metal, and ceramic objects (Sachs, Haggerty, Cima & Williams, 1993). Later, other companies designed improved commercial 3D printers and some developed biomaterials for printing.

2.2.2 Significance of 3D Printing Technologies

Three-dimensional printing technologies have influenced the approaches used in and the nature of product manufacturing processes, and they have stimulated innovative and new ways of thinking in social, economic, environmental aspects (Bhatia, 2015).

2.2.2.1 Customisation

According to Bhatia (2015), 3D printing has the potential to minimise the distance between the manufacturing process and end-users and, hence, to reduce supply chain limitations. Customisation is available for customers with small production batches, and it mitigates the stoking problem (Campbell et al., 2011; Palmer et al., 2000). Shipping can be avoided as end-users can print small parts at home by using their own 3D printers. Even the digital design or customised product can be downloaded from the Internet and the product can be produced at home. Customisation can minimise the need for production by a company, leading to savings in costs, time, and labour hours (Lopes et al., 2006).

2.2.2.2 Energy Savings

Compared with traditional manufacturing methods, 3D printing technologies offer energy savings since nearly 90% of the materials used are integrated in the manufacturing process, implying less waste generation (Campbell et al., 2011; Navarrete et al., 2007). Furthermore, as mentioned, 3D printing can facilitate customisation for end-users. It can provide a local manufacturing model as customers can use 3D print desired products at home, reduce the demand for physical products, and eliminate the logistics of shipping (Rayna & Striukova, 2016).

2.3 Three-Dimensional Printing Methods

Different types of printing methods require different types of 3D printers and materials. There are seven common types of 3D printing methods employed in 3D printers: photopolymerisation, extrusion deposition, material jetting, granular material binding, binder jetting, directed energy deposition, and sheet lamination. Moreover, 3D printing pens that can produce 3D objects are currently available in the market.

2.3.1 Photopolymerisation

In photopolymerisation, photopolymers are exposed to radiation or light to trigger a chemical reaction, which then cures liquid materials to form the required solid product. Ultraviolet radiation is commonly used in this method

(France, 2014; Reiss, Evans & Price, 2013). Photopolymerisation is typically referred to as stereolithography.

2.3.1.1 Stereolithography

Stereolithography (SLA) is the first commercial 3D printing method. In this laser-based method, photosensitive photopolymer resins are exposed to a laser beam, leading to their solidification and the formation of layers. In particular, the photopolymer resins are placed on a movable platform, and the laser beam moves along the *XY* axes according to the instruction in the 3D readable file. Because the resin is photosensitive, it can be hardened by being exposed to a laser beam. The solidification process is repeated for every layer, and finally, a 3D object is formed (Wicker & MacDonald, 2012).

2.3.2 Extrusion Deposition

Extrusion deposition is the most common 3D printing method and is also known as fused deposition modelling (FDM) because of its affordability and the ease of installation of the required equipment. The materials used are melted thermoplastics, which are extruded from a heated nozzle onto a movable bed. The computer sends coordinate information of 3D virtual object to the 3D printer for controlling the nozzle and the bed, and the thermoplastic material is hardened to form layers (Reiss et al., 2013).

2.3.3 Material Jetting

Material jetting is similar to the FDM process, but layers with specific patterns are formed by a liquid photopolymer that undergoes cooling or chemical changes. The printing process requires a supporting material to support the model material and help in shaping the model material during its solidification. The supporting material can be removed after the completion of printing. An ultraviolet laser is used for solidifying the photopolymer. Because of the use of several print heads, which can emit several photopolymers, material jetting is a type of multijet modelling (MJM), and it is commonly referred to as PolyJet (Kalita, Bose, Hosick & Bandyopadhyay, 2003; Landers & Mülhaupt, 2000). Drop-on-demand (DOD) printing is a variation of material jetting to create objects with wax materials (Varotsis, n.d.). NanoParticle Jetting (NPJ) also uses material jetting mechanism. The droplets of metal nanoparticles and supporting materials are jetted onto the layers and the liquid materials are heated for evaporating and the materials leave behind the metal parts (3D Printing Media Network, 2017).

2.3.4 Granular Material Binding

Granular material binding is a method for fusing layers of granular materials by partially or completely melting the materials; the materials are melted by irradiating them with a laser beam (selective laser sintering (SLS)), heating them (selective heat sintering (SHS)), or using other energy sources (such as selective laser melting and electron beam melting (EBM)). The energy sources move across the bed of 3D printer according to instructions contained in a 3D readable file, and when the powdered materials are energised, they coalesce or fuse and consequently harden to form a solid. This process is repeated for every layer, and finally, a 3D object is formed. Multi-jet fusion (MJF) is also a powder-based technology which does not involve the use of lasers. The granular materials could include metals, glass, plastics, and ceramics. However, there is a limit to the granule size (France, 2014; Reiss et al., 2013; Zamiska, Cole, Lu & Weise, 2013).

2.3.5 Binder Jetting

This method is similar to granular material binding, except that binder jetting involves the use of a liquid binding material (as a binder) rather than an energy source (such as a laser) for fusing granular materials. ZCorp owned this patented process, which is known as 3D printing (3DP). The printing mechanism is identical to that of 2D inkjet printers, and the print nozzles of the 3D printer move over the granular material instead of paper according to cross-sectional data provided by software. Droplets of the liquid binder, which acts as glue, are deposited on the powder for fusing the powder together to form the final object. The powder bed can be lowered by using a piston, and the process can be repeated for a new layer spread on the previous layer (Stucker, 2012).

2.3.6 Directed Energy Deposition

In directed energy deposition, thermal energy is used to melt powder materials and fuse them together. The energy source is typically a laser beam and the powder material is metal powder. The powder materials melt when being deposited, and unlike granular material binding, the powder material is spread on a movable platform. The platform is moved for shaping the cross section of the layers. Laser metal deposition (LMD), laser engineered net shaping (LENS), and electronic beam melting (EBM) are examples of directed energy deposition (Gibson et al., 2015; Wohlers, 2013)

2.3.7 Sheet Lamination

Sheet lamination, also termed laminated object manufacturing (LOM), involves adhesive lamination of sheets of materials. Paper or plastic sheets are originally bonded together with glue or a binder. The adhesive density is high in the main object part, whereas it is low in the supporting part for removal afterwards. On the basis of the information in a 3D readable data file, a CO_2 laser cuts the layers, and unwanted materials are selectively removed according to the density level (Reiss et al., 2013; Zamiska et al., 2013).

2.3.8 Three-Dimensional Printing Pen

This device offers an alternative approach to produce 3D objects. Unlike 3D printers, the printing process does not involve an additive manufacturing method, but the final product is similar to those produced by 3D printers. The pen releases melted plastic materials from its heated tip, and the released materials cool immediately to assume the desired shape or angle. The pen is portable, easy to control, and affordable. The materials used are available in numerous colours, and a possible material is a combination of acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA). ABS can form 3D flexible geometric objects, and PLA easily sticks to paper, glass, and metal.

The 3D printing pen can be used to easily produce products such as jewellery, construction models, clothing, and artwork (Veppumthara, 2013).

2.3.9 Summary of 3D Printing Methods

A summary of 3D printing methods is presented in Table 2.1.

Table 2.1 Summary of 3D printing methods

3D printing methods	Typical techniques	Materials form	Mechanism
Photo-polymerisation	SLA	Liquid (photosensitive polymer)	Light or radiation Solidification
Extrusion deposition	FDM	Liquid (melted thermoplastic)	Cooling Melting and solidification
Material jetting	MJM/PolyJet DOD NPJ	Liquid (liquid photopolymer, wax, metal nanoparticles)	Cooling or chemical changes Solidification
Granular materials binding	SLS SHS SLS EBM MJF	Powder	Laser or other energy sources Fusing and solidification
Binder jetting	3DP	Powder	Liquid binder Fusing and solidification
Directed energy deposition	LMD LENS EBM	Powder (metal)	Laser or other energy sources Fusing and solidification
Sheet lamination	LOM IC	Paper or plastic sheets	CO2 laser for selective cutting and bonding
3D printing pen	None	Liquid (melted plastic)	Cooling

2.4 Three-Dimensional Printing Technologies

In this section, major technologies used in the 3D printing process are introduced. Special 3D printing materials, software, post-processing, and colouring methods are reviewed in detail.

2.4.1 Three-Dimensional Printing Materials

Today, numerous materials can be used in 3D printing technologies. Researchers have also studied the use of biomaterials or food for 3D printing (Godoi, Prakash & Bhandar, 2016; Guvendiren, Molde, Soares, & Kohn, 2016). Thermoplastics, metals, and photopolymers are the materials commonly used for 3D printing (Gibson et al., 2015; Liska, 2007). Nylon and polyamide powders are commonly used for the sintering method and extraction deposition method. However, only white-coloured powder is available, and post-processing is necessary if other colours are to be added (Fabian, 2017).

Thermoplastics such as biodegradable plant-based PLA, ABS, polycarbonate (PC), and colourless polyethylene terephthalate (PET) can be shaped after heating, and they can be used to produce prototypes or final products. Thermoplastics are widely used in filament form in the extrusion decomposition method; the filament form is strong and different colours are available. Furthermore, transparent objects can be printed using PLA (France, 2014; Taylor & Unver, 2014).

Metals such as steel, titanium, stainless steel, silver, gold, and brass are mainly used for producing jewellery, electrical components, and engineering structures. Photopolymer materials, such as mixtures of epoxy and resins, can be transformed from the liquid state to the solid state through the process of irradiation. Apart from these two types of materials, other fusible granular materials, and ceramics can be used in 3D printing (Reiss et al., 2013; Unver, Swann, Bailey, Govindarajan & Dollan, 2013).

2.4.2 Software

Three types of software are required for 3D printing. One is for prototyping physical objects, a process referred to as CAD, another is a CAM program, which converts data in printer commands, and the third is printer control software, which conveys instructions provided at the user interface to the printer (France, 2014). A three-dimensional body scanning technique can be used for scanning in the CAD program (D'Apuzzo, 2007). The body size and data of the subject can be captured and designing can be directly performed using a virtual model.

The CAD program generates sliced layers on the basis of STL files. An STL file is designed to store triangular meshed face vertex components and the normal vector in the 3D Cartesian coordinate system (Iancu et al., 2010; Wong & Hernandez, 2012), and it includes numerous close-packed triangles with different *Z*-values. The CAD program converts the geometrical structures in a CAD file into small triangles with coordinates (*X*, *Y*, *Z*), and the normal vector. The triangles are constructed to be as small as possible to produce printed objects with the desired shape (Halloran et al., 2011). Users can vary the thickness of the slice layers at the horizontal levels of interest. STL files have limitations; for example, angles over 45° cannot be printed without supporting materials because the plastic would sag, and the printer cannot print non-manifold meshes by using unusual shape algorithms (Petrovic et al., 2011; Reiss et al., 2013).

After the CAM program receives the STL files from CAD program, it can send instructions to the printer about where and when to move the pointer and the amount of plastic materials to be extruded. This process is called slicing, and the programming language is called G-code. Finally, the printer control software that controls the printer’s control panel starts, stops, or pauses the printing process (France, 2014).

2.4.2.1 Three-dimensional Modelling

Three-dimensional virtual objects are created by combination of 3D modelling, texturing and rendering in CAD design. Each 3D object requires vertexes (points in 3D space), edges which are formed by vertexes, and after the connection of lines, it is a plane. A plane is an object surface and known as polygon mesh and polygons can be assembled together to form shapes. Furthermore, lines vertexes can form curve and curves are combined into objects. Primitive, polygonal and NURBS (Non-Uniform Rational B-Splines) modelling are common methods in 3D modelling process (Murdock, 2012). Primitive modelling involves basic geometric shapes, such as cylinders, boxes or spheres, they can be mesh base of 3D virtual object. Complex model can be created by modifying the vertexes and edges. In polygonal modelling, specific *X*, *Y* and *Z*-axes coordinates are defined to position the vertexes. The position of vertexes is connected by lines to form polygons or curves, where *X*, *Y*, *Z* represent width, height and depth, respectively. After connecting by edges, mesh planes are finally created. By applying different modifiers, forms of polygon mesh can be changed (Russo, 2006). NURBS modelling can create smooth free-form surfaced object as it represents curves and surfaces in mathematical method (Murdock, 2012).

2.4.2.2 Texturing in 3D Modelling

Texture mapping is a method to add illusive textures on 3D virtual objects. Texture can be pictures, hand painting in software or photographs which are modified in material editor by changing texture properties. UV mapping is the method to provide 2D axes of texture for projecting 2D texture on 3D object. Instead of using *X*, *Y* and *Z* coordinates in 3D object, *U* and *V* provide the axes of 2D image. During the render to texture process, the texture meshes are unwrapped to one flat image, then texture is projected onto the meshes. UVW mapping, stands for “Texture Coordinate System in 3D Environments”, is one of the modifiers for wrapping texture around entire object plane. UVW map provides the third dimension for texture mapping. Position, size, style of the texture can be modified by mathematical method (Ahearn, 2014; Mullen, 2011).

2.4.2.3 Rendering

Rendering is a mathematical process to calculate every pixel of the virtual object to produce final image. During the rendering process, textural, lighting and other information are analysed to present the reflections and shadow in order to determine the colour of the textured 3D object (Murdock, 2012).

2.4.3 Post-processing

Although 3D printing can be performed using numerous materials and high-resolution 3D printers, the visual quality of products may be unsatisfactory (Hohkraut, 2010). Because the product is produced layerwise, staircase or jaded effects may be visible on the final objects. Moreover, most of the final products are unattractively monocoloured due to 3D printers' specifications. (Gibson et al., 2015; MCor Technologies, 2014b). Grinding, sanding, polishing, and electroplating can help overcome these problems and raise the aesthetic value of the products, thereby rendering the surface and texture of the metal or polymer products appealing (Thompson, 2011).

2.4.4 Colour Printing Methods for 3D Objects

Because the traditional textile printing method typically requires a plain surface for printing, it is difficult to use it for 3D printing objects. This section discusses potential colouring methods that can be applied to 3D printing.

2.4.4.1 Direct Colour Printing Using 3D Printers

According to Gibson et al. (2015) and MCor Technologies (2014b), most of the final 3D printed products are monocoloured due to 3D printers' specifications. However, it is still possible to add colours onto the products. Powder-binder, layer-laminated, and PolyJet printers can produce coloured products that colour is texture mapped onto the objects (3D Systems, 2014; MCor Technologies, 2014a; Stratasys, 2018b). Powder-binder and layer-laminated printers use cyan, magenta, yellow, and black (CMYK) inks and apply them to white base materials. However, power-binder printer cannot produce opaque objects and objects with a smooth surface or high-resolution colour.

2.4.4.1.1 Powder-Binder 3D Printers

In powder-binder 3D printers, the printed product comprises layers of powder bonded by a liquid binder. Although the surface of the final product is not sufficiently smooth, colour 3D printing can be performed by introducing colourants in the printer's binders. According to Parraman, Walters, Reid & Huson (2008), wax infiltration can be used as the finishing process for 3D printed colour charts. A Z-Corp Spectrum Z510 3D printer was used in the current study for producing the initial prototype, and the colour gamut of the inkjet heads comprised cyan, yellow, magenta, and the colour of the liquid binder (Figure 2.1). An additional print head for black binder was added to the printer.

Figure 2.1 Three-dimensional printed colour charts

2.4.4.1.2 Layer-laminated Printers

Figure 2.2 Colour objects produced by MCor IRSI HD 3D printer

Layer-laminated printers are referred to LOM technology. MCor IRIS HD 3D printer is produced by MCor Technologies which is able to print over one million colours with high resolution and accuracy (Figure 2.2). Cyan, magenta, yellow and black inks can produce high and realistic colour combinations. The material used is paper and the printing cost is affordable comparing with other 3D printing technologies due to the material types (MCor Technologies, 2014a).

2.4.4.1.3 PolyJet 3D Printers

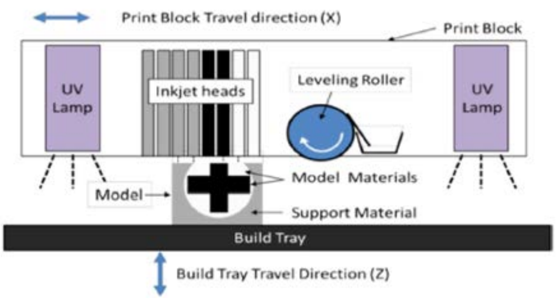


Figure 2.3 3D PolyJet printing process

PolyJet 3D printers capable of high-resolution and smooth surface colour 3D printing are available, and they are also capable of using translucent materials (Stratasys, 2018b; Vidimče, Wang, Ragan-Kelley & Matusik, 2013). Furthermore, they are the only printers that can use rigid and flexible materials simultaneously for producing a product; these printers can also mix multiple materials during the printing process. The material jetting printing method is used in these printers; in this method, droplets of a liquid photopolymer are deposited by nozzles and ultraviolet light is used to cure the photopolymer to harden the droplets (Figure 2.3). PolyJet is capable of pixelwise printing with different materials, and therefore, materials can be combined or blended to obtain a product with a specific colour or flex gradient. However, full colour printing with PolyJet printers is not possible because of software limitations (only approximately 50 palettes are permitted) and the limited number of nozzles (which decide the number of palettes that can be mixed) in the printer (Xiao et al., 2016; Stratasys, 2018b).

2.4.4.2 Dyeing

According to France (2014), 3D printed products made of polyamide (nylon) can be dyed with dyes because polyamide is a porous material and has high absorption affinity for fabric dyes. The dyeing process is easy to handle. The dye is boiled, and the products are immersed in the dye for approximately 30 minutes. The dyed objects are then removed and washed with cold water to remove excess dye, and they are then put into boiling water again for the colour to set. Finally, the dyed object is allowed to dry, marking the end of the dyeing process. Spray painting can also be used to colour products.

2.4.4.3 Electroplating or Anodising

Thompson (2011) and Yap & Yeong (2014) observed that electroplating or anodising can add aesthetic value to 3D printed products. Electroplating can be performed on polymer and metal surfaces, whereas anodising is possible only on metals. Anodising of aluminium and titanium allows the colouring of these metals with a wide range of colours without requiring the use of dyes. Molitch-Hou (2014) presented a new low-cost electroplating device, named Orbit 1, for electroplating 3D printed objects. In the study, ABS-printed objects with a polished smooth surface were sprayed with conductive paint. Subsequently, the objects were placed in the Orbit 1 machine and electroplated. The machine is user-friendly and can be used at home.

Other processes such as the electrostatic flocking process, which binds charged fibers to products' surfaces with the aid of an adhesive coating, can be used to introduce a texture or add colours to 3D printed objects (Thompson, 2011).

2.4.4.4 Hydrographic Transfer Printing

Because of the high cost of multicolour 3D printing and the limitation on materials that can be used in the process, Zhang, Yin, Zheng & Zhou (2015) developed a method involving a combination of 3D printing and hydrographic printing (Figure 2.4). Hydrographic printing is also referred to as water transfer printing, and it is a fast technique for introducing colour patterns on 3D objects. In this technique, a colour printed transparent film is put in a mixture of water and chemicals. When a 3D object is immersed in the mixture, the film wraps around and binds to the object. However, it is difficult to fit the printed pattern at a specific point. Zhang et al. (2015) developed a computational hydrographic printing system that involved the simulation of film stretching during the wrapping process, for obtaining high-quality hydrographic printing results.

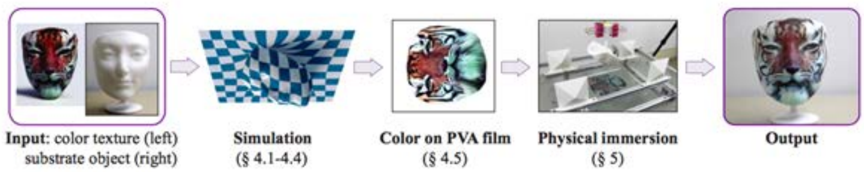


Figure 2.4 Hydrographic printing process

2.5 Current 3D Printed Products with Coloured or Texturised Surfaces

This section introduces 3D printed products with colouring or texturised surfaces, currently available in the market. Furthermore, fashion garments or products, textile products, and product design are reviewed.

2.5.1 Fashion Garments and Textiles

Recently, 3D printing has been introduced in the field of fashion design. Three-dimensional printing can create anything and can inspire fashion designers to create innovative designs (Lipson & Kurman, 2013). The famous fashion designer Iris van Herpen brought 3D printing technologies to the fashion runway. Furthermore, 3D printing can be used to produce not only textiles and fashion garments such as the N12 bikini (Continuum Fashion, 2011) but also fabric-like products with a special textile structure and unique characteristics such as high flexibility or stretchability. Such products are available in current ready-to-wear fashion. It can be predicted that 3D printing technologies will enter the domain of casual fashion.

2.5.1.1 Black Drape Dress

Figure 2.5 Black Drape Dress

The Black Drape Dress was created in 2000, and it is regarded as the first wearable piece created by industrial engineers (Figure 2.5). It was created by Jiri Evenhuis, an industrial engineer, and Janne Kyttänen, an industrial designer. The technology used was SLS technology, in which fine power is melted and used to form 3D shapes with the aid of lasers. Later, in 2005, Kyttänen developed the White Drape Dress (Taylor & Unver, 2014).

2.5.1.2 N12 Bikini

Figure 2.6 N12 Bikini

The N12 bikini was the world's first 3D printed ready-to-wear clothing, and it was formed layerwise using solid nylon through the SLS printing process (Figure 2.6). The garment had no sewing, and the material surface was thin and flexible and fit the body's curvature. The circular plates were connected by strings, resulting in a flexible fabric-like structure. It was comfortable to wear, and the price was affordable (Continuum Fashion, 2011).

2.5.1.3 Stained Glass Corset

Figure 2.7 Stained Glass Corset

Michaella Janse van Vuuren created a stained glass corset featuring colourful flowers and berries (Figure 2.7). The corset was produced by using an Objet500 Connex3 PolyJet 3D Printer, and pieces of the corset were combined using rigid and flexible materials, which comprised three types of digital materials with transparent and coloured panels. The corset combines the properties of opacity and flexibility and involves multiple materials. It is said to be the first 3D printed product in which a mixture of materials was used (Town, 2014).

2.5.1.4 Hard Copy

Hard Copy was a fashion collection created by designer Noa Raviv (Figure 2.8). The collection was inspired by ancient concepts of the human body and classical art evolution, which were represented by a series of crossing curve lines and distorted grids and contours. The 3D printed parts were built on textile fabrics and created confusing illusions, making it difficult to distinguish between the 3D printed objects and the textile garment's shell (Mendoza, 2014).

Figure 2.8 Hard Copy

2.5.1.5 Three-Dimensional Printed Swimwear

Zhang Hongyu, a Chinese fashion designer, presented her 3D printed swimwear collection at the Shanghai Fashion Week in 2014 (Figure 2.9). The swimwear was printed using silicon polymer, and therefore, it was soft and thin. The fashion designer used a 3D scanner to scan a model's body and sent the data files to a manufacturer to print the perfect-fit swimwear collection (Cross, 2014).

Figure 2.9 3D Printed Swimwear

2.5.1.6 Dita's Gown

Designer Michael Schmidt and Francis Bitonti collaborated to create a 3D printed dress for artist Dita Von Teese (Figure 2.10). The 3D printing technology used was SLS. The dress comprised over 3000 articulated movable parts for linkage and over 12000 Swarovski crystals for decoration. It is regarded as the first fully articulated 3D printed dress (Howarth, 2013).

Figure 2.10 Dita's Gown

2.5.1.7 Designer Iris van Herpen

Iris van Herpen, a Dutch fashion designer, started her 3D printed fashion collection in 2010. She was the first fashion designer to use 3D printing technologies on the runway and had the ability to use scientific technology in the fashion world. Her first collection was presented at the Amsterdam Fashion Week in 2010, and the collection was named Crystallisation (Figure 2.11). In January 2011, she presented a collection, named Escapism at the Paris Haute Couture Week (Figure 2.12), and the collection comprised twelve outfits of which four were 3D printed. In July

Figure 2.11 Crystallisation Collection

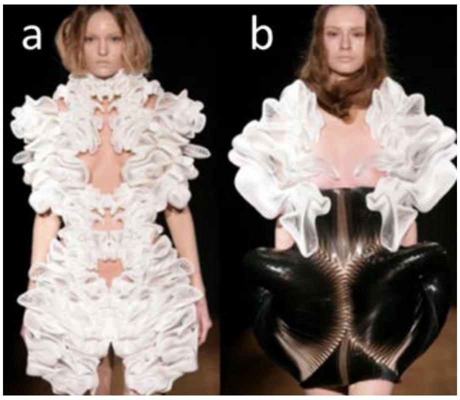


Figure 2.12 Escapism Collection

2011, she presented the Skeleton Dress of the Capriole Collection. The dress showed the structure of a skeleton in detail (Figure 2.13a). In January 2012, she used SLS technology to create a Cathedral Dress with polyamide materials (Figure 2.13b), and in the same year, she used the mammoth SL technique, which involved the use of a laser beam to harden a polymer in a container. The garment produced with the mammoth SLS technique was transparent and liquid like (Figure 2.14). In 2013, Herpen produced a flexible, multitexture, hard and soft dress; the dress combined different degrees of softness and elasticity (Figure 2.15a). In March 2014, she presented the Biopiracy Collection in which 3D printed outfits made of new flexible materials that showed high flexibility and allowed easy movement were introduced (Figure 2.15b). In September 2014, a transparent material was used for 3D printing a dress in the Magnetic Motion Collection (Figure 2.15c) (Herpan, 2015).

Figure 2.13a Skeleton Dress

Figure 2.13b Cathedral Dress

Figure 2.14 Liquid Dress

Figure 2.15 (a) Voltage Collection, (b) Biopiracy Collection, and (c) Magnetic Motion Collection

2.5.1.8 Wearable Skins

Ner Oxman's team collaborated with Stratasys to create four 3D printed garment pieces, which were produced by Object500 Connex3 PolyJet colour printer; multiple materials embedded living cells of different densities and plastic materials were used (Figure 2.16). The garments of the collection varied in opacity, colour, materials, and rigidity in vascular structure and presented the relationships between living beings and their environment (Howarth, 2014c).

Figure 2.16 Wearable skins

2.5.2.9 3D Printed Fashion Collection at Home

A fashion design student, Peleg, created the world first 3D printed ready-to-wear fashion collection by using 3D printers for the home (Figure 2.17). A rigid materials, namely FilaFlex, was adopted in the collection. The lace-like 3D printed textiles and the properties of materials provided certain flexibility on the garments (Leichman, 2015; Peleg, 2017).

Figure 2.17 3D printed fashion collection by Peleg

2.5.2.10 Multi-material 3D Printed Oscillation Dress

A multi-material 3D printed dress, namely Oscillation Dress, was created by threeASFOUR and presented in New York Fashion Week in 2016 (Figure 2.18). The dress was 3D printed by Stratasys Objet Connex3 3D printer (PolyJet technology) with flexible materials and involved 270 design files and 30 3D printed parts. The panels was 3D printed as flat pieces and the dress was formed by assembling the printed panels on human body (Koslow, 2016).

Figure 2.18 Oscillation Dress

2.5.1.11 3Doodled Seashell Lace Dress

The 3Doodled Seashell Lace Dress was created by SHIGO by using a 3Doodler pen (Figure 2.19). The designing of the dress began with paper modelling on a dummy, and a seashell pattern was then printed out and stuck on the base. On top of the printed pattern, the designer used the 3Doodler pen to draw a 3D pattern on the dress. Finally, buckles were attached to provide openings at the joints (The 3Doodler, 2014).

Figure 2.19 3Doodled Seashell Lace Dress

2.5.2.12 Three-Dimensional Printed Textiles

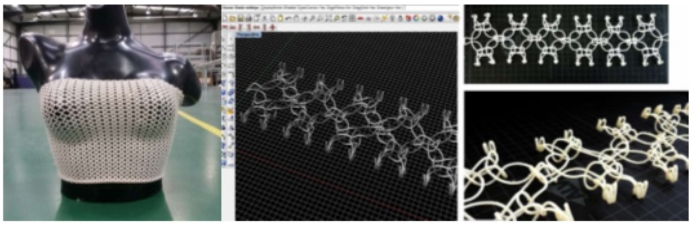


Figure 2.20 3D printed weave structure

Three-dimensional printing can be performed on textiles products for obtaining 3D printed fabrics; Taylor & Unver (2014) named the process Cosyflex (Figure 2.20). Textile fibers such as cotton, viscose, and polyamide are used in liquid form in the process, and they are then printed on a 3D structured base plate. Cosyflex can be used to create compression wearable woven garments with interlocking structures or 3D printed weave structures (Figure 2.20) (Kalmus, 2013).

2.5.2.13 Three-Dimensional Printed Fabrics on the Runway

Figure 2.21 3D printed knitwear

Pringle of Scotland used 3D printed laser-sintered nylon fabric to create outfits in the Autumn Winter 2014 Ready-to-Wear Collection (Figure 2.21). The nylon parts were made in movable interlocks by using a specific machine, and the printed sections were then hand woven into the knitwear by using hooks under or on top of the wool (Howarth, 2014a).

2.5.2.14 Metallic Space Fabric

A multi-funtional metallic space fabric was developed by National Aeronautics and Space Administration (NASA) (Figure 2.22). The fabrics is foldable and reflective and it can manage passive heat, and is flodable with high tensile strength.

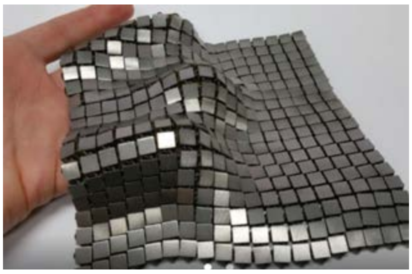


Figure 2.22 Metallic space fabric

The structure is similar to chain mail with small squares strung together. These fabrics can be applied in large antenna and deployable devices (Landau, 2017).

2.5.3 Product Design

Apart from fashion and textiles, 3D printing technologies are commonly used in product design, furniture design (Bloomfield, 2015), lighting design, and for even providing 3D printing customisation services to people.

2.5.3.1 Molecular Shoes

Molecular Shoes were designed by Francis Bitonti and manufactured by using Adobe software (Figure 2.23). The shoes were pixelated and blended different colours in layers, and they were produced using Stratasy's 3D printing technology (Howarth, 2014b).

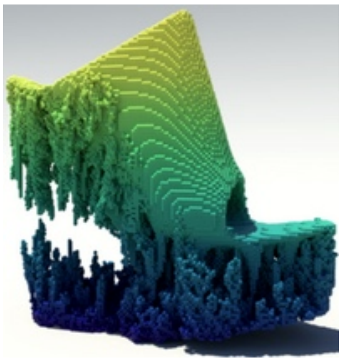


Figure 2.23 Molecular Shoes

2.5.3.2 Adhesive Joint Development

It is difficult to print out a large complete piece of garment panel, and therefore, it is necessary to assemble pieces together to obtain the final garment. Hence, appropriate joining mechanisms should be designed before printing. According to Yap and Yeong (2014), segments with cut lines can be masked in the design, and each segment is printed separately with support materials. After segment printing, the small pieces are joined together with suitable components, for example, screw threads in jewellery design, helical springs for flexible joints, and cufflink objects for snap buttons or other traditional openings. Nervous System's Kinematics applet provides ideas on foldable forms (Figure 2.24). The joints consist of interlocking small pieces that can be folded, compressed, and draped and that act like a real fabric. Joint design is already part of customisable jewellery design for jewellery such as bracelets and necklaces (Nervous Systems, 2013).

Figure 2.24 3D printed foldable form

2.5.3.3 Three-Dimensional Printed Furniture

Joris Laarman, a Dutch designer, began using 3D printing technologies in 2005 to create furniture (Figure 2.25). The first chair was designed on a computer by calculating the best support data, and it was moulded in ceramic

Figure 2.25 Puzzle Chair

by a 3D printer before being cast in aluminium. Later, the designer designed different types of chairs, including those with coloured patterns. The Puzzle Chair was uploaded on the internet for free downloading by the public, and it could be created by people having 3D printers (Bloomfield, 2015).

2.5.3.4 3D Printed Dazzle Lighting

Corneel Cannaert's Dazzle Lamps provide colourful lighting, and they can be 3D printed using a ProJet Z-Corp printer (Figure 2.26). The lamps appear different in light and darkness. When the lamp is turned off, it is oblique grey, and when it is turned on, it glows in a variety of colours. The software was coded by Cannaerts, and the public can use the libraries in the software to create their own designs with different sizes, shapes, and colours (Akel, 2014).

Figure 2.26 Dazzle Lamps

2.5.3.5 Petfig: Creating 3D Printed Sculptures

Petfig is a service developed by Japanese artist Yoshinobu Kakumrua and designer Roman. The service is about creating a 3D printed sculpture on the basis of a photograph of a pet (Figure 2.27). Customers can send a photograph of their pet and Kakumrua and Roman would create a 3D digital model and upload it to Shapeways for printing on 3D Z-Corp printers. The

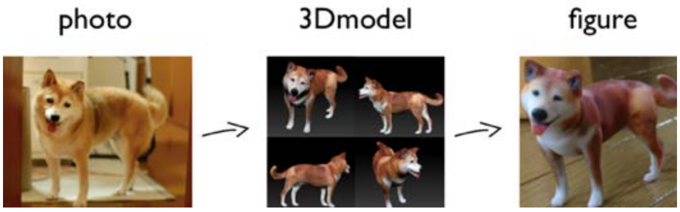


Figure 2.27 Process of Petfigs

material used for printing was sandstone, for obtaining appropriate colour and photorealistic designs (3Ders.org, 2013).

2.5.3.6 3D Printed Replica Based on 3D Body Scanning

A British retailer, Asda, collaborated with the Artec Group to build a booth with a high-speed, high-resolution 3D full body scanner. The scanner took 12 seconds to scan a customer, and then created and fused 700 surfaces to create a printable file (Figure 2.28). An 8-inch mini replica of customer could be printed using ZPrinter 650 (3Ders.org, 2014).

Figure 2.28 3D printed replica

2.5.3.7 MirrorMe3D

MirrorMe3D is a service that allows a person's face to be simulated on the basis of actual photographs (Figure 2.29). An appropriate simulated face can then be 3D printed and used for planning cosmetic surgery. MirrorMe3D facilitates a comparison of the face before and after cosmetic surgery. Dr. Glenn Jelks referred to MirrorMe3D as a paradigm shift because the printed model can help understand where and how reconstruction should be done on the face. 3D printing involved in medical professionals to enhance personal care (Matisons, 2015).

Figure 2.29 MirrorMe3D

2.6 Use of Three-Dimensional Printing for Creating a Fashion Prototype

The use of 3D printing for creating a fashion prototype can involve other processes. This section discusses 3D body scanning and ergonomics.

2.6.1 Three-Dimensional Body Scanning

According to D'Apuzzo (2007), in the pre-processing stage of 3D printing, scanning of the objects or body figure is necessary, and therefore, researches can obtain body measurements from a 3D whole body scanner. The main applications of body scanning technology are in anthropometry and ergonomics. This technology replaces the traditional body measurement method involving tapes and callipers, and it provides accurate body measurement data in a contact-free manner and in a short time (D'Apuzzo, 2009; Lu & Wang, 2008).

2.6.1.1 Background of 3D Body Scanning

The first 3D body scanning system was called the Loughborough anthropometric shadow scanner (LASS) and was developed in 1989 for collecting anthropometric survey data (Jones, West, Harris & Read, 1989). In 1998, [TC]2 developed the 3D body scanner technology and produced the first scanner for the fashion industry (D'Apuzzo, 2009). Today, new software and efficient scanning systems have been developed and they are used in different fields. Moreover, there are four major types of 3D body scanners: laser scanning, white light scanning, passive scanning, and touch sensors scanner.

2.6.1.2 Principle of 3D Body Scanner

Commonly a body scanner can capture over 300,000 scattered points from the objectives. Before the landmarking of the data for each scan, body parts are segmented at the armpits and crotch; nowadays, the software can automatically identify the landmarks (D'Apuzzo, 2009; Nurre, Connor, Lewark & Collier, 2000; Wang, Chang & Yuen, 2003). Landmarking can define the target body size and shape, and by applying markers or pasting stickers on the body surface, positions can be extracted and identified on the scanning image (Burnsides, Boehmer & Robinette, 2001). On the basis of the markers, the software can make measurements on scanned images and show a 3D surface model of the scanned body.

2.6.2 Ergonomics

High-quality clothing should satisfy the physiological and mechanical requirements of wearers and provide a high level of comfort; moreover, it should have high-quality appearance and fit the human body well (Geršak, 2002).

2.6.2.1 Definition of Ergonomics

Ergonomics is defined as the study of the relationship between humans and other elements in a system, together with applied theory, principle or method to design which can make it as well as possible in well-being design and overall system performance (International Ergonomics Association, 2014). In the field of fashion design, ergonomics helps produce fashion products that can satisfy the needs of the end users in terms of mobility, usability, and comfort. Users can easily use such fashion products during various activities despite their abilities or limitations (Martins & Martins, 2012). Study of body motion is crucial for ergonomically designing a garment. Human moves are accompanied by dynamic body changes, and therefore, the fit and ease allowance are the main factors affecting loads acting on garments. Different body postures would involve the bending of the body and stretching of the body tissues (Schmid & Mecheels, 1981). Accordingly, it is necessary to understand the relationship between body posture, changes in surface measurements of body, and changes in the shape of garments.

2.6.2.2 Ease Allowance

Two types of allowances can be considered, namely ease allowance (which is considered to improve comfort) and design ease allowance (which are used to create a design style or look). Appropriate ease allowance allows the wearer to perform different body movements without the clothing being deformed (Myers-McDevitt, 2004). Design ease allowance is considered to provide aesthetic value. There are four major types of ease allowances: standard ease allowance, dynamic ease allowance, fabric ease allowance, and ergonomic ease allowance. Standard ease allowance is related to the human body in standing and sitting postures, and it is the difference between the maximal and minimal perimeters (Aldrich, 2012). Dynamic ease allowance refers to the kinetic ability of the wearer or the availability of movement space for wearers with nonstandard body shapes. Fabric ease allowance depends on the mechanical properties of the fabrics used. Ergonomic ease allowance is the clothing construction solution of the light weight garment involving the design modulation, structure, or construction adjustment of the garments. Appropriate ergonomic ease allowance allows wearing comfort and high degree of movement (Geršak & Marcic, 2013).

The values of ease allowance for different types of clothing positioning on the body are shown in Table 2.2. However, clearly, the ease allowances suggested by different authors are highly inconsistent. A possible reason is that the authors did not classify the garments into close- and loose-fitting types. In this case, the use of additional ease allowance data is recommended, and such data are provided in Table 2.3; the data was obtained by Burgo (2013), who described ease allowance on the basis of four types of clothing on the body. Therefore, the suggested ease allowances can be used with advanced 3D printing technologies, such as 3D body scanning, and virtual simulations to determine the required ease allowance and to provide a feasible method for body comfort and human body morphology.

Table 2.2 Suggested ease allowances

Body area	Suggested ease allowance (cm)			
	Reader's Digest (1997)	**Gioello and Berke (1979)**	**Farmer and Gotwals (1982)**	**Haggar (2004)**
Neck (total girth)	-	6.4-1.2	-	-
Shoulder	-	1.2-2.5	-	-
Chest (total girth)	-	1.27	-	-
Bust (total girth)	7.5	6.35	5 (bust), 6 (high bust)	10
Bust front girth	-	3.18	-	0.6
Bust back girth	-	3.83	-	1.6
Total waist girth	2	2.5	1.3	4 (bodice), 1(skirt), 1(trousers)
Front waist girth	-	0.95-1.27	-	-
Back waist girth	-	1.27-2.54	-	-
Hip	5	-	5	5
Top hip	-	-	-	4-5
Upper arm	-	7.62-10.16	5	5
Elbow	-	2.54	-	Minimum 5
Forearm	-	1.91	-	-
Wrist	-	1.27	-	6.5
Neck to waist front	-	1.27-2.54	-	-

Neck to waist back	-	1.27-2.54	-	-
Front waist length	-	-	1.3	-
Shoulder length	-	-	1.3	-
Shoulder to waist front and back	-	1.27	-	-
Inseam	-	1.27	-	-
Shoulder to crotch	-	2.54-5.08	-	-

(Reader's Digest, 1997; Gioello & Berke, 1979; Farmer & Gotwals, 1982; Haggar & Haggar, 2004)

Table 2.3 Ease allowance for different clothing positioning

Body area	**Recommended ease allowance (cm)**				
	Zero degree*	**1st degree***	**2nd degree***	**3rd degree***	**4th degree***
Neck (total girth)	-0.25 - 0	0.25-0.75	0.75-1	1-2	2-3
Shoulder	-4 - 0	1-3	1-3	4-6	4-6
Chest (total girth)	-4 - 0	2-6	6-12	12-16	16-24
Bust (total girth)	-4 - 0	2-6	6-12	12-16	16-24
Waist (total girth)	-4 - 0	2-6	6-12	12-16	16-24
Hip	-4 - 0	2-6	6-12	12-16	16-24
Breast distance	-0.5 - 0	0.25-0.75	0.75-1.5	1.5-2	2-3
Lowering arm hole	-1 - 0	0.25-1.5	1.5-3	3-4	4-8

(Burgo, 2013) *Zero degree: close-fitting garments, directly in contact with skin; first degree: clothing worn on top of underwear; second degree: clothing worn on top of first-degree clothing; third degree: heavy clothing; fourth degree: clothing with lining

2.7 Research Gaps

The latest research studies on 3D printed products with colouration or texture in the fields of fashion and textiles, product design, technologies (including materials), software, post-processing, colouring methods, and the application of 3D printing to 3D body scanning and ergonomics were comprehensively reviewed. It was observed that there is no specific theoretical design process model that has been developed on the basis of aesthetic and innovative aspects of 3D printed fashion garments. Currently, in the fashion industry, 2D measurements with CAD technology do not fulfil the high requirements in terms of the fit and quality of garments, and therefore, many theoretical researchers employ 3D body measurements and technology for creating 3D designs (Gibson et al., 2015). Most of the final 3D printed products are monocoloured and are unaesthetic to consumers due to 3D printers' specifications (Gibson et al, 2015; MCor Technologies, 2014b). Although 3D printing is an innovative concept in the fields of fashion and textile, monocoloured products do not fully meet fashion customers' aesthetic expectations. Furthermore, the ergonomic aspect of current 3D printed fashion products has not been fully explored. In this study, the consideration of ergonomics helped increase the wearing comfort of wearable 3D printed garments. This study addressed the aforementioned shortcomings of 3D printed fashion products, and a 3D printed fashion prototype with innovative coloured printed texture and based on a consideration of ergonomic factors was produced. This study was aimed at designing fashion garments with an innovative texture surface by using 3D printing technologies and by considering the aesthetic aspect, technological requirements of 3D printing methods, 3D printing materials, and ergonomics factors. The following research gaps were identified:

a) To date, no structured theoretical design process model has been presented for 3D printed fashion.
b) The selection of 3D printing materials and printing methods for printing on garment surfaces to achieve aesthetic appeal and innovative designs have not been well explored; moreover, related prototypes have not been developed.
c) The colouration and introduction of innovative textures by texture mapping method in 3D printed garments have not been achieved.
d) The use of 3D body scanning data and consideration of ergonomics for designing 3D printed garments has not been well investigated.
e) The integration of 3D printing methods, printing materials, and technologies for creating fashion prototypes with fully consideration of silhouette, colouration, ergonomics, and texture pattern has not been developed.

2.8 Conclusion

In this chapter, 3D printed products in the fields of fashion and textiles and other markets are reviewed. Subsequently, a literature review of technologies related to and applications of 3D printing, including 3D printing methods, 3D printing materials, software, post-processing, 3D body scanning, and ergonomics, is presented. Finally, research gaps are identified and the significance of the present study is discussed.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

A practice-based methodology with theoretical design process model was adopted in this study. The aim of this study was to create a 3D printed fashion prototype with an innovative coloured surface texture base on the developed theoretical design process model. The study comprised five main processes: research stage, development of a theoretical design process model, development of initial prototypes, evaluation stage, and final design stage.

The research stage started by reviewing the available secondary research. Various relevant theoretical design process models were reviewed for developing a theoretical model for 3D printed fashion. The latest 3D printing technologies, materials used, CAD/CAM process, and current 3D printed fashion products were also reviewed. To produce a fashion prototype that facilitates easy body movement, ergonomic factors and 3D body scanning technologies were examined. On the basis of the research stage, a specific theoretical design process model for a 3D printed fashion prototype with an innovative surface texture was developed. The developed design process model was implemented and initial prototypes were developed and assessed. A final 3D printed prototype was then created by considering fine design details.

3.2 Definition of Practice-Based Research Methodology

Creative art research can be of two types: practice-based and practice-led research. Both refer to the practice in an interrogative process (Durling, 2002). Practice-based research should contribute to knowledge, whereas practice-led research contributes to a better understanding of practice. Candy (2006) mentioned that practice-based research should be an original investigation that can generate new knowledge in terms of practice and together with the new concepts and methods. In a doctoral thesis, knowledge contributed and the originality claimed can be expressed in the form of performance, design, exhibitions, music, and digital media. Hence, the focus of the practice should be the development of design activities. The research process requires original contributions to a specific field along with original creative work, and a practice-based doctoral research must provide extensive contextual material to indicate or demonstrate the originality of the work (Candy, 2006).

McLaughlin (2006. p.9) observed that the advantage of using a practice-based research method is, ‘the development of artefacts that allow us to see the world in significant new ways; engagement in and documentation of design processes that extend the depth and/or breadth of the referential contexts that are explored in the development of a genre of design outcomes; and the articulation of design processes in such a way as to bring clarity to the skills, orientation and processes that shape the development of design outcomes’.

3.3 Background of Practice-Based Research Methodology

The concept of practice-based research methodology was developed in 1968 with the aim of introducing the methodology to the mainstream of higher education. In 1974, in the United Kingdom, the Council for National Academic Awards framed regulations with a critical clause that required PhD students to submit material objects together with a thesis (Jordon, 2004). In 1984, the first practice-based PhD researches started in Australia in creative writing at the University of Wollongong and the University of Technology, Sydney (Candy, 2006). Later in 1997, the United Kingdom Council for Graduate Education (1997, p.15) mentioned the following about practice-based PhD: '…it required amongst other things that the final submission to be accompanied by a permanent record of the creative works, these works to be set in a relevant theoretical, historical, critical or visual context, and that… there be a written thesis'.

3.4 Development of Theoretical Design Process Model

A design process involves creative activity and the process of finding specific problems and their best solutions (Chapman, Bahill & Wymore, 1992; Hanks, Belliston and Edwards, 1977; Medland, 1992). By applying skills, experience, knowledge, and problem-solving techniques, a design process transforms the design concept into reality and provides possible solutions (Medland, 1992; Navinchandra, 1991). The aim of designing is to simplify a complicated concept/object, and hence, a systematic design approach is required (Jones, 1992). This approach can be found in engineering design process theory, on which the fashion and textile design process model formalised in 1974 is based (Lamb & Kallal, 1992; Orlando, 1979; Watkins, 1988). The model was an engineering-based model and was applied in the fields of engineering, architecture, and computer science (Newsome, Spillers & Finger, 2013).

The theoretical framework of the engineering-based design process theory consists of the following steps: a) identify the problem, b) define the problem, c) study the problem and search for alternative solutions, e) evaluate the solutions, f) specify the solutions, and g) communicate the solutions.

3.4.1 Problem Identification

The process begins with specifying the objectives through the following steps: a) write a problem statement, b) create solutions, and c) create ideas and sketches (Colton & Pun, 1990; Dixon, 1966; Leech, 1972; Lewis & Samuel, 1989). Designers should understand customer needs and create solutions to satisfy the needs; they should also create new products by generating a range of ideas with sketches (Chapman et al., 1992; Jenkins & Martin, 1993; Navinchandra, 1991).

3.4.2 Defining the Problem

It is necessary to identify and provide direction to the design process on the basis of the objectives, available resources, design limitations, and subproblems (Cross & Roy, 1989; Dixon, 1966; Lewis & Samuel, 1989). By following the design direction, designers can specify problems and decompose the problems into tasks to meet customer needs (Chapman et al., 1992; Dixon, 1966).

3.4.3 Studying the Problem and Searching for Alternative Solutions

In this step, possible ideas and solutions can be suggested through brainstorming (Chapman et al., 1992; Navinchandra, 1991). Old designs can be reused and transformed into new designs or original designs can be created (Dixon, 1966). The main steps include a) searching for information and past studies, b) purpose and estimate problem from the information, c) define the design strategy, d) consider critical factors of the design problems, e) consider the available resources, f) consider market needs, g) consider other relevant factors during the designing process (Leech, 1972; Lewis & Samuel, 1989; Middendorf, 1969). Designers should use their experience along with information obtained from the literature to find answers to the defined design problem and then make a study proposal (Leech, 1972; Lewis & Samuel, 1989).

3.4.4 Evaluation

Evaluation involves a series of steps to determine the satisfaction level of a design (Medland, 1992). The evaluation can help predict the performance of a proposal by indicating the feasibility of ideas and objectives, and the value of the design (Leech, 1972; Lewis & Samuel, 1989). It has to begin with a clear problem definition and create a numeric form of performance objectives (Cross & Roy, 1989; Middendorf, 1969).

3.4.5 Specification of Solutions

This step is aimed at creating the best design according to the specifications. Specifications of design require limits, and they are divided into two types: design specifications and performance specifications. Design specifications affect the materials used, whereas performance specifications are based on the desired performance parameters (Midddendorf, 1969).

3.4.6 Communication of Solution

Communication is required between a designer and audiences, and it is achieved using a verbal or visual format (Middendorf, 1969). The visual format can be drawings, sketches, written reports, photographs, or reality models (Lewis & Samuel, 1989).

3.5 Review of Theoretical Design Process Model

The design process model has been applied in the fields of architecture and environmental design, product design, engineering, and fashion and textile design. The process should clearly communicate and present the design, obtain quick solutions to problems by considering the market, users' needs, and organisation of working process. The design process involves various stages, which mainly include definition of the problem and its investigation, determination of feasible solutions for the problem, determination of solutions for subproblems, and synthesis of a specific solution to obtain the final conclusion (Goel and Pirolli, 1992; Schon, 1990; Wertheimer, 1959). According to Asimow (1962), Goel and Pirolli (1992) and Schon (1990), the design process can be defined as a problem-solving activity and it follows the analysis–synthesis–evaluation concept.

3.5.1 Design Process Model in Fashion and Textile Design

The design process model used in fashion and textile design is mainly based on the engineering design process theory. The followings design process models were reviewed in the present study.

3.5.1.1 Orlando's (1949) Design Process Model

Orlando's (1979) design process model was developed from Jones' (1973) model, and it was specifically for functional clothing design. It comprised six stages: a) making a request, b) exploring the design situation, c) determining the problem structure, d) establishing design criteria, e) drafting specifications, f) creating a prototype, g) evaluating prototype (DeJonge, 1984; Orlando, 1979).

3.5.1.2 DeJonge's (1984) Design Process Model

DeJonge (1984) developed a design process model for functional clothing on the basis of Jones' work. DeJonge (1984) first considered the requirements of the design solution from many viewpoints, to redefine the problem. After the main goals were set, deep research was conducted on the design factors. After prototype development, evaluation was performed by using a ranked and weighted method. DeJong (1984) delineated the flexibility of the design process, and the design process model could be applied to any functional clothing design research.

3.5.1.3 Watkins's (1988) Design Process Model

Watkins (1988) proposed a design process model comprising seven steps, and it was developed from the model proposed by (architect) Koberg & (graphic designer) Bagnall (1973). The steps were as follows: a) adopt, b) analyse, c) define, d) generate ideas, e) determine, f) apply, and g) evaluate. Watkins pointed out that creative was the most difficult part in the process and suggested the use of cognitive approaches for design application.

3.5.1.4 Lamb and Kallal's (1981) Design Process Model

On the basis of the model of Hanks et al. (1977), Koberg and Bagnall (1973) and Watkins (1988), Lamb and Kallal (1992) developed a design process model named the 'functional-expressive-aesthetic consumer needs model'. The model involved six steps: a) problem definition, b) idea generation, c) design refinement, d) prototype creation, e) evaluation, and f) implementation.

3.5.1.5 Regan, Kincade and Shelden's (1998) Design Process Model

Regan, Kincade and Shelden (1998) developed a design process model on the basis of the engineering design process theory, and the model involved a scientific and problematic building block process. The model comprised five steps: a) identify the problem, b) define the problem, c) investigate the problem, d) state the problem, and e) determine solutions.

3.5.1.6 LaBat and Sokolowski's (1999) Design Process Model

LaBat and Sokolowski (1999) concluded the design process in three major stages: a) identification of the problem, b) investigation of the problem with creativity, and c) implementation. Feedback loop was established to the previous steps to construct the entire process. The first stage (identification of the problem) was developed further; for example, the initial problem was defined, research was conducted, and the working problem was defined. In the second stage, ideas were initiated, design details were refined before the prototype creation process, and the prototype was then evaluated. In the final stage, the production process was focused on refinement and improvements.

3.5.1.7 Summary of the Design Process Model used in Fashion and Textile design

The reviewed design process models in fashion and textile design were summarised in Table 3.1.

Table 3.1 Summary of the design process model used in fashion and textile design

Name of the model creator(s)	Analysis	Synthesis	Evaluation	Remarks
Orlando (1949)	a) Made requests b) Explored design situations c) Found out the problem structures	d) Created design criteria e) Created specifications f) Created prototypes	g) Evaluation	- Based on Jones's (1973) model - For functional clothing design
DeJonge (1984)	a) Considered design solutions b) Redefined problems	c) Did deep research d) Developed prototypes	e) Evaluation	- For functional clothing
Watkins (1988)	a) Aadoption b) Analysis c) Definition	d) Created ideas e) Determination f) Application	g) Evaluation	- Based on Koberg and Bagnall's (1981) model
Lamb and Kallal (1992)	a) Defined problems	b) Created ideas c) Refined design d) Created prototypes	e) Evaluation f) Implementation	- Named as FEA
Regan, Kincade and Shelden (1998)	a) Identified problems b) Defined problems	c) Explored problems d) Sated problems e) Created solutions	None.	- Based on the engineering design process theory
LaBat and Sokolowski (1999)	a) Identified problems	b) Explored problems with creativity c) Refined design details d) Created prototypes	e) Evaluated on prototypes f) Implementation	- Each step was tracked to the previous steps

3.5.2 Design Process Model in Architecture and Environment Design

The main purpose of the design process model in architecture and environment design is to solve large problem as the final product should be evaluated with scale and balance to prevent safety problems. The model involves problem solving through analysis–synthesis–evaluation stages (Archer, 1984; Darke, 1979; Jones, 1984). Each stage should be evaluated without retesting the final product. This type of design process model is beneficial in fashion and textile design.

3.5.2.1 Koberg and Bagnall's (1973) Design Process Model

Koberg and Bagnall (1973) presented a design process model that involved analysis and synthesis throughout the process. The stages were divided into the following steps: acceptance, analysis of information, defining the problem, generating ideas, synthesis and decision-making, implementation, and evaluation.

3.5.2.2 Broadbent's (1984) Design Process Model

According to Grant (1986), Broadbent (1984) influenced modern thinking on theories related to decision-making, mathematics, social sciences, behaviour of the society, and architecture. He outlined the 'accept the belief' concept, where *belief* referred to problems faced by customers. The belief was analysed later. Broadbent (1984) stated that preconceptions were the main connections throughout his study and that they originated from the designers' experience, knowledge, and skills and were subjective. Hence, creativity was the main factor in the synthesis of the design process and provided various solutions for the design problem.

3.5.2.3 Zeisel's (1984) Design Process Model

Zeisel's (1984) design process model was aimed at solving problems in housing. He concentrated on the connection between the environment and the user, and therefore, the model was related to the reaction of the user. Zeisel (1984) indicated that the image, presentation, and test were the major factors in environmental design. Images included visual works and a written work plan, and they included sketches, plans, models, and tests. The process involved a 'feedback and feedforward process' involving visualisation to ensure product quality. The designer was required to evaluate the design by following the process.

3.5.2.4 Summary of the Design Process Model used in Architecture and Environmental design

A summary of design process model applied in the field of architecture and environmental design is presented in Table 3.2.

Table 3.2 Summary of the design process model used in architecture and environmental design

Name of the model creator(s)	Analysis	Synthesis	Evaluation	Remarks
Koberg and Bagnall (1973)	a) Acceptance b) Analysed information c) Defined problems	d) Created ideas e) Synthesis and decisions	f) Implementation and evaluation	None.
Broadbent (1984)	a) Defined problems: "accept the belief" concept"	b) Creativity synthesis c) Created solutions	None.	- Preconceptions were the main connection
Zeisel (1984)	a) Defined problems: The reaction of the user	b) Created ideas, including visual works	c) Evaluated the design back along the process	- Involved "a feedback and feedforward process"

3.5.3 Design Process Model in Engineering and Industrial Design

Most of the design process models in the fields of fashion and textiles are based on process models in the fields of engineering and industrial design (Lamb & Kallal, 1992; Orlando, 1979; Watkins, 1988). In design process models in engineering and industrial design, the main objective is to simplify problems by following a systematic method (Jones, 1992). During the process, testing and evaluation of prototypes are required.

3.5.3.1 Asimow's (1962) Design Process Model

Asimow (1962) was an early contributor to the design process used in engineering projects, and the main concept involved analysis, synthesis, and evaluation. Asimow (1962) introduced two main structures in the process: vertical structure, which focused on the solution of the design problems, and horizontal structure, which focused on the steps to be followed for obtaining solutions for subproblems. The vertical structure involved design criteria, and the horizontal structure pertained to the steps in the design process. Designers should analyse the problem by considering the materials or time limitations and subsequently synthesise the solution by drawing on their personal knowledge and experience. Initial prototypes were created for the solutions to determine the best solution to solve the problem. The evaluation could lead to perfection in the final products and reflected all the limitations of the process. Asimow's (1962) model involved refinement to ensure the quality of the final result.

3.5.3.2 Jones's (1970) Design Process Model

Jones (1970) developed a design process model comprising three major stages: a) increasing the design diversity to extend the boundary, b) transforming the creativity, and c) identifying the variables and objectives. Furthermore, Jones (1984) provided the basic structure of a model for systematic design, and the model mainly involved the analysis–synthesis–evaluation process.

3.5.3.3 Lawson's (1980) Design Process Model

Lawson's (1980) design process model comprised five stages: a) identifying the problem, after which the problem is perceived and formulated, b) proposing ideas and reconstructing the problem, c) development of the previous stage, d) identifying one solution for further development, and e) confirming the ideas and solution for obtaining conclusions.

3.5.3.4 Archer's (1984) Design Process Model

Archer (1984) presented a model with six activities: a) programming, which was identified as initial step, b) data collection for the analysis stage and identification of subproblems, c) synthesis for preparing the design, d) prototype development, e) communication process for the executive stage and documentation.

3.5.1.5 Cross and Roy's (1989) Design Process Model

Cross and Roy (1989) proposed a four-step model with the following steps: a) defining the problem, b) recognising subproblems, c) selecting the main problem and proposing feasible solutions, and d) synthesising the solutions and providing the conclusion.

3.5.1.6 Hollins and Pugh's (1990) Design Process Model

Hollins and Pugh's (1990) design process model started with background research for synthesis and analysis. After the synthesis, designers should detail the design features to determine the required materials and resources and finally input this information into the manufacturing process for producing the final product.

3.5.1.7 Ehrlenspiel and Dylla's (1993) Design Process Model

Ehrlenspiel and Dylla's (1993) design process model focused on problem solving. It started with identifying the problem and then proceeds with analysis, proposing solutions, selecting and combining feasible solutions through evaluation, and finally obtaining a conclusion (Ehrlenspiel & Dylla, 1993).

3.5.1.8 French's (1999) Design Process Model

French's (1999) design process model focused on the need for design. The model started with identifying the need and then analysed the problem. The design statement was created for the conceptual design and embodiment of schemes after the identification. The design was further developed and finally, drawings were created.

3.5.2.9 Takala, Keinonen and Mantere's (2006) Design Process Model

The design process model of Takala, Keinonen and Mantere (2006) included a framework for product design in three phrases, a) searching for information, b) idea generation, and c) evaluation. The process involved a feedback phase to reflect on the steps, and it also concentrated on users' needs and technical limitations for the perfection of design ideas.

3.5.3.10 Pahl, Beitz, Feldhusen & Grot's (2007) Design Process Model

Pahl, Beitz, Feldhusen & Grote (2007) design process model focused on identifying problems, establishing the structures and decomposing the problems into subproblems, developing the model structure, developing solutions through research, synthesising the information, and evaluating the solutions. Evaluation and prototype creation preceded the final product creation. Everything was well documented, including the written plans, sketches, or illustration on paper, for detailed evaluation.

3.5.2.11 Summary of the Design Process Model used in Engineering and Industrial design

The design process models in engineering and industrial design are summarised in Table 3.3.

Table 3.3 Summary of the design process model used in engineering and industrial design

Name of the model creator(s)	Analysis	Synthesis	Evaluation	Remarks
Asimow (1962)	a) Analysed the problem	b) Synthesised solutions c) Created initial prototypes d) Found out the best way	e) Evaluation	- Vertical structure on solution - Horizontal structure on sub-problems
Jones (1970)	a) Defined problems: Increase design diversity	b) Transformed the creativity c) Identified variables and objectives	None.	- Basic structure was analysis-synthesis-evaluation
Lawon (1980)	a) Identified problems	b) Purposed ideas and reconstructed problems c) Developed from previous stage d) Decided one solution e) Confirmed ideas and solution for conclusions	None.	None.
Archer (1984)	a) Programming which identified as the initials	c) Synthesised for preparing the design d) Create prototype	None.	None.

	b) Collected data and identified sub-problems	e) Communication process and documentation		
Cross and Roy (1989)	a) Defined the problems b) Recognised the sub-problems	c) Selected the main problem and purposed feasible solutions d) Synthesised solutions and gave final solution	None.	None.
Hollins and Pugh (1990)	a) Background research b) Analysis	c) Synthesis d) Detailed the design features	None.	None.
Ehrlenspiel and Dylla (1995)	a) Identified the problems b) Analysis	c) Purposed solutions d) Selected and combined feasible solutions	e) Evaluation and create a concluded solution	- Concentrated on problem solving
French (1999)	a) Identified needs b) analysed problems	c) Conceptual design and embodiment of schemes d) Detailed designs	None.	None.
Takala, Keinonen and Mantere (2006)	a) Searched information	b) Created ideas	c) Evaluation	- Involved feedback phrase
Pahl, Beitz, Feldhusen & Grote (2007)	a) Identified problems b) Established the structures and break into sub-problems	c) Developed structure d) Developed solutions with researching e) Synthesised information	f) Evaluation	- Everything was well documented

3.6 Development of Theoretical Design Process Model for 3D Digital Printed Fashion with Innovative Surface Texture

According to the literature on the design process models in the fields of fashion and textile design, architecture and environmental design, and engineering and industrial design, the theoretical design process model for 3D digital printed fashion should be based on the analysis–synthesis–evaluation concept, with three main stages. Lawson (2006) mentioned that '…Knowing that design consists of analysis, synthesis and evaluation will no more enable you to design than knowing the movements of breast stroke will prevent you from sinking in a swimming pool' (p.28). The analysis stage involves defining and considering the problem process and setting the objectives; synthesis involves a feasible solution generation process; and evaluation involves the critical assessment of the solutions (Wynn & Clarkson, 2005).

3.6.1 Analysis

Through a comprehensive review of the literature, the design problem should be analysed before the solution is obtained. The design problem can be analysed by using either a new innovative design or an improved version of an existing design (Baser, 2008; Suh, 1990).

3.6.1.1 Problem Definition

The first step of the design process should be the identification of the specific design problem. ‘This is clearly one of the most critical stages in the design process. This definitional step requires insight into the problem, and a knowledge base encompassing issues related to the problem (Suh, 1990, p.30)’. In the definition process, objectives were established and feasible resources and design boundaries were reviewed (Regan et al., 1998). In the current study, the research objective was to combine creative and artistic innovation, ergonomics, and 3D printing technologies to create high-value 3D printed fashion prototypes, namely 3D digital printed fashion prototype with an innovative surface texture that is appropriate for wearing in terms of fitting and ergonomics.

3.6.1.2 Identification of Sub-problems

A review of recent colour 3D printed products in various markets, including the product design, fashion design, textile design, and medical aspects, showed that the subproblems involved 3D printing technologies, materials that could be used in fashion design, and colour 3D printing methods appropriate for producing texturised colour 3D printed garments.

3.6.2 Synthesis

The problems are investigated with creativity and innovation. Jones (1984) mentioned that this stage could involve inspired guesswork. In this stage, preliminary ideas were generated by designers and design constraints were imposed by narrowing the possibilities. Prototypes were developed, and their evaluation can test the existing limitations and indicate whether further refinement was necessary.

3.6.2.1 Investigation of the Problem

The problems were investigated before conceptual solutions were generated through information searching, which can retrieve required information and help identify the design needs (Cross, 1994; French, 1999). 'Design associates determined what influenced their markets and used the information to make better design decisions (Regan et al., 1998, p.42)'. Designers could use different searching methods to have inspiration, including drawing, taking photograph, and recalling observations made in daily life and results of previous researches. Initial inspiration associated with each other would create new inspiration (Regan et al., 1998). Evaluation on the information against the objectives, design constraints, and design criteria is required, and a feedback loop connection was established between the generation and evaluation processes (Cross, 1999).

3.6.2.2 Conceptual Design

On the basis of the investigation of the problem, preliminary ideas were generated; these ideas should be developed further. The main factors on which ideas were generated include a) types of 3D printer bases used in 3D printing methods, b) 3D printing materials, c) texture pattern, d) colour print on the texture, and e) ergonomics. In this stage, designers were required to use their imagination for idea generation, which make possibilities for improvements (Fiore & Kimle, 1997; French, 1999).

3.6.2.3 Determination of Solutions

In this stage, the solutions were abstract, and they did not describe details and small activities involved in obtaining solutions (Wynn & Clarkson, 2005). In the present research, solutions were proposed on the basis of previous problems and ideas. a) The types of 3D printers were obtained from standard 3D printing methods: SL, extrusion deposition, granular materials binding, and LOM or photo-polymerisation. b) The 3D printing materials were ABS, PC, PET, metals, resins, photopolymer materials, or other fusible granular materials. c) Different types of texture patterns were designed by using computer software such as 3ds max, ZBrush, Rhino, SketchUp, Solidworks, and Maya, and texture patterns of various sizes and forms were obtained. d) Coloured print on the texture was obtained through direct colour printing with the 3D printers, combining different colour printed materials, or using other additional colouring methods. e) The ergonomic aspect involved creating style cutting lines and adding ease allowances or the opening of the garment. Furthermore, the silhouette, proportion, colour, and embellishment of the fashion prototype should be inspired.

3.6.2.4 Searching for Alternatives

The fashion prototype should be aesthetic, and hence, alternative design subsolutions could be generated by considering aesthetic requirements regarding the printing materials, texture pattern, colouring methods, and design cutting lines of the garments. According to Jones (1984), new designs could be produced by generating many preliminary ideas and imposing constraints and concept variants.

3.6.2.5 Development of Prototypes

In this stage, feedback on the conceptual design stage was reviewed to create various initial prototypes, and after experimental sampling, the final solution can be decided (French, 1999). The types of 3D printers, printing materials, printing texture designs, and colour methods were considered.

3.6.3 Evaluation

This stage includes various iterations and suggests an approach to the design problem. The objective of evaluation is to determine whether the design and proposed solutions are satisfactory (Lewis & Samuel, 1989; Medland, 1992).

3.6.3.1 Evaluation of Initial Prototypes and Decisions

In this stage, the initial prototypes were evaluated according to the aesthetic and technological characteristics of the 3D printing materials, printer types, colour, texture performance, and comfort that could be applied in fashion garments. Evaluation was performed by avoiding guesswork and using a numeric method for judging performance (Cross & Roy, 1989). This stage was not linear, and a feedback loop was established between the synthesis stage and evaluation stage for designers to redesign and improve an unsatisfactory design (Akin, 1984; Asimow, 1962; French, 1999).

3.6.3.2 Detailed Design with Specifications

The final stage provided the detailed design with specifications for the final prototype. The materials, printing method, colour, and texture of the pattern are identified with integration of ergonomics. All illustrations and specification documents were produced. The final 3D printed prototype had high-fashion value and an innovative coloured texture, and the features of the prototype are as follows:

a) Printing method of the 3D printer
b) Three-dimensional printing material
c) Texture pattern
d) Fitting, and cutting lines of the garment
e) Suitability of the opening of the garment
f) Silhouette of the garment
g) Colouration

3.7 Conclusion

In this chapter, practice-based methodology is discussed. A series of design process models used in different fields—fashion and textiles, architecture and environmental design, and industrial and engineering design—are reviewed. On the basis of the reviewed models, a theoretical design process model for 3D digital printed fashion with an innovative surface texture was developed (Figure 3.1), and it was applied in a later stage of this study for creating the final 3D printed fashion prototype.

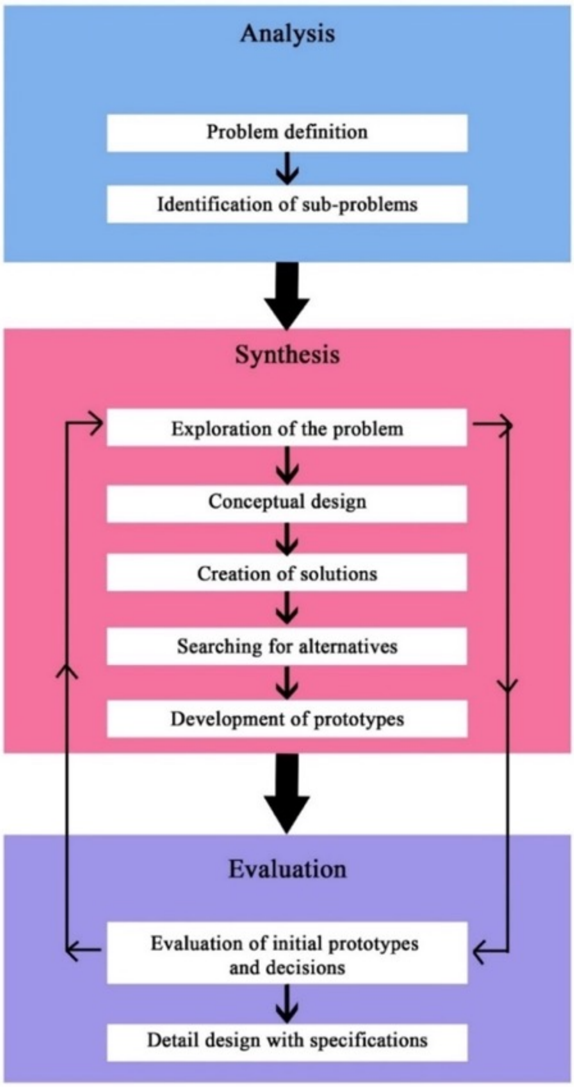


Figure 3.1 Theoretical design process model for 3D digital printed fashion with an innovative surface texture

CHAPTER 4: DEVELOPMENT AND EVALUATION OF INITIAL PROTOTYPES

4.1 Introduction

In this chapter, the design inspiration of the colour theory was examined and colours were arranged into groups according to the colour theory for colour pattern development. In 3D modelling using 3ds Max, virtual 3D patterns were developed. Various initial 3D printed prototypes were created using different materials, pattern densities, and design structures. Furthermore, joints and interlocks were designed and 3D printed for further evaluation.

Various assessments of the initial prototypes were performed to verify the materials, pattern designs, design structures, and joints and interlocks. The initial prototypes were evaluated according to the aesthetic and technological factors that could apply in creating 3D digitally printed fashion prototypes with an innovative surface texture. According to the theoretical design process model developed in Section 3.6, the aim of this evaluation was to judge the performance of the designs, possibly returning to the synthesis stage for redesigning and searching alternative solutions (Asimow, 1962; Akin, 1984; Cross & Roy, 1989; French, 1999).

4.2 Design Inspiration of the Colour Theory

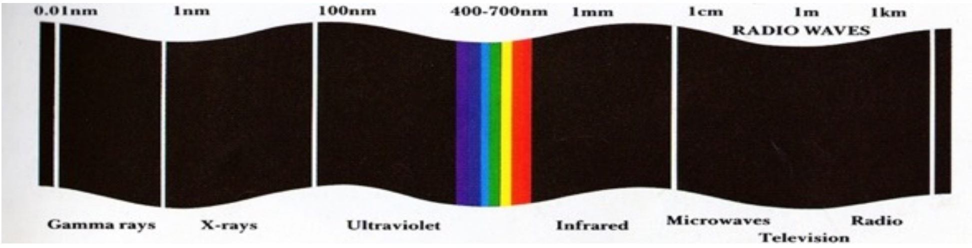


Figure 4.1 Electromagnetic spectrum

Because the focus of this study was multicolour 3D printing technology, the design inspirations originated in the colour theory. All visible colours are light energy and derive from the electromagnetic spectrum, whose wavelengths (measured in nanometre (nm)) determine colours. Humans perceive colours through vision and recognise them using the brain (Koenig, 2012). Humans can only distinguish wavelengths within the 400–700-nm range of the electromagnetic spectrum, which is called visible light (Fehrman & Fehrman, 2015; Koenig, 2012) (Figure 4.1). When light arrives at an object, a certain amount of light energy is absorbed while the rest is reflected in a specular, scattered, and diffused manner, separately or simultaneously. If the object has a perfectly smooth or flat surface, such as the shiny surface of an aluminium mirror, light can be reflected spectacularly. However, most objects have a surface texture or roughness, and thus scattered (or diffused) reflection occurs, whereby light rays reflect at all angles (Gilbert & Haeberli, 2011; Harold, 2001). Reflected light energy is perceived by the human eye and a specific colour is recognised according to the wavelength value assimilated by the brain (Koenig, 2012).

There are two systems of the colour theory, additive and subtractive. An additive colour system refers to the mixture of light waves. Scientists have noted that colour perception should be described in terms of the additive mixture of three primary colours, red, green, and blue violet (RGB), which can mix to produce secondary and tertiary hues (Figure 4.2). A subtractive colour system refers to the mixture of colour pigments. Industrial chemists have introduced a range of colour pigments and improved the saturation of dyes, paints, and inks. The primary colours adapted in inks or dyes are cyan, magenta, yellow, and black, known as the CMYK system (Farris, 2012; Gerritsen, 1975; Fehrman & Fehrman, 2015; Koenig, 2012) (Figure 4.2).

Figure 4.2 CYMK and RGB

Three components are used in the colour theory to specify colour: hue, value, and chroma. Hue is connected to a specific colour's wavelength (Cumming & Porter, 1990; Koenig, 2012). Value is defined as a colour's lightness or darkness. Chroma, also called

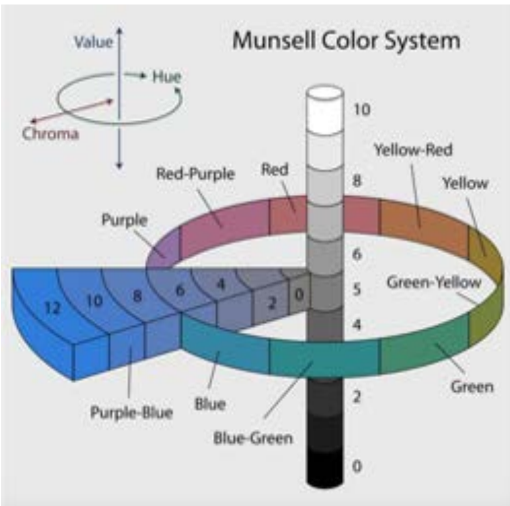


Figure 4.3 Munsell's colour system

saturation, refers to the vividness or intensity of a hue (Koenig, 2012; Levkowitz, 1997). Munsell's 3D system represents the relationship of hue, value, and chroma as angle, height, and radius, respectively (Best, 2017; Farris, 2012) (Figure 4.3).

4.2.1 Colour Wheel

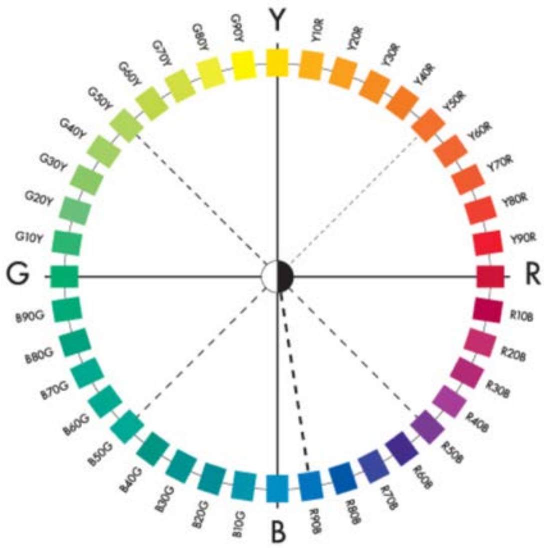


Figure 4.4 Colour hue code in NCS system

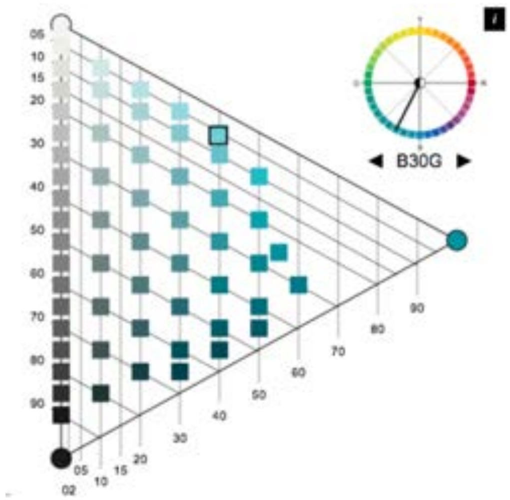


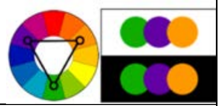
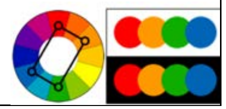
Figure 4.5 Colour values and shades proportion in NCS system

The colour wheel has varied in its historical development according to user requirements, and thus, has been assigned various definitions. Pure hues presented in a logical sequence can be termed a colour wheel. A representative colour wheel was developed by the Scandinavian Colour Institute of Stockholm, Sweden, called the Natural Colour System (NCS). This colour wheel has been adopted internationally for colour communication across industries. The system is based on human perception and enables colours to be created visually (Best, 2017). It begins with the six elementary colours that humans perceive as pure: white (W), black (S), yellow (Y), red (R), blue (B), and green (G). Four elementary colours are placed on the wheel at points perpendicular to each other, with 100 equal steps divided between them (Figure 4.4). Each hue is marked by using a code comprising letters and numbers that indicate its values and shades (Figure 4.5). For example, the code NCS S1050-R90B denotes 10% blackness, 50% saturation, 95% blue, and 5% red; in the hue code, it is expressed as R90B (i.e. 90% resemblance to blue and 10% resemblance to red) (NCS, 2017).

4.2.2 Colour Harmony and Colour Schemes

Colour harmony aims to achieve balance and instil a sense of order. Under-stimulating or difficult-to-organise signals are rejected by the human brain. Therefore, it is necessary to seek a dynamic equilibrium to sustain visual interest (Morton, 1998). Six common colour schemes have been devised for colour combinations in harmony or contrast. They have been developed by choosing colours from colour wheels and comprise the monochromatic, analogous, complementary, split complementary, triadic, and tetrad schemes. These colour schemes are summarised in Table 4.1.

Table 4.1 Summary of Colour Schemes

Colour Scheme	Description	Examples
Monochromatic	This scheme includes a single hue from the colour wheel. Tints and shades are changed by adding white or black, respectively (Gerritsen, 1975; Koenig, 2012).	
Analogous	This scheme involves adjacent colours on the colour wheel. These colours are usually harmonious. One is the dominant colour while the others are secondary (support) and tertiary (accent) colours (Koenig, 2012).	
Complementary	Colours are paired according to their mutually opposite position on the colour wheel for high contrast, creating vibrant feelings (Gerritsen, 1975**;** Koenig, 2012).	
Split complementary	This scheme is based on the complementary scheme, with one colour acting as the base and the two other adjacent colours as complements (Koenig, 2012).	
Triadic	Three colours picked from an equilateral triangle are defined as a triadic scheme (Koenig, 2012).	
Tetrad	Four colours in the colour wheel bound by a square or rectangle form a tetrad scheme, which involves two complementary schemes (Koenig, 2012).	

4.3 Creation of Colour Patterns

Inspired by the colour theory and aiming to ensure harmony and balance, colour patterns were developed from the six colour schemes mentioned in Section 4.2.2. Before creating the patterns, suitable colours were generated by Colour Wheel Pro, a software tool that can automatically generate harmonious colour schemes based on the colour theory. The selected colours can be customised according to saturation and lightness values. Furthermore, the palette can be exported in the Adobe Colour (ACO), ACO Table (ACT), and Graphics Interchange Format (GIF) formats and imported to other software for further development (Colour Wheel Pro, 2015). Although the software can choose colours according to specific schemes, the brightness of secondary colours is higher than that of the primary one. Because the three primary colour technology of the cathode ray tube (CRT) of computers are applied in most tools, with one phosphor applied in the primary colours and two in the secondary colours, and hence the secondary colours are lighter than the primary one. Thus, computer interfaces are presented in the software's colour wheel (Lyons & Moretti, 2004).

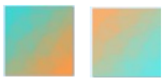
According to the researchers (Helson and Lansford, 1970 Saito, 1994; Wiegersma & Van der Elst, 1988), blue or blue green were the colour groups preferred most across different cultures. Hence, first, the primary colour was chosen from the blue-green tone of NCS colour wheel and soft cyan (S0540-B30G), hex code #74d1d7, was selected because it is available to print out by CMYK colorants (Figure 4.6). Next, Colour Wheel Pro generated a series of colour groups based on the six colour schemes and hex codes, the colours were refined that were available to print out by CMYK colorants. Hex codes were then converted colours into Photoshop CS6 format for the colour pattern creation process. Details of colour pattern groups generated in Colour Wheel Pro are shown in Appendix I. The colour variations groups of each colour scheme involved three colours, except for the monochromatic and complementary schemes, for which only two variations were produced because of the limited number of colours. Colour patterns were then designed in Photoshop CS6 to prepare for texture mapping. The patterns were drawn on a segmented square and filled in with

Figure 4.6 Primary colour chosen in NCS system

Figure 4.7 Segmentation of the design pattern and after filling in colours in triadic colour

colours according to the groups generated by Colour Wheel Pro (Figure 4.7). Colour sequence was the only variable, whereas the pattern segmentation, gradient colour direction, and texture of the 3D virtual object were kept constant. All the colours involved and colour patterns generated in each colour scheme are presented in Table 4.2.

Table 4.2 Colours involved in each colour scheme

Colour Scheme	Colours Involved #Hex code (RGB)/ Colour's name	Colour patterns generated
Monochromatic	#ffffff / White #c5f1f4 / Very soft cyan #74d1d7 / Soft cyan #33cccc / Moderate cyan #339999 Dark cyan	
Analogous	#74d1d7 / Soft cyan #5171b6 / Soft sapphire blue #71bc4f / Soft lime green	
Complementary	#74d1d7 / Soft cyan # ff9966 / Soft orange	
Split Complementary	#ffcc66 / Light gamboge #74d1d7 / Soft cyan #eb6665 / Soft red	
Triadic	# ffea89 / Soft yellow #74d1d7 / Soft cyan #d43c8f / Bright Pink	
Tetrad	#74d1d7 / Soft cyan #718fc9 / Soft blue #ffcc66 / Light gamboge #ff9966 / Soft orange	

4.4 Design Creation in 3D Modelling

Figure 4.8 Creation of basic object

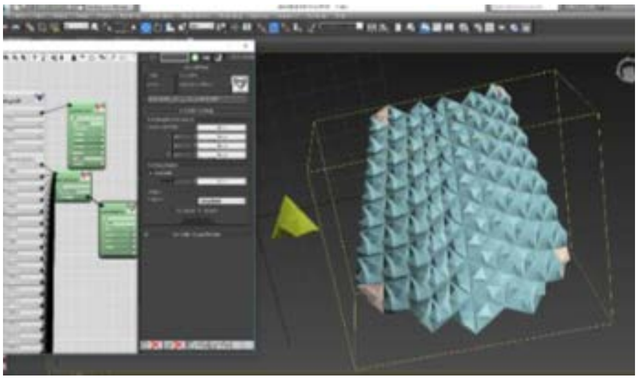


Figure 4.9 Creation of 3D object by Para 3D

The 3D virtual modelling process was performed in 3ds Max with a Para 3D plugin. A basic 3D object was created through polygonal modelling, with three modifiers (blending, tapper, and twist) involved in the process (Figure 4.8). The basic 3D object was then calculated automatically by the Para 3D plugin and laid out on a curved plane (Figure 4.9).

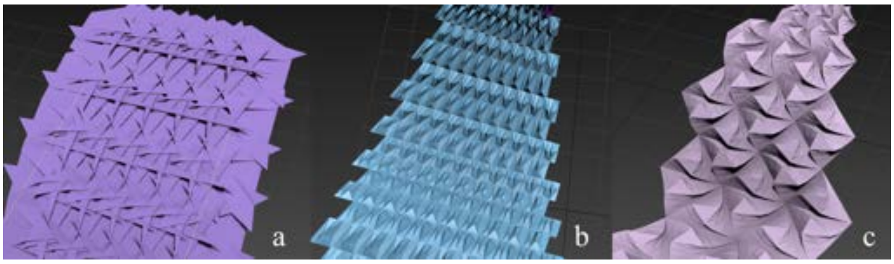


Figure 4.10 a) Star shape design, b) rectangular based design, c) triangular based design

The first 3D model design was in a star shape, which involved various twisting strips (Figure 4.10a). However, the mesh faces were more than 1000 in number because of the complicated structure, and thus, the rendering time was extended. The second design created a rectangular base object, but after arranging the object on a plane, the plane's edges were non-uniform (Figure

4.10b). Finally, a triangular base object was chosen for further development (Figure 4.10c).

4.5 Texture Mapping on Meshes

After creating the 3D virtual design, colour patterns were texture-mapped using a UVW map modifier for modification of pattern position, size, and transparency (Figure 4.11). The texturised 3D virtual design was intended to process UVW unwrapping process and render the texture to create a flat UV map as mentioned in Section 2.4.2.2, so that the 3D printer could recognise the texture coordinates in a later stage of this study (Figure 4.12). Based on the six colour schemes, colour pattern variations with different sequences developed in Photoshop CS6 (Section 4.3) and various textures were wrapped onto the 3D virtual object. Rendering was the final stage for previewing the virtual object to verify whether the colour is satisfactory. Accordingly, the 3D design structure selected in Section 4.4 according to aesthetic and technological characteristics and the colour patterns from Section 4.3 were texture-mapped onto the 3D virtual design during rendering to preview colour performance.

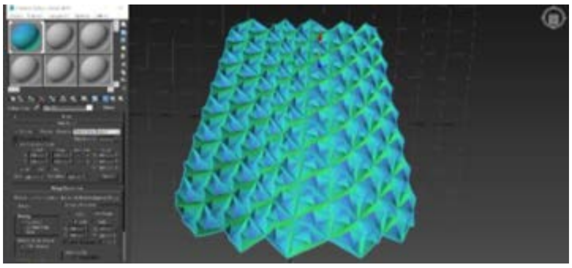


Figure 4.11 Texture mapping by UVW map

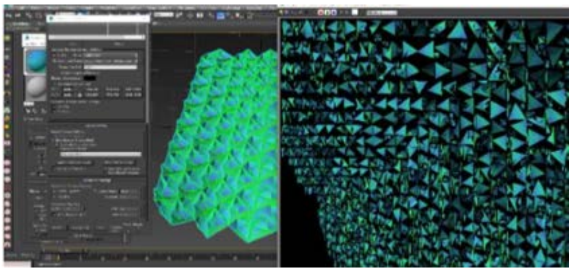


Figure 4.12 UVW unwrapping and render to texture process

4.6 Development of Initial 3D Printed Prototypes

After creating the initial 3D virtual design with texture pattern mapping, object files (OBJ), material files, and UV map files were exported using 3ds Max. Object files were converted in Photoshop CC into Virtual Reality Modelling Language (VRML) which is a format specific for texture mapping files. The 3D printer software received the files and process slicing. The material consumption, weight, cost, and printing time required for the final physical prototypes or supporting materials, if required, could be estimated and calculated. The software then sent instructions to the 3D printer for control and process 3D printing. At this stage, two materials—plaster and resin—were selected for creating the physical prototypes. Two different densities and structural designs were used for 3D printing. Moreover, joints and interlocks were developed for evaluation.

4.6.1 Three-dimensional Printing Materials

The colour pattern in the triadic colour scheme, prototype size of 7.5 × 7 × 2 cm^3, was used as a fixed variable for assessment. Because of resource limitations, only the Zprinter 310 and Stratasys J750 printers were available for multicolour printing, which the files were using texture mapping on meshes colouring method during 3D modelling in CAD. Therefore, two physical prototypes in (a) plaster, printed by the Zprinter 310 with 3DP technology, and (b) resin, printed by Stratasys J750 with PolyJet technology, were created, as shown in Table 4.3. Both prototypes were photographed in daylight in an indoor environment with cool white light.

Table 4.3 Plaster and resin prototypes

<table>
<tr><th colspan="5">Plaster Prototype</th></tr>
<tr><td rowspan="4"></td><td>Colours involved</td><td>Colour Pattern</td><td colspan="2">3D Printing Information</td></tr>
<tr><td rowspan="3"></td><td rowspan="3"></td><td>Printer</td><td>Zprinter310</td></tr>
<tr><td>Method</td><td>3DP</td></tr>
<tr><td>Materials</td><td>Plaster</td></tr>
<tr><td>Overall outcomes and details</td><td colspan="4"> </td></tr>
<tr><th colspan="5">Resin Prototype</th></tr>
<tr><td rowspan="4"></td><td>Colours involved</td><td>Colour Pattern</td><td colspan="2">3D Printing Information</td></tr>
<tr><td rowspan="3"></td><td rowspan="3"></td><td>Printer</td><td>Stratasys J750</td></tr>
<tr><td>Method</td><td>PolyJet</td></tr>
<tr><td>Materials</td><td>Resin</td></tr>
<tr><td>Overall outcomes and Details</td><td colspan="4"> </td></tr>
</table>

4.6.1.1 Assessment of 3D Printing Materials

Each type of 3D printer can print specific materials, and therefore, materials defined the 3D printing methods used in this study, based on the printer specifications. The criteria for 3D materials assessment included colour performance, tactile sensation, rigidity, and weight.

4.6.1.1.1 Colour Performance of Plaster and Resin Prototypes

In plaster prototype, the 3DP technology mechanism was binder jetting, which can print plaster materials, by using binder fuses granular materials to form 3D object, the surface texture of final object was rough due to the granular materials. In resin prototype, PolyJet was one of the material jetting technologies, and liquid resin (photopolymer) was solidified by ultraviolet laser and hence the surface performed was smooth and flat.

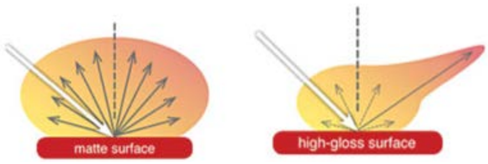


Figure 4.13 The light reflection on matte and gloss surfaces

As mentioned in Section 4.2, colour is perceived by the reflection of light. A rough surface process diffuses the reflection in many different angles, producing a light-scattering effect. Light reflection on a rough surface is weaker and more diffuse, whereas a glossy surface has a higher reflection value (Figure 4.13). As Becker (2016) stated, “As an example, a glossy surface can yield a much more intense colour where a matte or highly textured colour can appear much more subdued” (p.181). A colour’s appearance can thus be affected by the roughness of material surfaces. Smooth surfaces have a high specular reflectance and colours appear more chromatic and vivid, whereas matte surfaces have a high diffuse reflectance, with colours appearing dull and less saturated (Leggett, 2013; Micom, 2014).

As shown in Table 4.2, although both the plaster and resin prototypes gave satisfactory results for colour performance, the plaster prototype's colours were visually slightly faded compared with those of the resin prototype because of the light reflectance principle. In addition to colour performance, colour pattern details were also affected by the printing mechanism. The resin prototype was observed to achieve fine detail in colour segmentation. Furthermore, some defects and ragged edges could be found on the plaster prototype.

4.6.1.1.2 Tactile Sensation of Plaster and Resin Prototypes

Tactile sensation is a major factor in creating fashion garments because they are worn in contact with human skin, which affects comfort during wearing. As already mentioned, the surface texture of the plaster prototype was much rougher than that of resin. On contact with the skin, the plaster prototype caused an itchy and uncomfortable feeling, whereas the resin prototype afforded adequate comfort.

4.6.1.1.3 Mechanical Properties of Plaster and Resin Prototypes

All 3D printing materials have specific mechanical properties designated by the manufacturers. The specification data can help customers make the right decision in purchasing 3D printing materials. According to Formlabs (2018), the definition of mechanical properties were as follows:

(a) Tensile strength is defined as the maximum tension capacity of a material before it breaks (Figure 4.14). High tensile strength means the material affords high load bearing.

Figure 4.14 Tensile strength

(b) Elongation at break is a measure of tensile elongation indicating a breakage point (Figure 4.15). This specification demonstrates whether a material will stretch or break instead of becoming deformed by stretching. Brittle material has a low elongation at break, which means it has a low capability to resist stretch force.

Figure 4.15 Elongation at break

(c) Flexural strength is the amount of force that a material can support before rupturing (Figure 4.16). It is similar to tensile strength, except that here the test is bending rather than breaking under tension. Thus, the compressive and tensile strength of a material.

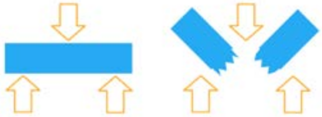


Figure 4.16 Flexural strength

(d) Flexural modulus is the amount of load resistance to bending, which indicates the stiffness or flexibility of a material (Figure 4.17). Stiff materials have high flexural modulus, whereas elastic materials have a low flexural modulus.

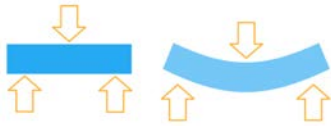


Figure 4.17 Flexural modulus

The mechanical properties of plaster and resin, namely their Vero series, are listed in Table 4.4 and details are shown in Appendix II (3Faktur, n.d.; Stratasys, 2018c). Resin had an approximately 3.5–4.5 times higher tensile strength and 2–3.5 times higher flexural strength than plaster. Resin was also observed to have higher ductility and toughness compared with plaster. Based on elongation at break data, plaster proved to be brittle even when stiff. A brittle material could easily cause breakage due to its low flexibility. Resin achieved an elongation at break of 10%–25%. Although this was higher that than for plaster, it still did not represent a particularly satisfactory value for flexibility in 3D printing materials. The data for flexural modulus indicated that both materials had no elasticity, with the high value for plaster indicating stiffness. The flexural modulus of resin was approximately two times lower than that of plaster, indicating resin's higher flexibility. In summary, resin had better strength and flexibility properties. However, because it had no elasticity and low flexibility compared with other 3D printing materials, appropriate ease allowances should be made when creating 3D printed garments. Furthermore, suitable panel cutting should be designed for easy wear without causing breakage. These considerations will assist the development of subsequent parts of this study.

Table 4.4 Mechanical properties specification of plaster and resin

Mechanical Properties	Plaster	Resin (Vero*)
Tensile strength (MPa)	14.2	50-65
Elongation at break (%)	0.23	10-25
Flexural strength (MPa)	31.1	60-110
Flexural modulus (Mpa)	7163	1900-3200

*Vero in different colours have variation in values.

4.6.1.1.4 Weight Comparison of Plaster and Resin Prototypes

To provide satisfactory comfort to the wearer, a 3D printed garment should weigh as little as possible. The weight of prototypes can thus predict the approximate final garment weight. The weight of plaster prototype was 45.95g and of resin prototype was 31.57g, although both prototypes were printed using the same CAD files in the same sizes (7.5 × 7 × 2 cm^3), resin was 18.6% lighter than plaster.

4.6.1.2 Summary of 3D Printing Materials

The properties and performance of the resin prototype were found to be considerably better than those of the plaster one. Thus, resin was selected as the 3D printing material for further development in this study. A summary is presented in Table 4.5.

Table 4.5 Summary of plaster and resin prototypes

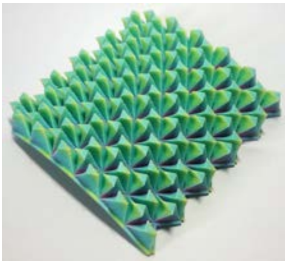
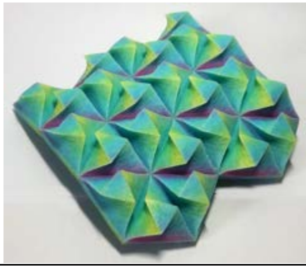
	Plaster	Resin
Colour performance	Excellent but some vision deviation due to light reflection on rough surfaces.	Excellent. Colour patterns were shown with details.
Sensation of touch	Rough surface and may cause itching when in touch.	Smooth surface texture.
Rigidity and flexibility	Stiff but brittle.	Rigid with low flexibility.
Weight	Heavy.	Heavy but lighter than plaster.

4.6.2 Pattern Density Design

Although software rendering can present and preview an object's colour or texture performance, there may be visual or colour tolerance in the virtual effects shown on computers. In the 3D modelling stage, a 3D pattern structure with a controlled size and density can be formed and prototypes of different density and structural design 3D printed for further evaluation.

As shown in Table 4.6, two pattern prototypes different in size and density were produced using the Stratasys J750 3D printer. Both had a size of 7.5 × 7 × 2 cm^3, but the side length of each triangulate pattern was 0.9 cm and area was 0.35 cm^2 in high pattern density prototype and 2 cm and area was 1.73 cm^2 in low pattern density prototype. The pattern arrangement of high pattern density prototype was 10 (row) × 12 (column), so that the total number of triangulate patterns was 120. Similarly, the pattern arrangement of low pattern density prototype was 4 (row) × 6 (column), for a total of 24 triangulate patterns.

Table 4.6 Pattern density design of prototypes

	High pattern density prototype	**Low pattern density prototype**
Side length (cm)/ arrangement of triangle pattern	0.9/ 10 x 12	2/ 4 x 6
Weight of 3D object (g)	21.86	31.68
Weight of supporting materials (g)	62.31	45.95
Rendering time in 3ds max (s)	13	5
Colour performance		

4.6.2.1 Assessment of Pattern Density Design

Pattern size could affect the colour's visual performance. As shown in Table 4.7, a smaller pattern size caused a chameleon effect, with the colour changing at different viewing angles. Moreover, because the pattern size was smaller in scale, the resolution of the mapped-mesh pattern texture was higher, providing clear, sharp colour results. Because higher-density 3D meshes involve more mesh faces, more time was required to render the process after texture mapping. The shell thickness was limited by the size of triangulate pattern, the smaller the size, the thinner the shell. The weight of prototypes was affected by the shell thickness and thus the weight of the low pattern density prototype was lower than the high pattern one. Furthermore, high density pattern generated more cavities and hence increased the consumption of supporting materials.

4.6.2.2 Summary of Pattern Density Design

Due to the material consumption factor, the higher the density, the greater the supporting material's weight and the more time required in the rendering process. Although the colour result was superior for high pattern density, it has not been recommended for use in creating 3D printed garments. A summary is shown in Table 4.7.

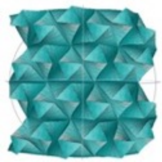
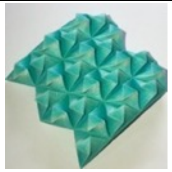
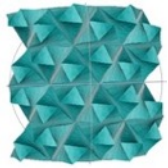
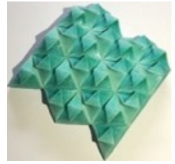
Table 4.7 Summary of pattern density design

	High pattern density prototype	**Low pattern density prototype**
Weight	Lower, but more supporting materials were consumed.	Higher, fewer supporting materials were consumed.
Colour performance	Better with interesting chameleon effect.	Good with sharp colour performance.
Rendering time in 3ds max	Longer time for rendering.	Shorter time for rendering.

4.6.3 Colours

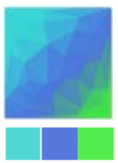
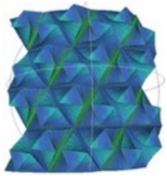
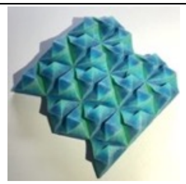
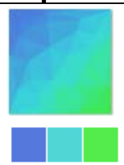
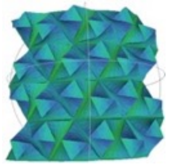
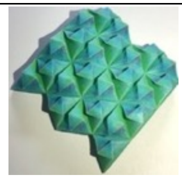
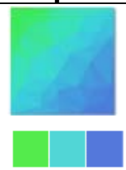
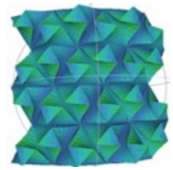
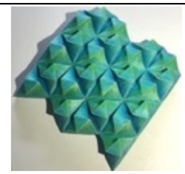
The colour patterns in Section 4.3 were developed and texture-mapped onto meshes. The final 3D virtual designs were verified according to colour pattern, pattern design, density, and structure. All the virtual designs were 3D printed with the size of 7.5 × 7 × 2 cm^3 as physical prototypes to assess their aesthetic and colour performance. In total, 16 physical prototypes were grouped into six colour schemes (Table 4.8 to 4.13), where comments are given for each prototype. All prototypes were photographed in daylight in an indoor environment with cool white light.

Table 4.8 Initial 3D printed prototypes with monochromatic colour scheme

Mono-1			Mono-2		
Pattern/ Colour sequence	**Virtual model rendering picture**	**Physical prototype**	**Pattern/ Colour sequence**	**Virtual model rendering picture**	**Physical prototype**
					
Comments: Good performance but segment pattern and colour variations were not obvious.			**Comments:** Good performance but segment pattern and colour variations were not obvious.		

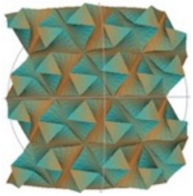
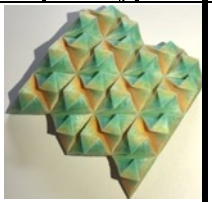
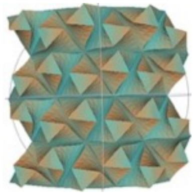
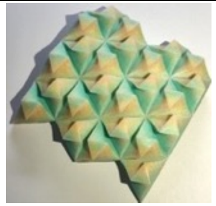
Colour hex code and name: #ffffff White #c5f1f4 Very soft cyan #74d1d7 Soft cyan #33cccc Moderate cyan #339999 Dark cyan

Table 4.9 Initial 3D printed prototypes with analogous colour scheme

Ana-1			Ana-2			Ana-3		
Pattern/ Colour sequence	**Virtual model rendering picture**	**Physical prototype**	**Pattern/ Colour sequence**	**Virtual model rendering picture**	**Physical prototype**	**Pattern/ Colour sequence**	**Virtual model rendering picture**	**Physical prototype**
								
Comments: Colour fidelity appeared on the gradual colour change from moderate cyan to soft lime green.			**Comments:** Soft lime green faded and soft sapphire blue was greenish.			**Comments:** Soft lime green faded.		

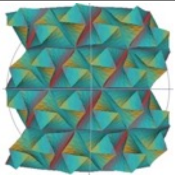
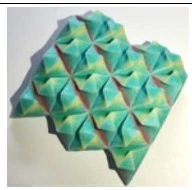
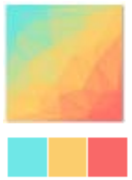
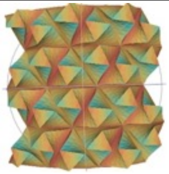
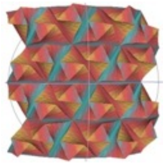
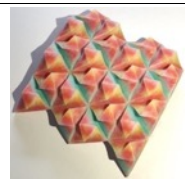
Colour hex code and name: #74d1d7 Soft cyan #5171b6 Soft sapphire blue #71bc4f Soft lime green

Table 4.10 Initial 3D printed prototypes with complementary colour scheme

Comple-1			Comple-2		
Pattern/ Colour sequence	**Virtual model rendering picture**	**Physical prototype**	**Pattern/ Colour sequence**	**Virtual model rendering picture**	**Physical prototype**
					
Comments: Serious colour fidelity appeared, whole piece paled.			**Comments:** Serious colour fidelity appeared, whole piece paled.		

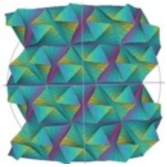
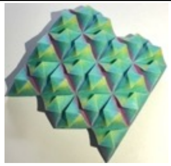
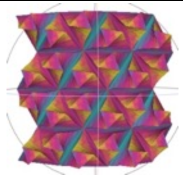
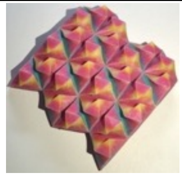
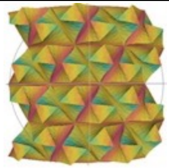
Colour hex code and name: #74d1d7 Soft cyan #ff9966 Soft orange

Table 4.11 Initial 3D printed prototypes with split complementary colour scheme

Split Comple-1			Split Comple-2			Split Comple-3		
Pattern/ Colour sequence	**Virtual model rendering picture**	**Physical prototype**	**Pattern/ Colour sequence**	**Virtual model rendering picture**	**Physical prototype**	**Pattern/ Colour sequence**	**Virtual model rendering picture**	**Physical prototype**
								
Comments: Satisfactory result but soft red did not reach standard.			**Comments:** Both soft red and light gamboge faded.			**Comments:** Soft red faded.		

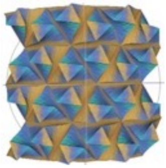
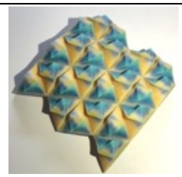
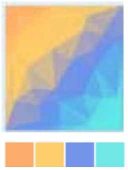
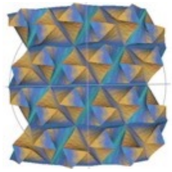
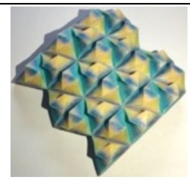
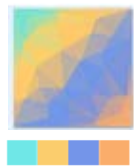
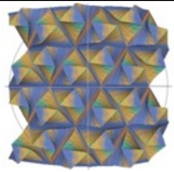
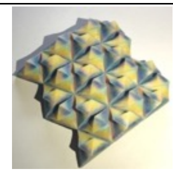
Colour hex code and name: # ffcc66 Light gamboge #74d1d7 Soft cyan #eb6665 Soft red

Table 4.12 Initial 3D printed prototypes with triadic colour scheme

Tri-1			Tri-2			Tri-3		
Pattern/ Colour sequence	**Virtual model rendering picture**	**Physical prototype**	**Pattern/ Colour sequence**	**Virtual model rendering picture**	**Physical prototype**	**Pattern/ Colour sequence**	**Virtual model rendering picture**	**Physical prototype**
								
Comments: Good result with satisfactory sharpness and clear pattern details.			**Comments:** Good but bright pink slightly faded			**Comments:** Good but segment pattern was not obvious, and sharpness did not reach expectations.		

Colour hex code name: # ffea89 Soft yellow #74d1d7 Moderate cyan # d43c8f Bright Pink

Table 4.13 Initial 3D printed prototypes with tetrad colour scheme

Te-1			Te-2			Te-3		
Pattern/ Colour sequence	**Virtual model rendering picture**	**Physical prototype**	**Pattern/ Colour sequence**	**Virtual model rendering picture**	**Physical prototype**	**Pattern/ Colour sequence**	**Virtual model rendering picture**	**Physical prototype**
								
Comments: Serious colour fidelity appeared, soft orange was yellowish.			**Comments:** Serious colour fidelity appeared, soft orange was yellowish and soft blue was greenish.			**Comments:** Serious colour fidelity appeared, soft orange was yellowish.		

Colour hex code and name: #74d1d7 Soft cyan #718fc9 Soft blue #ffcc66 Light gamboge #ff9966 Soft orange

4.6.3.1 Colour Assessment

Although the 3D printer Stratasys J750 can achieve nearly full-colour printing in both CMYK and RBG, with more than 360,000 colours, it still has technical limitations in terms of colour accuracy (Goehrke, 2016; Stratasys, 2018b; Xiao et al., 2016;). Colour fidelity represents a major challenge for full-colour 3D printing technology, and manufacturers are still searching for solutions to improve the overall quality of 3D colour printed products. Colour fidelity problems occur not only in 3D printing but also in image processing during CAD (Xiao et al., 2016).

In assessing colours, physical prototypes with serious colour fidelity problems were eliminated from the study. These problems included (a) fading on the Ana-1, Ana-2, Ana-3, Comple-1, Comple-2, Split Comple-2, Split Comple-3, Te-1, Te-2, and Te-3 prototypes; (b) colour switching on the Ana-2, Te-1, Te-2, and Te-3 prototypes; and (c) colour pattern image blurring on the Mono-1, Mono-2, Comple-1, Comple-2, Split Comple-2, Tri-3 and Te-3 prototypes. The results showed that light and soft colour prototypes could not achieve satisfactory performance on gradient colours changing. Also, it was found that light gamboge (#ffcc66), soft orange (#ff9966), and soft lime green (#71bc4f) had the most serious colour fidelity defects, and therefore the corresponding prototypes in the analogous, complementary, split complementary, and tetrad schemes were eliminated from the study. The Split Comple-1 prototype achieved satisfactory results but was still removed from the study because it was involved in the split complementary scheme and light gamboge (#ffcc66) was included in this prototype.

In the monochromatic group, colour performance was satisfactory owing to the monochromatic harmony effect, which is “used to suggest some kind of emotion since every hue bears specific psychological intensity” (Ivanova & Stanchev, 2009, p. 182). However, because the colours were chosen from the same hue with different shades and tones, the colour segmentation pattern was less obvious than that of the triadic scheme. Moreover, researchers (Lauer & Pentak, 1995; Stewart, 2002) have indicated that the triadic colour scheme is perceived as lively and can be used for a strong effect. Therefore, the Tri-1 and Tri-2 prototypes were the focus of further evaluation.

Blue was the dominant hue in Tri-1, and red of Tri-2. Several studies have indicated that longer-wavelength colours such as red and orange are perceived as arousing, whereas shorter-wavelength ones are viewed as calming (Kwallek, Woodson, Lewis & Sales, 1997; Stone & English, 1998). Blue was the colour preferred most across different cultures (Wiegersma & Van der Elst, 1988). Helson and Lansford (1970) examined 125 colours in preference studies and noted the following:

> “Taking the top 25 rankings, we find that 11 are either B or PB, eight are G or BG and only six are R, RP, or Y ...In grouping colours into colour families ... the blues, purple-blues, greens and blue-greens are among the

> top seven colour families, while five of the seven bottom colour families are yellow or have a yellow component." (pp. 1523-4)

Saito (1994) studied colour preferences among Asians and found that blue was preferred most among hue groups, followed by green and purple-blue. The results for red varied by chroma and value, with medium value and low chroma red considered the most pleasant and high-chroma red viewed as pleasant regardless of the value, whereas bright red with medium or low chroma was deemed unpleasant (Hogg, Goodman, Porter, Mikellides & Preddy, 1979). Blue was thus found to have less variation in terms of colour preference, with overall constant positive preference results.

Moreover, perceptions and associations of blue were mostly positive and related to pleasant feelings such as secure, comfortable, tender, and soothing (Wexner, 1954); calm, pleasant, and soothing (Sundstrom & Sundstrom, 1986); limitless, calm, and serene, relating blue to the ocean and sky (Hemphill, 1996). Red had more discrepant colour associations, with some researchers found red to be associated with happiness (Soldat, Sinclair, & Mark, 1997), but other authors suggested other negative meanings (Cimbalo, Beck & Sendziak, 1978; Valdez & Mehrabian, 1994). Some studies have associated red with excitement because of its arousing, stimulating effect (Clarke and Costall 2007; Wexner 1954; Murray & Deabler 1957). However, red was also related to signs of threat, danger, or blood in certain nonhuman animals (mandrills and rhesus macaques), and red bodily patterns or colours indicated dominance or attack-readiness (Setchell & Wickings, 2005). Similarly, for humans redness of face can be caused by anger or aggressiveness (Changizi, 2009). Red is usually the representative colour in warning symbols and alarms, or in marking errors (with a meaning of failure) (Elliot, Maier, Moller, Friedman & Meinhardt, 2007; Moller, Elliot, & Maier, 2009).

4.6.3.2 Summary for Colours

In summary, following assessment of 16 physical prototypes and comparison with virtual rendering models, the Tri-1 and Tri-2 prototypes showed satisfactory performance. Moreover, blue was the preferred hue in most studies of colour perceptions and associated meanings. Therefore, the Tri-1 prototype was selected for further examination in this study.

4.6.4 Initial 3D Printed Prototypes of Interlocks and Joints

Because of size limitations in 3D printing platforms, garments must be printed in parts; joints and interlocks have thus been designed to connect the panels of the final 3D printed garment.

4.6.4.1 Initial 3D Printed Interlock Prototypes

The interlock design concept was based on existing designs in the recent fashion market. Designers have developed various interlocks for joining 3D printing garment panels. Most 3D printed fashion garments or accessories are divided into small segments without printer size limitations, which means that both joints and interlocks are printed integrally, with no assembly required. In this study, large separated panels were used and cutting was required; therefore, joints and interlocks were created. Because joints and interlocks work in pairs, designing them together according to the specifications was necessary. Two interlocks created by other designers were studied and modified for application in this study.

4.6.4.1.1 Interlock Design Concepts

The first interlock design was inspired by the Spire dress, designed by Alexis Walsh and Ross Leonardy in 2014, consisting of more than 400 nylon tiles 3D printed using the SLS method (Figure 4.18). The garment was hand assembled using metal wire rings connecting two hole-like joints and an inconspicuous zipper at the back (Walsh, 2014).

Figure 4.18 Connecting method of the spire dress

The second interlock design inspiration was the 3DTie developed by Rabinovich, whose unique interlocking design was created using the 3D CAD software PTC Creo

Figure 4.19 Interlock designs of 3DTi

(Figure 4.19). Each 3DTie was composed of more than 100 tiles clipped onto one another to provide flexible movement. The ties were 3D printed on PLA plastic and were wrinkle free and freely foldable for storage (Kira, 2016).

A new interlock design was developed in the current study according to these two designs. Because large separate panels were being designed, the interlocks had to provide a sufficiently large opening for assembly. The interlock's dimensions are shown in Figure 4.20. After 3D modelling was performed using 3ds Max, the STL files were transferred to 3D printers. Three 3D printing materials were selected, namely ABS, PLA, and tough PLA with FDM technology. Both ABS and PLA are common thermoplastics with high flexural strength and elongation at break—they possess flexibility and tolerance under heavy force. However, because of the FDM mechanism, the layers are visible in the final product. ABS products appear matte and PLA products appear semi-glossy. Moreover, PLA is stable and biodegradable within 50 days in industrial composters or 48 months in water, whereas ABS is nonbiodegradable but recyclable (Giang, n.d.).

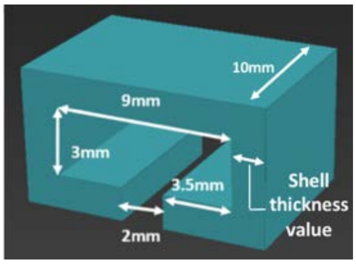


Figure 4.20 The design and measurement of interlock

4.6.4.1.2 Interlock Assessments

The prototype interlocks were examined according to their given material's features, and the results are shown in Table 4.14. Although these three materials could achieve satisfactory performance for strength or flexibility, according to the mechanical properties provided by suppliers (see Appendix III), both tough PLA and PLA have higher strength than ABS (MakerBot, n.d.). Also, only PLA could provide a suitably translucent material colour and was therefore selected for further development.

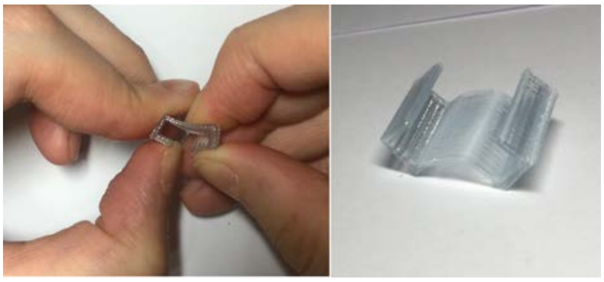


Figure 4.21 Deformation of the 1-mm prototype

According to a suggestion by Giang (n.d.) that the minimum wall thickness of the interlock design should be 1–2 mm, three shell thicknesses of 1, 1.5, and 2 mm were 3D printed on PLA for evaluation. The 1-mm PLA interlock was easily deformed by manual force (Figure 4.21), whereas the 2-mm one was highly tough and lacked flexibility. Therefore, the 1.5-mm transparent blue PLA interlock prototype was finally chosen for joint development.

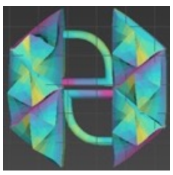
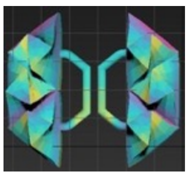
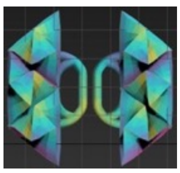
Table 4.14 Interlock assessments

	Interlock Prototype 1	Interlock Prototype 2	Interlock Prototype 3
Pictures			
Materials	ABS	Tough PLA	PLA
Colour	Only white was available.	Only dark grey was available.	14 solid and 7 translucent colours were available.
Texture	Rough.	Rough.	Rough with glossy surface.
Mechanical properties	Achieve the least strength.	Tough and can deform elastically but achieve the least flexibility.	Can bear large load but less tolerance on deflection before break.

4.6.4.2 Initial 3D Printed Joint Prototypes

Based on the interlock dimensions specified in Section 4.6.4.1.1, four joint designs of different shapes and directions were developed, with a 6-mm slit distance between panels as a precondition. The joint thickness was unified to 3-mm. Joint prototype 1 was folded along the y-axis, whereas joint prototypes 2 to 4 were folded along the x-axis. Because the joints would be part of the final garment panels, all the prototypes were printed on resin materials using the Stratasys J750 printer. The prototype renderings were shown in Table 4.15.

Table 4.15 Joint design renderings

Joint Prototype 1	Joint Prototype 2	Joint Prototype 3	Joint Prototype 4
			

4.6.4.2.1 Joints Assessments

The aim of assessing the joints and interlocks was to investigate the panel-joining method in terms of feasibility, flexibility, fastening performance, convenience of opening, and folding angles. The joint designs were 3D printed for assessments. Because the joints and interlocks were closely related, assessments were performed by joining them together. The interlock prototypes were fastened to the joints and each group was then tested by (a) slipping upwards and downwards (Figure 4.22a), and (b) twisting (Figure 4.22b), and two types of digital callipers, one with long jaw (Figure 4.23a) and one with point jaw (Figure 4.23b), were applied to record the resulted values of tests. For the slippage test, the prototypes were placed on a flat surface and then sliding upwards and downwards, and the amount that the joints moved away from the original position was measured by using calliper. In the twisting test, the joints in pair were twisted by hand and the gap amount (y) created between two joints was recorded, while the length (x) of joint was fixed. By using the

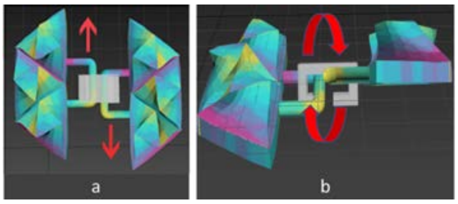


Figure 4.22 Method of assessment a) slipping upwards and downwards, b) twisting

Figure 4.23 a) Long jaw digital calliper b) point jaw digital calliper

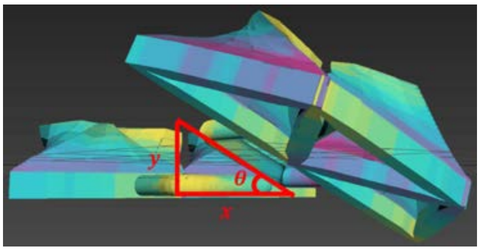


Figure 4.24 The position of twisting angle

basic formula of trigonometry, $\tan\theta = \frac{y}{x}$, maximum possible angle for twisting the joint was calculated (Figure 4.24).

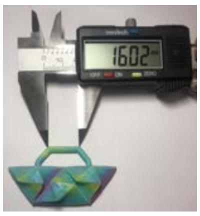
The folding direction of joint prototype 1 was unsuitable for placement on a vertical seam and was therefore eliminated from this study. According to the results in Table 4.16, joint prototype 3 had the largest amount of slippage. Because joint slippage can cause distortion of the garment silhouette, this prototype was also eliminated. The twisting test is shown in Table 4.17. Since the twisting angle was limited by the inner width of the interlock, three joint prototypes achieved similar values around 18°. However, the smaller the twisting angle value, the lower the flexibility of ease allowances on the final garment. The interlock design thus has to be further developed to find a suitable solution on flexibility.

Prototypes 2 and 4 achieved similar results in both tests, but prototype 4 provided additional reinforcement support at the root and could add design details to the final garment, whereas prototype 2 provided higher stability in avoiding slippage between panels and consequent deforming of the silhouette. Therefore, joint prototype 4 was used for all panel connections, whereas joint prototype 2 was placed at the opening seams.

Table 4.16 Joint assessment of slipping upwards and downwards

	Joint Prototype 2	Joint Prototype 3	Joint Prototype 4
Picture of original position			
Picture of position after slippage			
Slipping value (mm)	3.1	7.4	4.3

Table 4.17 Joint assessment of twisting

	Joint Prototype 2	Joint Prototype 3	Joint Prototype 4
Gap amount during twisting (y)	 5.33 mm	 5.30 mm	 5.14 mm
Length of joint (x)	 16.73 mm	 16.02 mm	 15.17 mm
Twisting angle (θ)	17.67°	18.31°	18.72°

4.6.4.3 Alternative Interlock Solutions

Figure 4.25 The breakage on resin joint

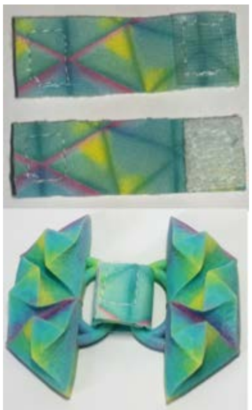


Figure 4.26 Neoprene Interlock and after joining with joints

Because resin has low flexibility and elasticity, a resin joint can easily cause breakage in a large prototype when connecting with PLA interlock because of the force concentrated on the joints (Figure 4.25). Moreover, the assessment results in Section 4.6.4.2.1 showed PLA interlock limited the twisting angle of the joints that could cause low flexibility on the final garment. The interlock design thus returned to the conceptual development stage to seek alternative methods of solving the problems of flexibility and elasticity. Because of the limitations of 3D printing materials, other materials were considered. Neoprene fabric was selected for a modified design based on the interlock designed in Section 4.6.4.1.1. It was cut and digitally printed with colour patterns, and Velcro was sewn on both sides to form a loop closure. The neoprene was 1.5×5 cm^2 in size, whereas the Velcro was 1×1 cm^2, based on the dimensions of the joints (Figure 4.26).

4.6.4.4 Summary for Interlocks and Joints

The neoprene interlock design was finally adopted for flexibility and elasticity. Moreover, digital printing on neoprene enabled better design element performance than 3D monocoloured printed prototypes did. When the joints and interlocks were assessed together, the design of prototype joint

4 was applied to all panel connections for its reinforcement properties, whereas joint prototype 2 was placed on the opening seams for its stability against slippage.

4.7 Conclusion

In this chapter, the initial prototypes were created and then evaluated according to their design elements and technological characteristics. Specific solutions were discovered and new problems were resolved through the feedback loop between evaluation and synthesis. Moreover, 3D printed materials, 3D model structure designs, texture density structure, colouration, and joint and interlock design were selected and applied in designs with detailed specifications for creating a final 3D printed fashion prototype in the next stage of this study. A summary is given in Figure 4.27.

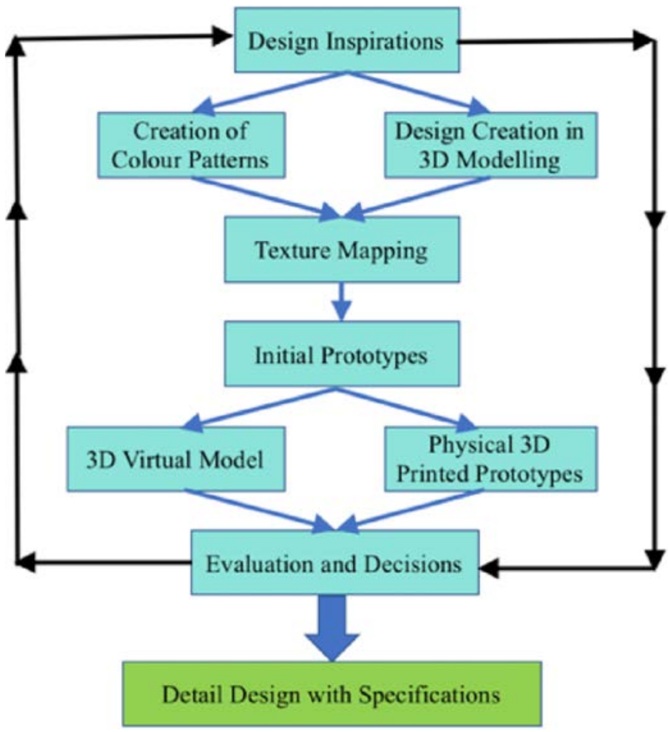


Figure 4.27 Summary of Chapter 4

CHAPTER 5: CREATION OF A 3D PRINTED FASHION PROTOTYPE WITH INNOVATIVE SURFACE TEXTURE

5.1 Introduction

In this chapter, the development of a 3D printed fashion prototype with an innovative surface texture is presented. After the evaluation of initial prototypes according to different criteria and considering technological and aesthetic factors in Chapter 4, decisions are made and applied to development of the final prototype. Suitable ease allowances are evidenced using 3D body scanning data. Design considerations for selection and development of the silhouette, panel cutting design, and shell thickness distribution are made, and finally, a 3D printed fashion prototype with an innovative surface texture is created.

5.2 Preparation for 3D Modelling of the Final Prototype

Figure 5.1 Scanning a size 10 dummy by 3D body scanner

Similar to the draping method used in real pattern-making, a 3D virtual dummy was required as a template for 3D modelling of the virtual garment and mapping of the virtual fabric mesh. A 3D body scanner was used to adapt the 3D virtual model and obtain accurate measurement data for a standard size 10 dummy (Figure 5.1 & 5.2). In addition to providing body measurement data at specific points, the scanner software converted the 3D mesh model into STL or OBJ format. Redundant mesh, such as that for the dummy stand, could be deleted in the software. However, some blind spots emerged during the 3D body scanning process because the laser could not reach certain angles on the dummy, and the missing data would thus appear as holes in the model mesh. Therefore, repairing the broken mesh by using the software before file conversion was necessary. In some cases, it may not be possible to auto-repair serious mesh defects by using the scanner software; thus, the repair process must be performed later using 3ds Max by creating a new mesh (Figure 5.3). After the body measurement data was obtained and basic repairs were made, the 3D model of the dummy was imported into 3ds Max as a basic template for 3D modelling development of the final garment.

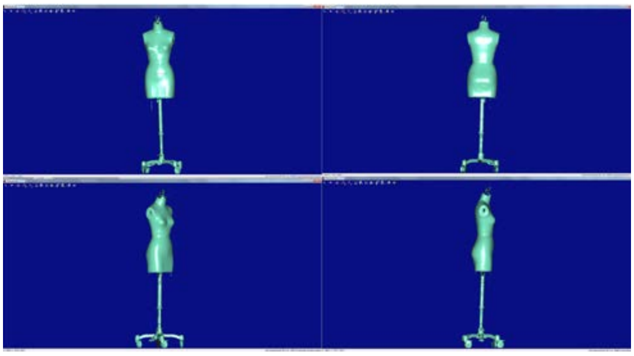


Figure 5.2 A 3D mesh of a size 10 dummy scanned by 3D body scanner

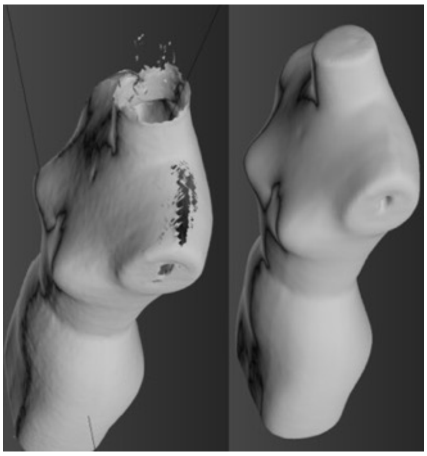


Figure 5.3 Before and after repairing meshes on the size 10 dummy's 3D model

5.2.1 Ease Allowance Through 3D Body Scanning

Ease allowances applying ergonomics for increased wearing comfort of the final 3D printed garment were examined. The final prototype was regarded as first-degree garment (clothing worn on top of underwear). According to the ease allowance data in the literature reviewed in Section 2.6.2.2, an ease allowance percentage was calculated and applied to the 3D virtual dummy. The ease allowance percentage used and data before and after adding ease allowances are shown in Table 5.1. A final 3D model of the size 10 dummy with added ease allowances was created and prepared for the 3D modelling process of the final garment (Figure 5.4).

Figure 5.4 The original size 10 dummy and 3D model after adding ease

Table 5.1 Size 10 dummy measurements before and after ease allowances

Measurement point	Original measurement (cm)	Ease allowances (cm) suggested by journals	Measurement after adding ease (cm)	(+) %
Neck	34	0.75	34.75	2.2
Shoulder	38	3	41	7.9
Bust	82	6	88	7.3
Waist	64	4	68	6.3
High hip (4" below waist)	79	6	85	7.6
Top hip (9" below waist)	89.5	6	95.5	6.7

5.3 Detailed Design with Specifications

Suitable 3D printing materials, colour pattern, pattern density, and joint and interlock designs were selected for implementation in development of the final 3D printed fashion prototype, after thorough consideration of the assessment criteria. On the basis of the design considerations, detailed design specifications for the final 3D printed fashion prototype with an innovative surface texture comprised the following: (a) panel cutting, (b) silhouette and texture density, (c) shell thickness, (d) joints and interlocks, (e) colouration and texture mapping, and (f) 3D printing materials and process.

5.3.1 Design Considerations for the Final 3D Printed Prototype

The garment panel's weight distribution on the body and the amount of additional load bearing that its weight added would cause discomfort to different body parts. The load tolerance of body parts has been studied (Gemperle, Kasabach, Stivoric, Bauer & Martin, 1998; Scribano, Burns & Barron, 1970; Watkins, 1995) and researchers have suggested that, from a physiological point of view, the lower torso can bear higher loads than the upper torso. Sensitive areas, such as the nipples, area around the neck, or areas where veins, arteries, or nerves are concentrated beneath the skin, are highly sensitive to both weight and pressure; even a minor load added to the neck area can hinder blood supply to the brain and cause discomfort. Moreover, pain can result if weight is applied to bony areas. To avoid affecting balance, weight should be evenly distributed over the body, mainly on the stomach, waist, and hips, which form the centre of gravity. A body map of affordable load values for different body parts was developed by Zeagler (2017) and modified according to the factors considered in this study, with the new developed body map shown in Figure 5.5.

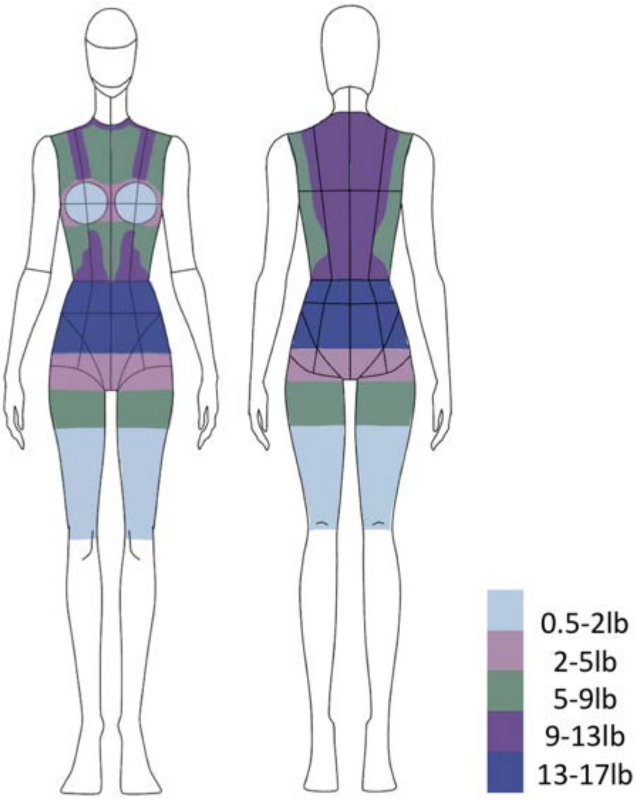


Figure 5.5 Body map of affordable load values for different body parts

From a psychological perspective, design elements can disrupt human perception through psychological forces. Arnheim (1974) stated,

> "What a person or animal perceives is not only an arrangement of objects, of colours, shapes, of movements and sizes. It is, perhaps first of all, an interplay of directed tensions. … Because they have magnitude and direction they are called psychological forces." (p. 11)

A symmetrical design can create centred balance and achieve stability and rhythm can create a flow that guides the eye's focus. The visual weight generated by an object's size, shape, or colour can cause rhythmic effect; it will be explained later in this study (Arnheim, 1974; Technology & Living Resource, 2011).

Thus, the design considerations for the final 3D printed garments were as follows:

a) Placement of weight or load on bony areas, particularly the spine or ribcage, should be avoided.
b) Concentration of weight or load on the bust should be avoided because the nipples are sensitive and because it may cause breathing difficulties.
c) Placement of weight or load on the neck—a location where blood vessels and nerves are concentrated—should be avoided.
d) Hips are the least sensitive to pressure and thus can carry the heaviest weight.
e) Shoulder area can tolerate weight over a long period.
f) Weight of the garment should be focused on the centre of gravity.
g) Weight of the garment should be evenly distributed on the body.
h) Design details that may hinder the perception of wearers or affect psychological factors, such as using silhouette or texture to lend a sense of rhythm to the garment.

5.3.2 Panel Cutting

The final garment prototype was divided into several panels according to the specifications of the 3D printer, where the maximum size of the printing platform was $49 \times 39 \times 20\ cm^3$ (Stratasys, 2018b). Thus, each panel had to be designed within this size limitation. According to Leach and Farahi (2017),

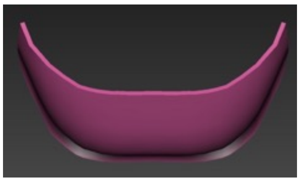
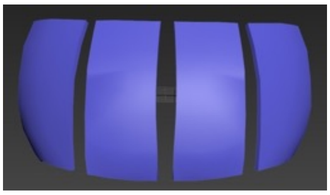
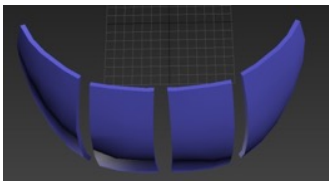
> "In fashion, 3D digital garment design eliminates the need of seam locations for cutting patterns and blueprints. They are irrelevant now. The additive manufacturing process determines new locations of seams in relation to the size and bounding box of the machine build platform. Further, the locations of seams depend on the decision of the computational designer who develops strategies of assembly from part to whole." (p. 43)

It was also necessary to consider the effect of seams or cutting lines on bodily movement. Cutting lines should be placed on areas with joint stretch or flex to enable the body to bend and move effectively.

To achieve a balanced and stable appearance in the final prototype, a symmetrical design was adopted. The bottom panel seams were in dynamic flow, which was a visual weight factor that imparted a rhythmic effect and guided focus from the top to the bottom of the garment (Technology & Living Resource, 2011). Moreover, the curve lines could express fluidity, femininity, and correct body shape (Khurana, 2007). Based on the design considerations of weight distribution and cutting lines in this study, location on the front central, rear central, waist, and thigh areas of the garment was considered for the panel's cutting. The total number of panels was 12, with 10 small connecting segments. The top garment was divided into four main panels, namely the right bust (RB), left bust (LB), back top (BT), and neck collar (NC), and the connection of the NC with the RB and LB was designed using small segments whose length could be finely adjusted when worn on a real human body. Because the neck area is sensitive to loads, the NC was designed across the back of the shoulder below the neck to avoid adding weight to the neck area; across the back could result the weight distributed evenly to avoid heavy loads concentrate on both shoulders. Moreover, the rear central area was located on the spine and designed by connecting several segments to fit the spine's concave shape and disperse weight or load on that area. Because of the panels' joint connection design, the BT was designed as one integrated panel, rather than as two separate panels, in the rear central area.

The bottom garment was divided into eight main panels, namely centre front right (CFR), centre front left (CFL), side front right (SFR), side front left (SFL), centre back right (CBR), centre back left (CBL), side back right (SBR), and side back left (SBL). In addition to mobility factors, the reason for designing with eight, rather than four, panels was material consumption. Because PolyJet 3D printing would require water-soluble supporting materials during the printing process, which the function of supporting materials is to aid the overhanging parts that are over 45°.

Table 5.2 Comparative material consumption of an integrated panel and a panel divided into four

	One integrated panels	Divided into four panels
Rendering picture	 	 
Estimate resin weight (g)	1540	1470
Estimate supporting materials' weight (g)	6828	4503

As shown in Table 5.2, both curved objects were in 10 x 25 x 45 cm^3, with 2-mm thickness. If the object was printed as one integrated panel, the amount of resins consumed would be nearly the same as that for the one divided into four panels, but the consumption of supporting materials would be approximately 1.5 times more. This is because the angle of overhanging parts in an integrated panel is much larger than that of separate panels, due to the location of printing objects on the printer platform. The larger the overhanging angles, the higher the consumption of supporting materials. Nevertheless, a BT of one integrated panel was unavoidable because of joint design considerations. Because focusing the weight on the centre of gravity was a design consideration, the bottom garment's central panel size in front

(CFR and CFL) and back (CBR and CBL) was larger than on both sides and in a round leaf shape pointing toward the ground, with the highest weight at the centre front and back. The compact leaf shape with a tip pointing downward could also create an illusion of weight because the mass was concentrated at the centre (Arnheim, 1974). The size of the long panels was limited by the maximum length of the printer platform. After all these details had been considered, the numbers of panels and the location of seams were confirmed, as shown in Figure 5.6. Base on the location of seams, fashion illustration and production drawings were created (Figure 5.7).

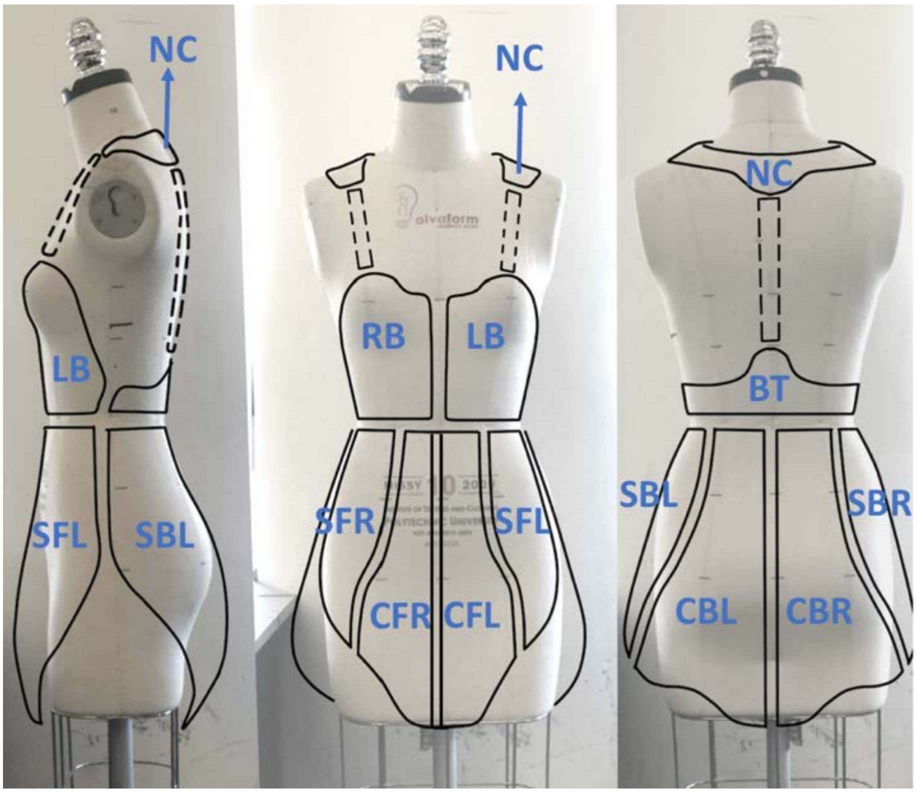


Figure 5.6 The panels' design draft on the size 10 dummy

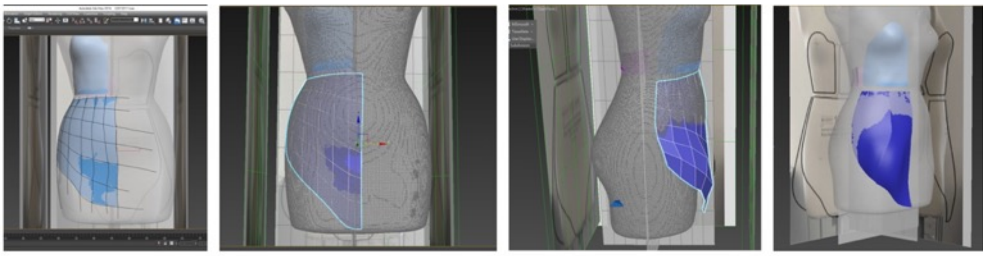
Figure 5.7 Fashion illustration and production drawings of the final fashion prototype

5.3.3 Silhouette and Texture Density

Silhouette is the overall outline of the garment that gives its first impression (Technology & Living Resource, 2011; Wolfe, 2012). One of the design considerations in this study was to apply shape factors for visual weight. Arnheim (1974) noted that regular, simple, geometrically or vertically oriented forms were perceived as heavier than irregular or oblique shapes. Considering this, the final 3D printed garment was designed with an hourglass silhouette, and the bottom part was given an irregular, tulip-like shape for fullness.

Figure 5.8 Dummy's 3D model with reference template

At this stage, a dummy's 3D model and a drawing draft of the final garment with panel cutting specified should be ready for import into 3ds Max, as a reference template for the 3D modelling process (Figure 5.8). After the virtual model has been defined using body measurements with suitable ease allowances, the PolyDraw function in 3ds Max can quickly outline the desired silhouette to create mesh that project on or said as "Draw On" the surface of the dummy's 3D virtual model. Topology is a geometry tools in PolyDraw, during the drawing process lines were drawn to form a grid of quads. The tools can transform the quads into polygon faces and create new faces. The new mesh was plastered beyond the dummy’s 3D model, it was necessary to drag and move the meshes to create the desired silhouette according to the draft template. The intersection points on the meshes were vertexes that could be dragged or moved away from the dummy. If the vertexes were moved below the dummy or too far away from it, the Conform Brush function could move them forward or mould and plaster the meshes onto the dummy. The panel meshes were then smoothed to form the basic silhouette of the final garment, forming the base template for the Para 3D plugin to work on. The creation process is outlined in Figure 5.9 and more details can be founded in Appendix IV.



a) Drawing grid of quads b) Creating into a new mesh c) Dragging vertexes d) Smoothing the mesh

Figure 5.9 The creation process of panels by PolyDraw tool

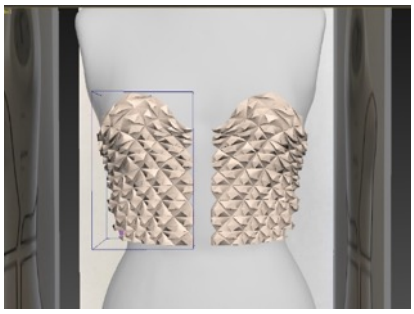


Figure 5.10 Texture created by Para 3D

Similar to initial prototype development in Chapter 4, Para 3D helped to tile and place the basic object on the panel meshes and create pattern density (Figure 5.10), process details are shown in Appendix IV. The appropriate number of rows and columns had to be entered in the one-dimensional array (1D) and two-dimensional array (2D), respectively; the number of rows and columns for each panel are shown in

Table 5.3. The bottom panels were hollowed out to minimise the weight of the final garment, thus also reducing materials consumption. Because of social acceptability factors, the top garment was not designed with hollows. Moreover, the pattern density was graduated from higher in the top garment to lower in the bottom one, creating a repetitive rhythm whose flow would guide the viewer's eye from top to bottom.

Table 5.3 Number of rows (1D) and columns (2D) in each panel

Name of the panel	**Row (1D)**	**Column (2D)**
Right bust (RB)	8	10
Left bust (LA)	8	10
Back top (BT)	3	28
Neck collar (NC)	3	40
Centre front right (CFR)	15	5
Centre front left (CFL)	15	5
Side front right (SFR)	15	8
Side front left (SFL)	15	8
Centre back right (CBR)	15	6
Centre back left (CBL)	15	6
Side back right (SBR)	15	8
Side back left (SBL)	15	8
Small segment (each, total 10 pieces)	2	3

5.3.4 Shell Thickness

After the texture mapping process was finished, the shell was added onto the meshes. The wall of the virtual rendering object can be as thin as possible, but there should be thickness constraints for a physical 3D printed object.

Shell thickness greatly affects the weight of the prototype and final garment. A solid structure has the greatest weight; moreover, because of materials consumption, the thinner the shell, the lower the weight. According to the 3D printer specifications, however, the minimum layer thickness is 0.8-mm, below which tearing may occur or 3D printing may not be possible (4D Concepts, n.d.). Furthermore, a garment with low shell thickness is delicate and fragile. Because the pattern design in this study did not require delicate details, a minimum thickness of 1.5–2 mm was selected for better reinforcement.

According to the design considerations and the weight distribution body map in Section 5.3.1, garment panel weights were kept within the defined values. The panel weight with different shell thicknesses was calculated using GrabCAD Print, which is recommended for the Stratasys J750 3D printer. This software has an add-on GrabCAD Voxel Print Utility for controlling 3D colour printing in every pixel of a 3D object, both on its outer surface and inside it; this is called Voxel Printing in reference to a 3D version of the pixel (GrabCAD, 2018). By using this software, the final weight and materials consumption of 3D objects and supporting materials can be estimated automatically. The panel weights and related shell thicknesses are listed in Table 5.4. The total weight of the final 3D printed garment was 5684 g (12.53 lb), which was within the maximum amount that the shoulders could bear (9–13 lb). Because the lower torso (below the waist) can bear 13–17 lb before

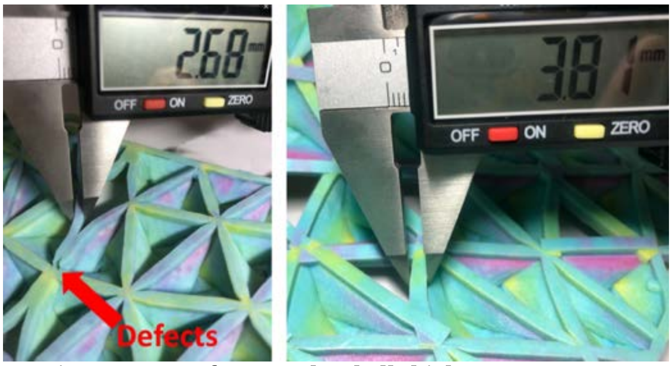


Figure 5.11 Defects on the shell thickness 2-3 mm on hollow area

feeling discomfort, the total weight of bottom garment panel was 3830 g (8.45 lb), with a shell thickness of 1.5 to 2 mm. Similarly, because the waist can bear 9–13 lb, the total weight of top garment panels was 1854 g (4.09 lb), with a shell thickness of 2 to 3 mm, except for the bust panels. Because the bust is sensitive and should not carry too much load, the RB and LB shell thickness was designated as 1.5 to 2 mm, with a weight of 252 g (0.56 lb), whereas the NC and BT shell thickness remained at 2 to 3 mm. Furthermore, the shell thickness of hollow structures was increased to 3–4 mm because a thickness of 2–3 mm would have caused defects (Figure 5.11).

Furthermore, the design consideration specified that the garment weight should be evenly distributed over the body, and therefore, when the final garment was divided vertically (front and back portions of body) and horizontally (left and right portions of body), the weight of both front and back garment or left and right garment should be nearly the same. On the vertical plane, the front portions, comprising panels RB, LB, CFR, CFL, SFR, and SFL as well as six small segments, weighed 2620 g (5.78 lb), whereas for the back portions, comprising NC, BT, CBR, CBL, SBR, and SBL and four segments, the weight was 3064 g (6.76 lb). The difference was 444 g (0.98 lb) which was an inconspicuous weight difference. On the horizontal plane, the weight of both sides had to be the same because the garment was symmetrical.

Table 5.4 Panel weights

Name of the panel	Weight (g/lb)	Shell Thickness (mm)	
		Minimum	Maximum
Right bust (RB)	252/0.56	1.5	2
Left bust (LA)	252/0.56	1.5	2
Back top (BT)	201/0.44	2	3
Neck collar (NC)	109/0.24	2	3
Centre front right (CFR)	522/1.15	1.5	2
Centre front left (CFL)	522/1.15	1.5	2
Side front right (SFR)	224/0.49	1.5	2
Side front left (SFL)	224/0.49	1.5	2
Centre back right (CBR)	883/1.95	1.5	2
Centre back left (CBL)	883/1.95	1.5	2
Side back right (SBR)	286/0.63	1.5	2
Side back left (SBL)	286/0.63	1.5	2
Small segment (each, total 10 pieces)	104/0.23	2	3
Total weight	5684/12.53		
Weight of front garment	2620/5.78		
Weight of back garment	3064/6.76		
Weight of top garment	1854/4.09		
Weight of bottom garment	3830/8.45		

5.3.5 Joints and Interlocks

The function of the joints and interlocks was to combine all the panels into one garment. As defined in Section 4.6.4, the design of the joints and interlocks provided a certain degree of flexibility and distribution of force to avoid any breakage during development of the final prototype. Moreover, the opening in the final prototype was on either side. Because the edges of the panels had an uneven shape, the joints were placed in concave or convex position, except at the waist, where the edges on both sides of the panels were smooth, so that the joints were evenly distributed on both ends. However, because all the panel edges were curved and did not align automatically, marking the positions manually was necessary (Figure 5.12). All the joints were evenly distributed in pairs.

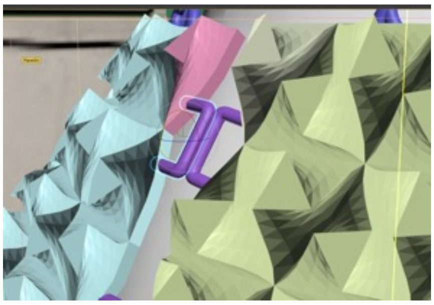


Figure 5.12 Position marking of the joints

Because the interlocks were not 3D printed and would be applied to the garment after the 3D printing process, for convenience and to save composing time, the interlocks between small segments at the front and back were completely sewn, except for the two connecting with the RB and LB, which represented the opening for the head to pass through when putting on the garment. The others were not completely sewn because the large panels could be separated for easy storage and transportation.

5.3.6 Colouration and Texture Mapping

Colouration and the related colour patterns were defined in Section 4.6.3. The colour patterns were applied using the bitmap tools in the materials editor of 3ds Max (Figure 5.13). After choosing suitable parameters and previewing colour performance, a render to texture process was performed to unwrap the meshes and create a UV map (Figure 5.14).

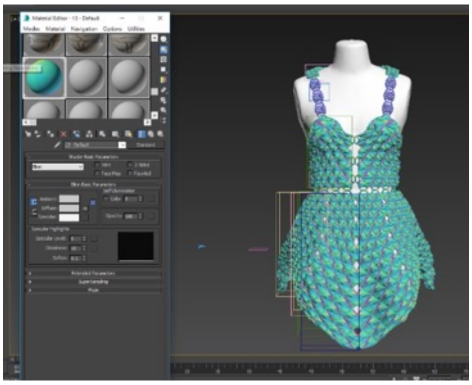


Figure 5.13 Texture mapping by materials editor

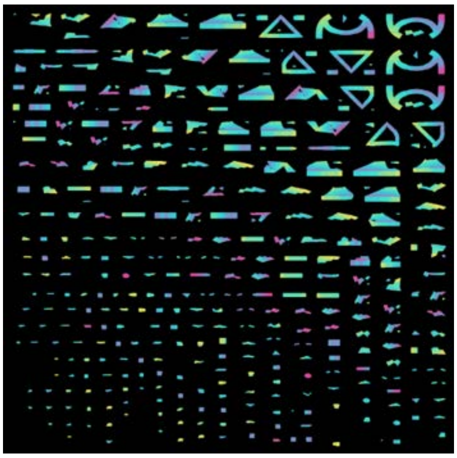


Figure 5.14 A UV map of one of the small segments

From a design aspect, colour and pattern create a rhythm in the final 3D garment. As Stecker (1996) observed, "Colours can convey a sense of visual weight. Warm, dark and bright colours tend to look dense or heavy, and cool, light and dull colours are visually lighter in weight" (p.63). The main colour of the final 3D garment was blue, which belongs to the cool colour temperature category; it was light and without any reflective effect because of the texture. Moreover, as Khurana (2007) noted,

> "Repetition is used to create a movement and is done to achieve a rhythm. Rhythm can also be achieved through alternations, radiation or

> progression. It is important to create interest in the design. This can be done in the form of lines, colours, shapes or design details.” (p. 26)

Because of the effect of texture density and colour pattern, the bright pink on the groove between the triangulate pattern created diagonal lines and formed a V-shaped pattern. Diagonal lines lend strength and a dramatic effect, whereas opposing diagonals provide balance (Wolfe, 2012). Humans perceive a garment as lighter if the meeting point of two opposing diagonals points downward, owing to the illusion of an uplifting movement (Technology & Living Resource, 2011). Looking at the front of the final 3D garment, the red line has an uplifting effect, whereas viewed from the back, the red line pattern presents an inverted V-shape, because the BT garment was designed as a halter and the whole back is nearly devoid of visual weight, and therefore, visual weight had to be created at the bottom for balance. The final 3D model is presented in Figure 5.15.

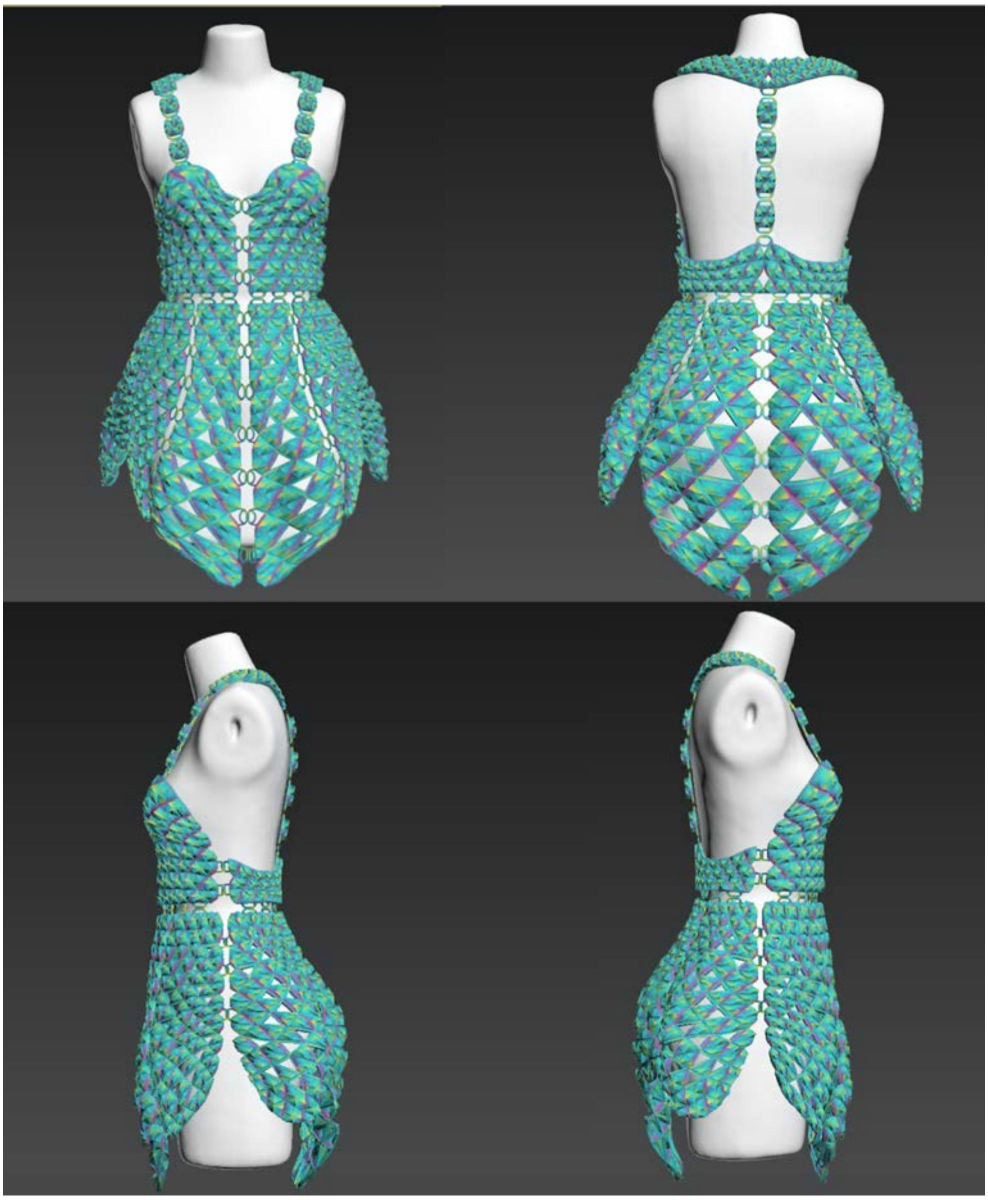


Figure 5.15 The render pictures of the final 3D model

5.3.7 Materials and 3D Printing Process

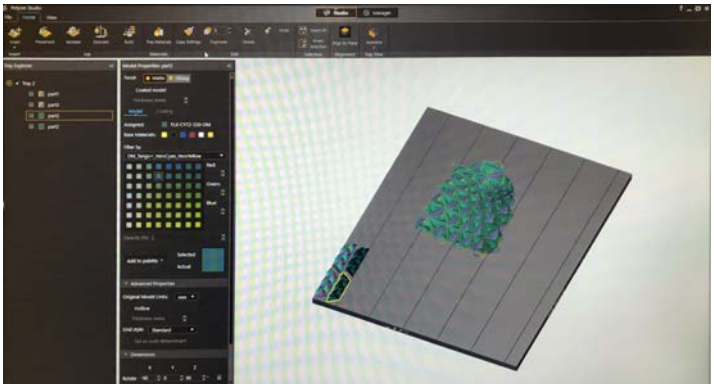


Figure 5.16 The working screen print picture of PolyJet Studio

Resin was the 3D printing material (Section 4.6.1), and the final stage of development was the 3D printing process. The final 3D garment model was exported in the OBJ format and converted in Photoshop CC into VRML, a format specific for texture mapping files, along with the material files and UV map in BMP format. All the files were then imported into the 3D printer software PolyJet Studio (Figure 5.16). This software can monitor and manage printing jobs and 3D garment size; matte or glossy hue can be selected, and minor errors, such as open edges or intersecting shells, in the 3D model can be corrected. The software sliced the 3D model and automatically calculated the amount of 3D materials required. In this study, matte resin materials, namely Vero Blue, Vero Magenta, Vero Yellow, Vero Black, and Vero Pure White, and SUP706 soluble supporting materials, were involved in the 3D printing process. The estimated consumption for each material and time for each panel are presented in Table 5.5. The total printing time was approximately 309 hours.

Table 5.5 Estimated consumption of materials and time

Name of the panel	Vero Blue (g)	Vero Magenta (g)	Vero Yellow (g)	Vero Black (g)	Vero Pure White (g)	Supporting materials (g)	Time required (hours)
Right bust (RB)	13	13	13	15	198	1048	19
Left bust (LA)	13	13	13	15	198	1048	19
Back top (BT)	9	9	9	11	163	650	20
Neck collar (NC)	5	5	5	7	87	463	17
Centre front right (CFR)	28	28	28	32	406	1376	29
Centre front left (CFL)	28	28	28	32	406	1376	29
Side front right (SFR)	11	11	11	12	179	948	17
Side front left (SFL)	11	11	11	12	179	948	17
Centre back right (CBR)	48	48	48	52	687	2981	40
Centre back left (CBL)	48	48	48	52	687	2981	40
Side back right (SBR)	15	15	15	18	223	1462	21
Side back left (SBL)	15	15	15	18	223	1462	21
Small segment (each)/ total 10 pieces	4/40	4/40	4/40	7/70	85/850	772/7720	2/20
Total	284	284	284	346	4486	24463	309

5.4 Presentation of the Garment

After the washing post-processing, all the panels were joined using the interlocks, and the final 3D printed fashion prototype with an innovative surface texture was complete. It is presented on a size 10 dummy, with different side views and details, in Figure 5.17 and 5.18.

Figure 5.17 Different views of the final 3D printed fashion prototype

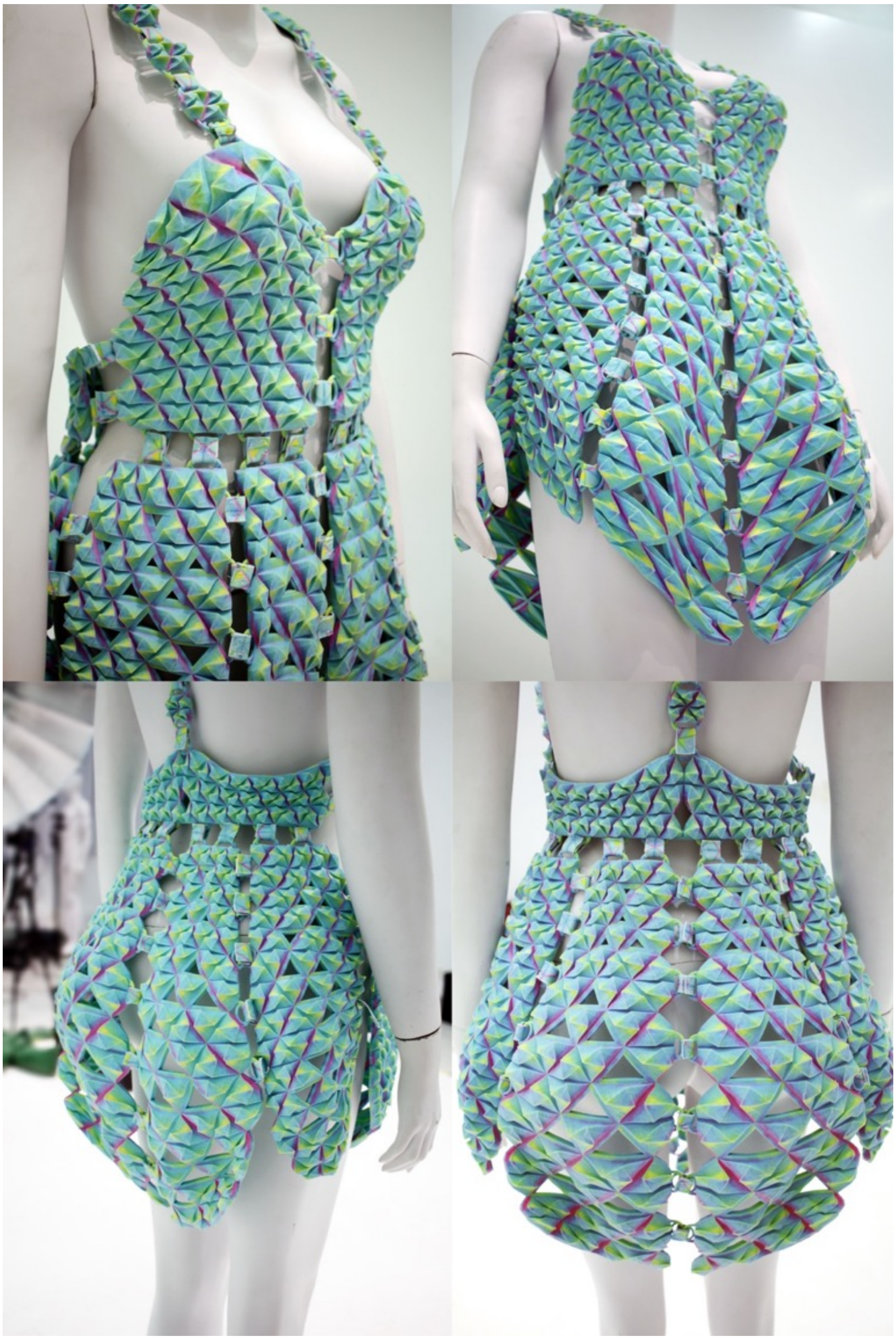


Figure 5.18 Details of the final 3D printed fashion prototype

CHAPTER 6: CONCLUSION

6.1 Introduction

The purpose of this study was to combine innovative fashion design, ergonomics, 3D printing technology, and related 3D computer modelling techniques to develop high-quality 3D printed fashion prototypes with an innovative surface texture. The research objectives were to (a) review previous design process models; (b) identify the latest 3D printing technologies, 3D colour printing techniques, and related CAD/CAM processes for possible application in 3D printed fashion with an innovative surface texture; (c) apply 3D scanning technology for improved ergonomics in a CAD (3D modelling) process; (d) investigate the latest 3D printed fashion and textile products in the market; (e) develop a theoretical design process model for developing 3D printed fashion prototypes with an innovative surface texture; (f) create and evaluate initial prototypes and define various requirements for integration into the final 3D printed prototype; (g) provide a detailed design for the final 3D printed prototype with specifications; and (h) create a final prototype with an innovative surface texture.

6.2 Conclusions Regarding Research Problems

This study conducted an in-depth review of the literature on 3D printing technology, including its principles, the development process from CAD to physical prototypes, and practical applications related to the fashion and textile field. Based on this literature review, a specific design process model for a 3D printed fashion prototype with an innovative surface texture was fully developed. Implementation of the theoretical design process resulted in creation of a final 3D colour printed fashion prototype using texture mapping in 3D modelling and applied ergonomics, with full consideration of aesthetic values for colour, colour pattern, and the design elements of contemporary fashion; the technical requirements for surface texture design and 3D computer modelling, 3D printing materials, and 3D printing methods; and other design considerations in both their physiological and psychological aspects. None of these contributions have appeared in studies published thus far.

6.3 Contributions

This practice-based study involved development of a theoretical design process, a practical design concept, and physical prototypes through the application of 3D colour printing technology, 3D modelling using CAD, and consideration of ergonomic and aesthetic factors. The resulting high-quality 3D printed fashion prototype with an innovative surface texture contributes both theoretically and practically to the fields of high fashion, education, and research related to fashion and textiles.

6.3.1 Contributions to Theoretical Research

The design process model for 3D digital printed fashion was based on an analysis–synthesis–evaluation concept derived from the fields of fashion and textile design, architecture and environmental design, and engineering and industrial design. Each stage was subdivided into different steps, as illustrated in Figure 3.1, p.73.

The first stage, analysis, consisted of two steps, namely problem definition and identification of subproblems. The second stage, synthesis, involved five steps: investigation of the problem, conceptual design, defining solutions, searching for alternatives, and prototype development. The third stage, evaluation, had two steps, namely evaluation of initial prototypes and deciding on a detailed design with specifications, with a feedback loop connection between the synthesis and evaluation stages. The design process model provided a knowledge framework for designing and producing 3D printed fashion.

The design process model developed in this study could benefit fashion designers, researchers, design students, and engineers. Because 3D printing is an evolving breakthrough technology in the fashion and textile fields, it still represents a new phenomenon for designers and researchers integrating 3D printing into fashion to create innovative products. The design process model developed in this study can provide a structured framework to assist them in the problem-solving process. Moreover, it can effectively educate students by providing a contextualised framework for problem-solving and encouraging them to develop their potential by creating 3D printed fashion prototypes with surface textures.

For fashion designers and engineers, creating 3D printing prototypes requires computer knowledge, such as 3D modelling with CAD, during the development process and exporting into file formats suitable for different types of 3D printers. However, fashion designers may not possess such computer skills, and design may not be an area of expertise of engineers. As Loy and Canning (2016) stated, “One of the challenges to collaboration in relation to bringing together disparate disciplines, such as fashion and engineering, is that the conventions of each have not developed in conjunction, and are not necessarily recognised or understood by both parties” (p. 32). This leads to a knowledge gap between design and practical computer skills. The practice-based methodology and design process model established in this study could help integrate technology with practice and ensure the development of successful projects according to specific criteria, thus creating stronger links between design skills and the practical context.

During 3D modelling with CAD, a method of texture mapping a colour image onto 3D meshes and a specific 3D printing method for colour printing were determined. No such attempt was found in the literature. This study examined design and practical considerations concerning the method of texture mapping colouring in CAD for creating innovative textures in the field of fashion and textile products. This practice-based study can assist academic researchers or design practitioners using the texture mapping colouring method in 3D printing by contributing considerable technical knowledge and a unique approach to 3D printed fashion.

6.3.2 Contributions to Practical Research

This study integrated 3D colour printing technology and related applications with fashion design, using the concept development for creation processes organically. It presented the criteria for developing a 3D colour printed fashion prototype with an innovative surface texture, such as selection of 3D printing methods and materials, texture pattern design, prototype construction, and texture mapping with coloured patterns. This resulted in the creation of corresponding prototypes and a process assessment that identified the most suitable decisions, followed by a detailed design using 3D body scanning technology and considering ergonomics factors.

The final 3D printed prototype was unique in presenting visual innovation through a special, colourful surface texture. Such contributions to both concept development and prototype creation have not been found in the field of 3D printed fashion. Because monocoloured products have dominated the 3D printed fashion and textile market, 3D colour printed fashion prototypes with a complex pattern structure could not be feasibly created using traditional techniques. A unique aesthetic could evolve to provide an element of novelty for design practitioners in developing fashion-related 3D printed collections or products, such as garments, textiles, or fashion accessories.

Moreover, this study presented the application of 3D body scanning technology to 3D printing and provided a model for generating 3D garment meshes with suitable ease allowances. Designers could use a 3D body scanner to develop their own methods to assist the 3D modelling process, such as 3D scanning of the desired paper pattern or directly build the garment structure in CAD. Such contributions would offer attractive elements and high-quality innovative designs to the fashion and textile design fields.

Furthermore, the solutions to ergonomic problems offered here could assist in improved body movement or comfort when wearing, although the prototype is rigid, with low flexibility. Because the size specifications of a 3D model can be freely changed in CAD, the final prototype could be custom made for an exact fit. Even the pattern density, colouration, or texture map pattern could be customised in different variations, and the results could be previewed by computer rendering without making a physical prototype. The resulting prototype would be unique, custom-made for one person according to their personal taste.

The final 3D printed prototypes could be employed in stage performances because of their strongly expressive colours, innovative texture and structure, and detailed design elements. The wearer could achieve an individualistic, attractive image because of the unique texture in terms of both the tactile and visual aspects. In addition to stage performances, the prototypes could serve as artworks at exhibitions, where the visual aesthetic of their silhouette and colours and their fantastic fusion of new technology and fashion design could be appreciated. Thus, the final 3D printed prototype presented here possesses both a dynamic beauty when worn in stage performances and a static one when exhibited as an artwork.

6.4 Study Limitations

Although this study applied 3D printing technology to make considerable contributions from both the theoretical and practical aspects, and in recent market 3D printing technology started implicating into the field of fashion and textile, several technical limitations exist, for which researchers are still seeking solutions. Because PolyJet was the main 3D printing method used in this study, the following limitations related to PolyJet colour printing:

a) Colour fidelity is a major challenge in 3D colour printing, and manufacturers continue to seek new methods to address this problem. Although the Stratasys J750 printer can print more than 360,000 colours with high accuracy by compositing six materials and printing objects in colour per vertex at high resolution, colour limitations still exist (Goehrke, 2016). Visual colour differences also existed between the 3D computer model and the real object, leading to colour fidelity problems (Xiao et al., 2016).

b) Only PolyJet can 3D print objects with a mixture of materials, but because it cannot use both soft and hard materials in texture mapping, only rigid resins would be available. Employing hard materials exclusively in fashion or textile design is difficult because the final product could cause discomfort or hinder body movement when worn. Moreover, resin is heavy and requires a specific design to reduce the weight of the final garment. Even in this study, where the weight of the final prototype was greatly reduced and suitable ease allowances were added, it remained heavier than a fabric garment and might have caused inconvenience when worn.

c) Because the 3D printer platform size was limited to $49 \times 39 \times 20$ cm^3 (Stratasys, 2018b), it was not possible to 3D print a full garment without is separating it into panels with suitable interlocks and joints. Another method involves using a folding method during printing, such as Kinematics (developed by Nervous System), in which all panels are designed with hinges and interlocks and the objects are compressed and folded during 3D printing (Nervous System, 2014). However, supporting material consumption will increase greatly due to overhanging objects those are over 45°.

d) Colour printing in 3D is time-consuming because it is a pixelwise type of colour printing. It is also a high-cost technology because of high material costs in the current market. Therefore, it is not practical for the mass production of 3D colour printed garments.

e) Because a long time is required to print large panels, environmental factors, such as humidity, temperature, and sunlight, may distort the 3D printed object, leading to unsatisfactory performance.

f) Environmental problems connected with 3D printing have also been discussed. In Section 2.2.2.2, 3D printing was mentioned as an energy-saving process. However, PolyJet colour printing requires considerable energy resources, such as electricity and water, during the process and for postprocessing. The supporting materials are washed out after the printing process and are non-recyclable. Furthermore, of all 3D printing methods, PolyJet was found to have the worst ecological impact; by not including supporting materials, 40% of the materials were wasted during printing. Although 3D printing facilitates customisation, eliminates logistics, and causes less material waste than traditional manufacturing methods, it still causes some environmental problems, which require further attention (Faludi, 2013).

g) Interdisciplinary knowledge and skills are required to master 3D printing technology, and time is required for learning and practice. As Vance (2011) stated, "The actual design programs are pretty easy for designers to use but harder for average people. And that remains one of the great limitations of 3-D printing" (p. B10). Although designers have innovative ideas that they wish to integrate into garment design, limited working knowledge of computers hinders their creativity. This limitation has created a knowledge gap between innovative fashion design and practical computer skills.

h) According to the safety data information provided by Stratasys (2018a), the resin material Vero may cause skin allergies (Appendix V). Therefore, it has been recommended that the undergarments be worn when trying on the final 3D printed prototype.

6.5 Implications for Future Research

A 3D digital printed fashion prototype with an innovative surface texture was created in the final stage of this practice-based study, which involved conceptual design development, innovative contemporary fashion design, and practical application of 3D printing technology and physical prototyping processes. Nevertheless, various technical limitations in 3D printing technology hindered its full implementation in fashion and textile design. The implications for future research, based on the design process model and prototypes developed here, are as follows:

a) Further investigating joint and interlock designs to improve the flexibility of the final garment (e.g. separating the panels into small segments and adding joints and interlocks to each segment).

b) Developing a feasible combination of hard and soft materials in a 3D model using the texture mapping method for colour surface textures. This could solve flexibility problems and minimise the panel composing time. For instance, after 3D printing of hard and soft resins separately, the materials could be joined using a clear liquid resin and solidified through UV light (Figure 6.1).

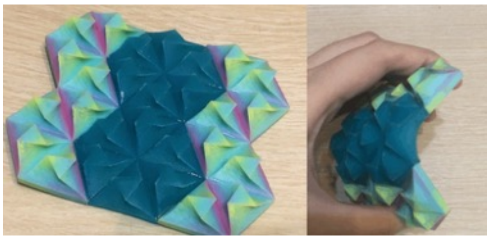


Figure 6.1 Combination of rigid and soft resin prototype

c) Developing methods for minimising material consumption and reducing the weight of 3D printed prototypes in both physiological and psychological aspects (e.g. employing hollow or net structures in 3D modelling).

d) Examining transparent materials that can add design interest to the prototypes (e.g. making transparent layers or designing solid-coloured objects within a transparent resin to create visual depth for the design).

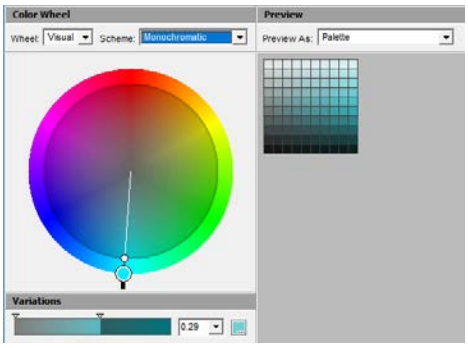
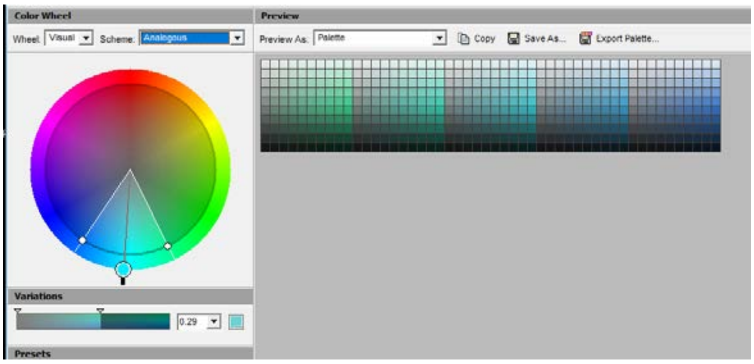
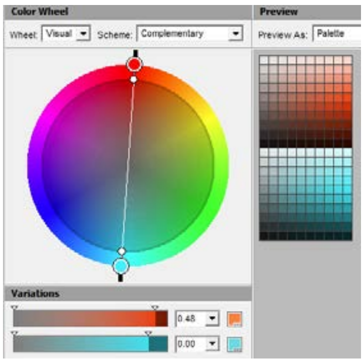
e) Exploring other 3D printing materials that could be integrated into fashion or textile design.

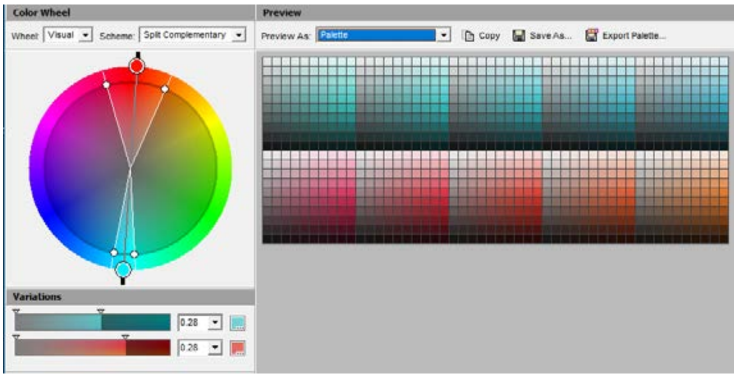
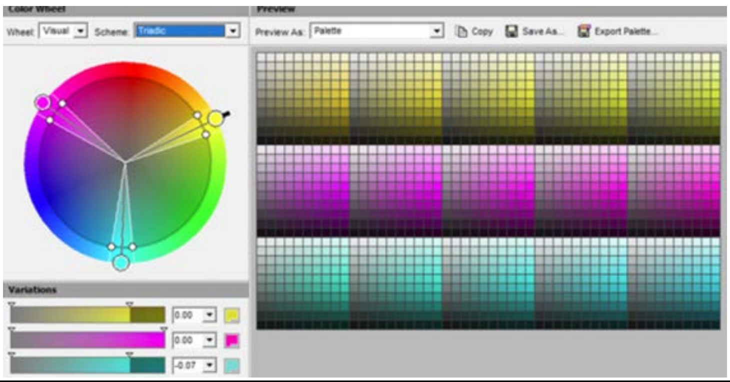
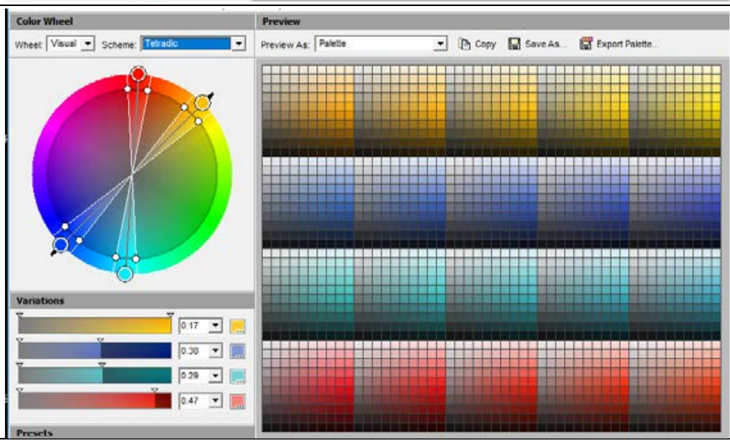
f) Integrating sustainability into 3D colour printed fashion (e.g. using biodegradable or renewable 3D printing materials, or reducing printing time to minimise energy consumption).

In conclusion, 3D printing technology represents an industrial revolution with potential to change the future of manufacturing (Lipson & Kurman, 2013). It benefits not only design but also the business of manufacturing and distribution (Sedhom, 2015). Although 3D printing technology still has many limitations, it is developing at a considerable speed and “the fashion industry can ill afford to ignore the inevitability of 3D printing” (Sedhom, 2015, p. 880). Colour printing represents a potential development area in 3D printed fashion, given that colour is one of the most attractive design elements for designer innovation. Therefore, more research into 3D colour printing is required to resolve current problems and create more successful 3D printed garments that can be integrated into the fashion and textile fields.

APPENDICES

Appendix I Colour variations generated by Colour Wheel Pro

Colour scheme	Colour variations
Monochromatic	
Analogous	
Complementary	

Split Complementary	
Triadic	
Tetrad	

Appendix II Data sheet of Vero and plaster

Vero

At the core: PolyJet Technology

PolyJet™ technology creates precise prototypes that set the standard for finished-product realism. Its fine resolution makes complex shapes, intricate details and smooth surfaces possible. PolyJet 3D Printing works by jetting layers of liquid photopolymer onto a build tray and instantly curing them with UV light. The fine layers build up to create a precise 3D model or prototype. Models are ready to handle right out of the 3D printer, with no post-curing needed, although some materials gain better temperature resistance with a thermal post-processing.

Keep valuable resources in-house

You'll be amazed when you see how easy it is to produce realistic models in-house. PolyJet 3D Printers offer not only unparalleled speed, they make it easy for you to print with the widest range of material properties.

Good ideas sell easier

PolyJet 3D Printers improve communication and collaboration because they produce amazingly accurate representations of your ideas that you can share with your team and your clients for a faster, more confident buy-in.

VERO PUREWHITE, VEROBLACKPLUS, VEROCYAN, VEROGRAY, VEROMAGENTA, VEROWHITEPLUS, VEROYELLOW

	ASTM	ENGLISH	METRIC
Tensile strength	D-638-03	7,250-9,450 psi	50-65 MPa
Elongation at break	D-638-05	10-25%	10-25%
Modulus of elasticity	D-638-04	290,000-435,000 psi	2,000-3,000 MPa
Flexural Strength	D-790-03	11,000-16,000 psi	75-110 MPa
Flexural Modulus	D-790-04	320,000-465,000 psi	2,200-3,200 MPa
HDT, °C @ 0.45MPa	D-648-06	113-122 °F	45-50 °C
HDT, °C @ 1.82MPa	D-648-07	113-122 °F	45-50 °C
Izod Notched Impact	D-256-06	0.375-0.562 ft-lb/inch	20-30 J/m
Water Absorption	D-570-98 24hr	1.1-1.5%	1.1-1.5%
Tg	DMA, E»	126-129 °F	52-54 °C
Shore Hardness (D)	Scale D	83-86 (Scale D)	83-86 (Scale D)
Rockwell Hardness	Scale D	73-76 (Scale M)	73-76 (Scale M)
Polymerized density	Scale M		1.17-1.18 g/cm³
Ash content (VeroGray, VeroWhitePlus)	USP281	0.23-0.26 %	0.23-0.26%
Ash content (VeroBlackPlus)	USP281	0.01-0.02 %	0.01-0.02%

VEROBLUE

	ASTM	ENGLISH	METRIC
Tensile strength	D-638-03	7,250-8,700 psi	50-60 MPa
Elongation at break	D-638-05	15-25%	15-25%
Modulus of elasticity	D-638-04	290,000-435,000 psi	2,000-3,000 MPa
Flexural Strength	D-790-03	8,700-10,200 psi	60-70 MPa
Flexural Modulus	D-790-04	265,000-365,000 psi	1,900-2,500 MPa
HDT, °C @ 0.45MPa	D-648-06	113-122 °F	45-50 °C
HDT, °C @ 1.82MPa	D-648-07	113-122 °F	45-50 °C
Izod Notched Impact	D-256-06	0.375-0.562 ft-lb/inch	20-30 J/m
Water Absorption	D-570-98 24hr	1.5-2.2%	1.5-2.2%
Tg	DMA, E»	118-122 °F	48-50 °C
Shore Hardness (D)	Scale D	83-86 (Scale D)	83-86 (Scale D)
Rockwell Hardness	Scale D	73-76 (Scale M)	73-76 (Scale M)
Polymerized density	Scale M		1.18-1.19 g/cm³
Ash content	USP281	0.21-0.22%	0.21-0.22%

stratasys

THE **3D PRINTING SOLUTIONS** COMPANY™

3Faktur GmbH
Moritz-von-Rohr Str. 1A | 07745 Jena | Germany
www.3Faktur.com | info@3Faktur.com | +49.(0).3641-3200067

3Faktur

Material Specification Sheets

Colorjet

Parameter	Unit	Full- Colored Plaster
Build Space	**mm**	**350x250x200**
Tensile strength	MPa	14,2
Elongation at break	%	0,23
Modulus of elasticity	MPa	9450
Flexural Strength	MPa	31,1
Flexural Modulus	MPa	7163
HDT, °C @ 0.45MPa	°C	k.A.
HDT, °C @ 1.82MPa	°C	k.A.
Izod Notched Impact	J/m	k.A.
Water Absorption	%	k.A.
Tg (Glass Transition Temperature)	°C	k.A.
Shore Hardness (D)	Scale D	k.A.
Shore Hardness (A)	Scale A	k.A.
Rockwell Hardness	Scale M	k.A.
Polymerized density	g/cm3	k.A.
Ash content	%	k.A.

Appendix III Data sheet of tough PLA and material performance of ABS, PLA and tough PLA

MakerBot

THE ALL-NEW MAKERBOT SLATE GRAY TOUGH PLA FILAMENT BUNDLE

As Tough as ABS and as Reliable as PLA

TOUGH PLA BUNDLE PRODUCTS

for Replicator+	SKU: 111746-00
for Replicator	SKU: 111746-00
for Replicator Z18	SKU: 111752-00

SPECIFICATIONS

Filament diameter	0.07 in	[1.75 mm]
Spool diameter	9.84 in	[25.0 cm]
Spool width	1.57 in	[4 cm]
Spool hub hole	2 in	[5.08 cm]

TEMPERATURE

Glass Temp:	140-149ºF	[60-65ºC]
Melting Temp:	302-320ºF	[150-160ºC]
Nozzle Temp:	419ºF	[215ºC]

SHIPPING WEIGHT

7.81 lb [3.54 kg]

Similar Tensile, Impact, and Flexural Strength to ABS

Made with designers and engineers in mind, the Slate Gray Tough PLA Filament Bundle allows you to create durable, high-impact strength prototypes and fixtures. It includes three spools of Tough PLA Filament and the Tough PLA Smart Extruder+.

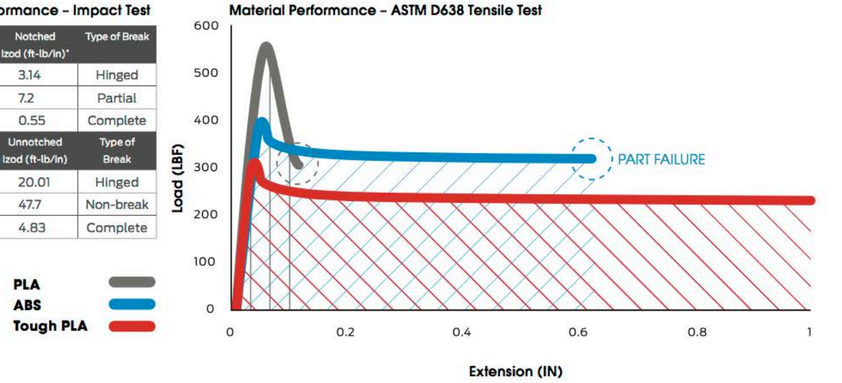
Print without the hassles of ABS or the brittleness of PLA. You can print prototypes, jigs, and fixtures with features that demand wear and impact-resistance, such as snap fits and living hinges. Tough PLA is also a workable material that responds well to sanding, thread-tapping, and post-processing.

Tough PLA exhibits similar behavior to ABS under flexural, tensile and impact loads. The stress and strain curves below show the tensile similarities. Whereas PLA can bear a larger load at once, it can't endure much deflection before break — resulting in a stiff, brittle characteristic. Tough PLA by comparison, will deform elastically and return to its original shape before hitting peak strength; after which, it exhibits a very long plastic deformation range before break that outperforms ABS. This results in a pliable, workable material that flexes before failure.

Material Performance – Impact Test

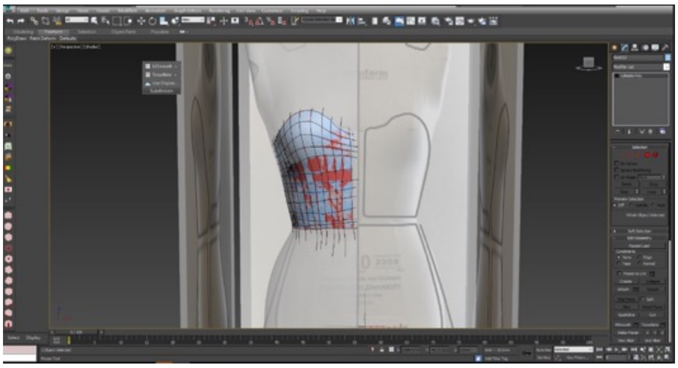
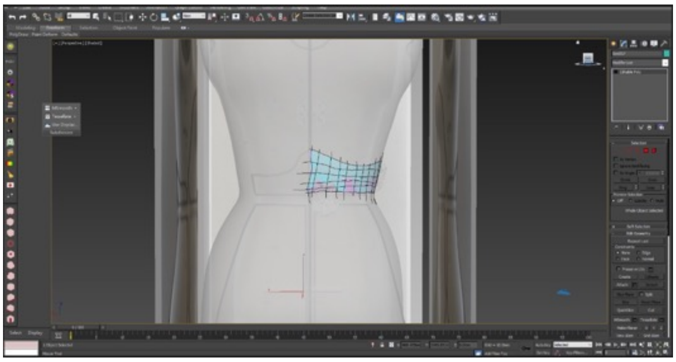
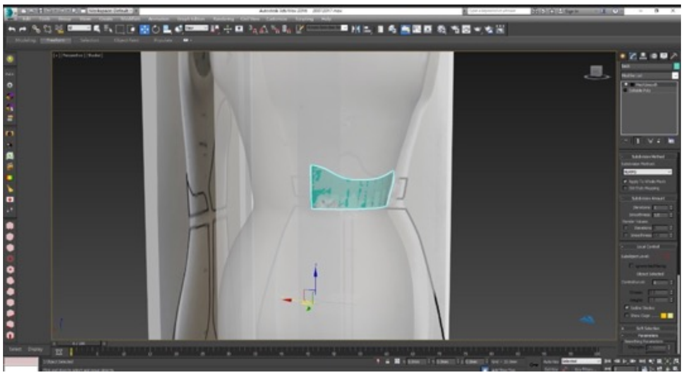
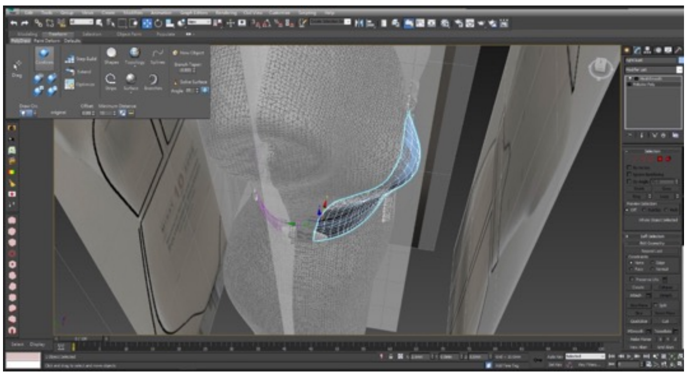
Filament	Notched Izod (ft-lb/in)*	Type of Break
ABS	3.14	Hinged
Tough PLA	7.2	Partial
PLA	0.55	Complete
Filament	**Unnotched Izod (ft-lb/in)**	**Type of Break**
ABS	20.01	Hinged
Tough PLA	47.7	Non-break
PLA	4.83	Complete

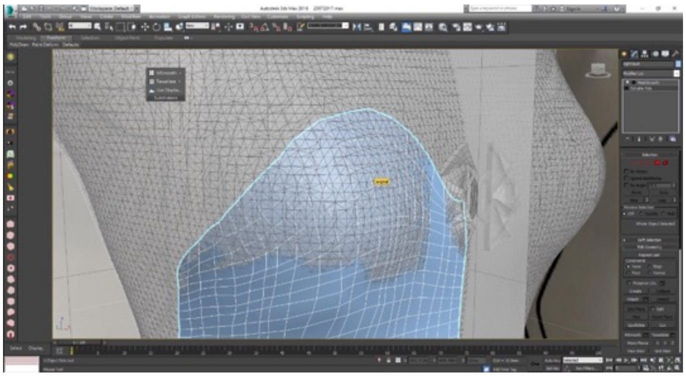
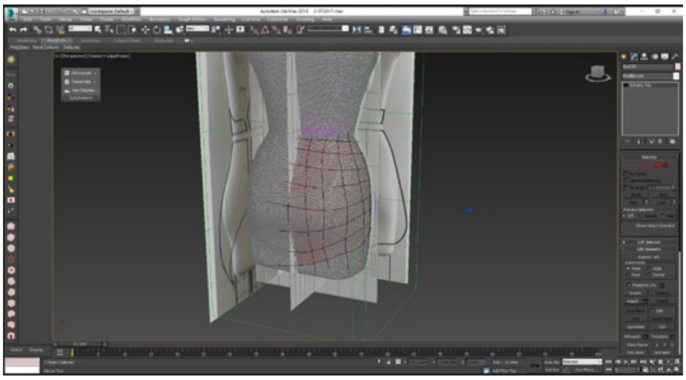
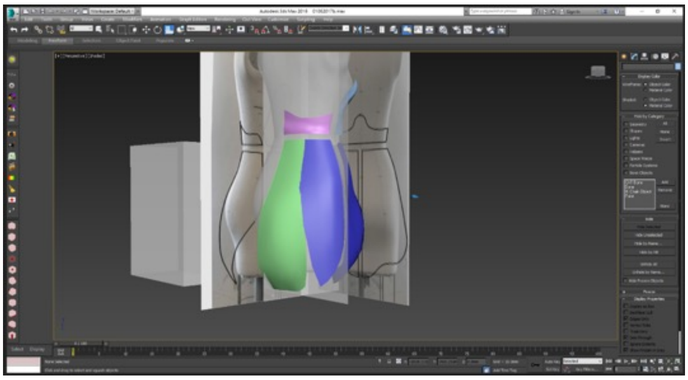
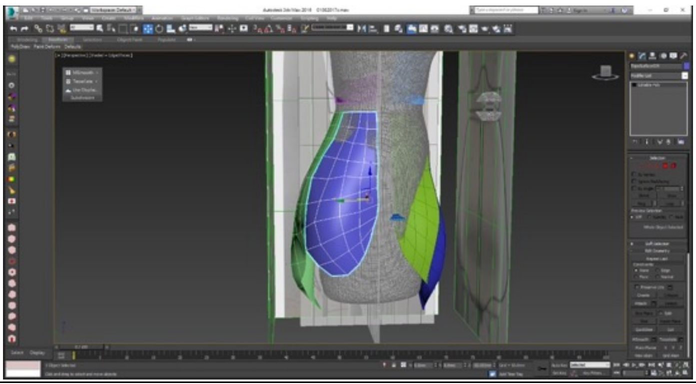
Material Performance – ASTM D638 Tensile Test

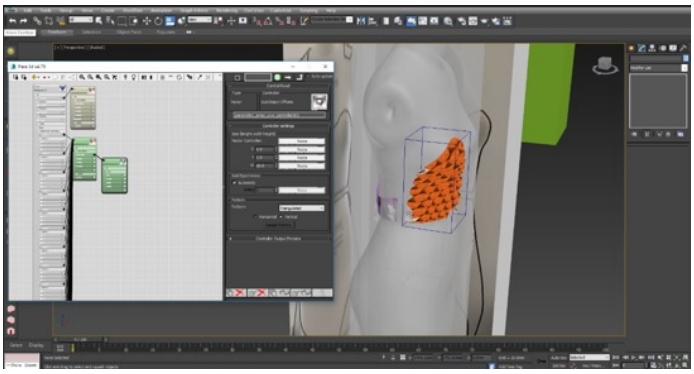
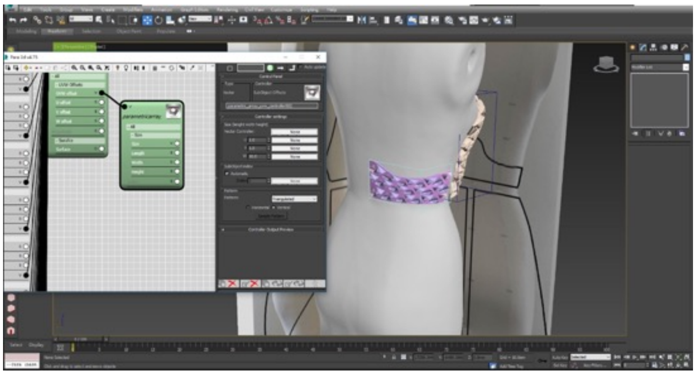
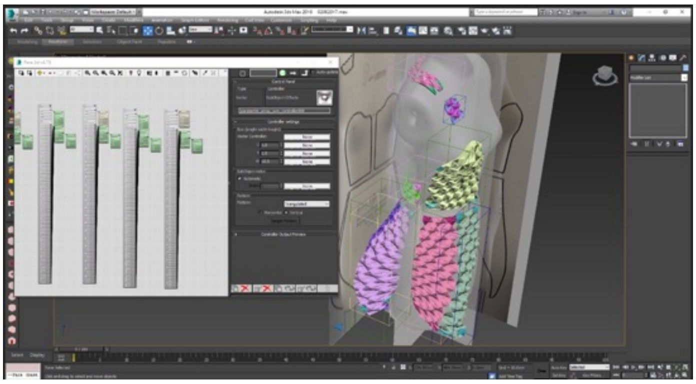
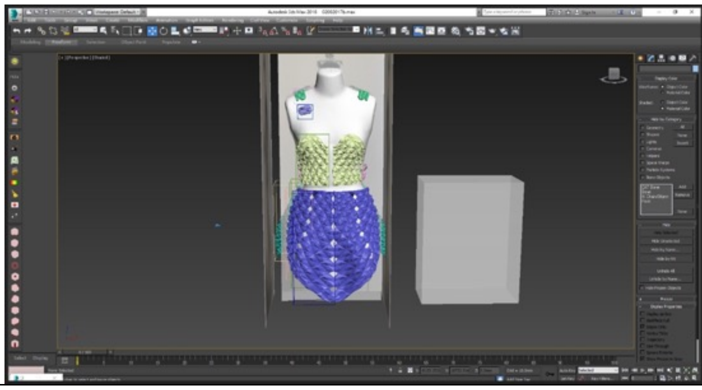


All tests were performed following ASTM standard protocol with injection molded specimens from the same resin used to create MakerBot filaments. The performance characteristics of these materials may vary according to application, operating conditions, or end use, and the information is only presented for reference purposes only. They should not be used for design specifications or quality control purposes. Product specifications are subject to change without prior notice. Each user is responsible for determining that the MakerBot material is safe, lawful, and technically suitable for the intended application, as well as for identifying the proper disposal (or recycling) method consistent with applicable environmental laws and regulations. Except as may be specified in the MakerBot Limited Warranty, MakerBot makes no warranties of any kind, express or implied, including, but not limited to, the warranties of merchantability, fitness for a particular use.

Appendix IV Details of the 3D modelling process

Process descriptions	**Screen print picture of the process**
Drawing grids and creating new mesh on RB panel by the function of Topology in PolyDraw tool.	
Drawing grids on BT panel and creating new mesh by the function of Topology in PolyDraw tool.	 
Using Conform Brush tool to move the vertex of mesh.	

Dragging the vertexes to refining the edges.	
Drawing grids and creating new mesh by the function of Topology in PolyDraw tool.	
Separate the new mesh into CBR and SBR.	
Dragging and moving the meshes to create the desired silhouette.	

Process of using Para 3D.	   

Appendix V Safety data sheet of Vero

SAFETY DATA SHEET

Issuing Date 12-Dec-2017 **Revision Date** 08-Nov-2017 **Revision** F

Section 1: Identification: Product identifier and chemical identity

Product identifier

Product Name	VeroBlue, RGD840
Product Code(s)	SDS-06125 EN U

Other means of identification

Proper Shipping Name	OTHER REGULATED SUBSTANCES, LIQUID, N.O.S. (2-Propenoic acid)
UN Number	UN3082
Pure substance/mixture	Mixture

Recommended use of the chemical and restrictions on use

Recommended Use	Printing inks
Uses advised against	This product is a cartridge containing ink. Under normal conditions of use, the substance is released from a cartridge only inside an appropriate printing system, and therefore, exposure is limited

Details of manufacturer or importer

Importer
Objective3D Pty Ltd
33-35 Yazaki Way
Carrum Downs, 3201
Victoria, Australia
Phone: +03 9785 2333
Local: +1300 559 454
Fax: +03 9785 2322

For further information, please contact

E-mail address info@Stratasys.com

Emergency telephone number

Emergency telephone number

- +44 1865 407333 - Global – English Language response
- +44 1235 239670 - Europe - Multi lingual response
- +1 215 207 0061 - USA – Multi-lingual response
- +65 3158 1074 - Asia Pacific - Multi lingual response
- +61 2 8014 4558 - Australia - English Language response
- +86 512 8090 3042 - China - Chinese response

Section 2: Hazard(s) identification

GHS Classification

Acute toxicity - Oral	Category 4 - (H302)
Serious eye damage/eye irritation	Category 1 - (H318)
Skin sensitisation	Category 1B - (H317)

Specific target organ toxicity (single exposure)	Category 3 - (H335)
Specific target organ toxicity (repeated exposure)	Category 2 - (H373)
Acute aquatic toxicity	Category 1 - (H400)
Chronic aquatic toxicity	Category 1 - (H410)

Label elements

Exclamation mark
Health hazard
Corrosion
Environment

Signal word
Danger

Hazard statements
H302 - Harmful if swallowed
H317 - May cause an allergic skin reaction
H318 - Causes serious eye damage
H335 - May cause respiratory irritation
H373 - May cause damage to organs through prolonged or repeated exposure
H410 - Very toxic to aquatic life with long lasting effects

Precautionary Statements - Prevention
Wash face, hands and any exposed skin thoroughly after handling
Do not eat, drink or smoke when using this product
Wear protective gloves/protective clothing/eye protection/face protection
Contaminated work clothing should not be allowed out of the workplace
Use only outdoors or in a well-ventilated area
Do not breathe dust/fume/gas/mist/vapours/spray
Avoid release to the environment
Precautionary Statements - Response
Get medical advice/attention if you feel unwell
IF IN EYES: Rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing
Immediately call a POISON CENTER or doctor/physician
IF ON SKIN: Wash with plenty of soap and water
If skin irritation or rash occurs: Get medical advice/attention
Wash contaminated clothing before reuse
IF INHALED: Remove victim to fresh air and keep at rest in a position comfortable for breathing
Call a POISON CENTER or doctor/physician if you feel unwell
IF SWALLOWED: Call a POISON CENTER or doctor/physician if you feel unwell
Rinse mouth
Collect spillage
Precautionary Statements - Storage
Store in a well-ventilated place. Keep container tightly closed
Store locked up
Precautionary Statements - Disposal
Dispose of contents/container to an approved waste disposal plant

Other hazards
May be harmful in contact with skin.

Section 3: Composition and information on ingredients, in accordance with Schedule 8

Substance

REFERENCES

3D Printing Media Network (2017). *NanoParticle Jetting (NPJ).* Retrieved January 11, 2018 from https://www.3dprintingmedia.network/additive-manufacturing/am-technologies/what-is-nanoparticle-jetting/

3D Systems (2014). *Projet 860Pro.* Retrieved November 10, 2015 from https://www.3dsystems.com/3d-printers/projet-cjp-860pro

3Ders.org. (2013). *Petfig transforms photo of your pet into 3D sculptures.* Retrieved October 15, 2015 from http://www.3ders.org/articles/20130527-petfig-transforms-photo-of-your-pet-into-3d-sculptures.html

3Ders.org. (2014). *Full body scanning booths open in Asda, print a 3D Selfie for £60.* Retrieved October 10, 2015 from http://www.3ders.org/articles/20140625-full-body-scanning-booths-open-in-asda-print-a-3d-selfie.html

3Faktur (n.d.). *Colorjet: Full-color plaster.* Retrieved March 8, 2017 from https://3faktur.com/en/3d-printing-materials-technologies/colorjet-3d-printing-technology-overview/colorjet-3d-printing-material-full-color-plaster/

4D Concepts (n.d.). *PolyJet 3D printing*. Retrieved January 5, 2017 from https://www.4dconcepts.de/3dprinting/polyjet-3d-printing/?L=1

Ahearn, L. (2014). *3D game textures: create professional game art using photoshop*. CRC Press.

Akel, C. (2014). *3D printed Dazzle Lamps play with light and colour*. Retrieved October 15, 2015 from https://www.3dprintingelectronicsconference.com/uncategorized/3d-printed-dazzle-lamps-play-with-light-and-colour/

Akin, O. (1984). An exploration of the design process. In N. Cross (Ed.), *Developments in design methodology* (pp.189-207). New York: John Wiley.

Aldrich, W. (2012). *Metric pattern cutting for menswear*. John Wiley & Sons.

Archer, L.B, (1984) Systematic methods for designers. In cross, N, ed, *Developments in Design Methodology*, New York: John Wiley, 57-82

Arnheim, R. (1974). *Art and visual perception : A psychology of the creative eye* (New version, expanded and rev. ed.). Berkeley: University of California Press.

Asimow, M. (1962) *Introduction to Design,* Prentice-Hall, Englewood Cliffs, New Jersey.

Baser, G. (2008). Engineering approach to industrial design of woven fabrics. *International Journal of Fashion Design, Technology and Education, 1*(2), 79-87.

Beaman, J. (2015). 3D Printing, Additive Manufacturing, and Solid Freeform Fabrication: The Technologies of the Past, Present and Future. *Bulletin of the American Physical Society, 60.*

Becker, D. (2016). *Color Trends and Selection for Product Design: Every Color Sells A Story* (Plastics Design Library). Elsevier Science.

Best, J. (2017). *Colour design : Theories and applications* (Second ed., The Textile Institute Book Series). Duxford, England: Woodhead Publishing.

Bhatia, U. (2015). 3D printing technology. *International Journal of Engineering and Technical Research*, *3* (2), 327-330.

Bloomfield, R. (2015). *Joris Laarman's Furniture of the Future*. Retrieved October 1, 2015 from http://www.wsj.com/articles/joris-laarmans-furniture-of-the-future-1431530144

Broadbent, G. (1984). Design and theory building. *Developments in Design Methodology, John Wiley & Son, Chichester, UK.*

Brosheer, B. C. (1948). How smooth is smooth? Part-I, specification and evaluation of machined finishes. *American Machinist, McGrow-Hill Publishing Company*, 97-112.

Burgo, F. (2013). *Il Modellismo: Tecnica del Modello Sartoriale e Industriale / Pattern Making Programe* (6th ed.). Istituto di Moda Burgo, Milano.

Burnsides, D., Boehmer, M., & Robinette, K. (2001). 3-D landmark detection and identification in the CAESAR project. *In Proceedings of the third international conference on 3-D digital imaging and modeling conference* (pp. 393–398). Quebec City.

Campbell, T., Williams, C., Ivanova, O., & Garrett, B. (2011). Could 3D printing change the world. *Technologies, Potential, and Implications of Additive Manufacturing, Atlantic Council, Washington, DC.*

Candy, L. (2006). Practice based research: A guide. *CCS Report* V1.0, pp.1-19. University of Technology, Sydney.

Changizi, M. A. (2009). *The vision revolution: How the latest research overturns everything we thought we knew about human vision.* Dallas, TX: BenBella Books.

Chapman, W.L., Bahill, A.T. & Wymore, A.W. (1992). *Engineering modeling and design*. Boca Raton: CRC Press.

Cimbalo, R.S., Beck, K.L. and Sendziak, D.S. (1978), "Emotionally toned pictures and color selection for children and college students", *Journal of Genetic Psychology,* Vol. 33 No. 2, 303-4.

Clarke, T., & Costall, A. (2007). The emotional connotations of color: a qualitative investigation. Color Research and Application, 33 (5), 406–410.

Colour Wheel Pro (2015). *Color Wheel Pro: See Color Theory in Action*. Retrieved March 3, 2017 from http://www.color-wheel-pro.com

Colton, J. S., & Pun, R. C. (1994). Information frameworks for conceptual engineering design. *Engineering with computers, 10*(1), 22-32.

Continuum Fashion. (2011). *N12 bikini*. Retrieved October 1, 2015 from http://www.continuumfashion.com/N12.php

Cross, L. (2014). *3D printed swimwear takes Shanghai Fashion Week by storm*. Retrieved October 1, 2015 from http://top43dprinting.com/3d-printed-swimwear-takes-shanghai-fashion-week-by-storm/

Cross, N. (1994). *Engineering design methods: strategies for product design*. New York: John Wiley, Chichester.

Cross, N., & Roy, R. (1989). *Engineering design methods* (Vol. 2). New York: Wiley.

Crump, S. S. (1992). *U.S. Patent No. 5,121,329*. Washington, DC: U.S. Patent and Trademark Office.

Cumming, R., & Porter, T. (1990). *The colour eye*. London: BBC Books

D'Apuzzo, N. (2007). 3D body scanning technology for fashion and apparel industry. *Electronic Imaging 2007*. Retrieved January 12, 2016 from http://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?articleid=1727554

D'Apuzzo, N. (2009). Recent advances in 3D full body scanning with applications to fashion and apparel. *Optical 3-D Measurement Techniques IX*.

Darke, J. (1979). The primary generator and the design process. *Design Studies* 1(1), 36-44.

DeJonge, J. O. (1984). Forward: The design process. *Watkins, SM Clothing: The portable Environment*. Ames, IA: Iowa State University Press.

Dixon, J. R. (1966). *Design engineering: Inventiveness, analysis, and decision making*. New York: McGraw-Hill Companies.

Durling, D. (2002). Discourses on research and the PhD in Design. *Quality Assurance in Education*, *10*(2), 79-85.

Ehrlenspiel, K., & Dylla, N. (1993). Experimental investigation of designers' thinking methods and design procedures. *Journal of engineering design*, *4*(3), 201-212.

Elliot, A. J., Maier, M. A., Moller, A. C., Friedman, R., & Meinhardt, J. (2007). Color and psychological functioning: The effect of red on performance attainment. *Journal of Experimental Psychology: General, 136*, 154-168.

Fabian (2017). *How 3D Printing in Polyamide (Nylon Plastic) Really Works*. Retrieved May 5 2017 from https://i.materialise.com/blog/en/how-professional-3d-printing-works/

Faludi, J. (2013). *Environmental Impacts of 3D Printing* . Retrieved March 15, 2018 from https://sustainabilityworkshop.autodesk.com/blog/environmental-impacts-3d-printing

Farmer, B.M. & Gotwals, L.M. (1982). *Concepts of fit: an individualized approach to pattern design.* New York: McMillan Publishing Company.

Farris, S. (2012). *Color: Color theory, mixing and perception of color*. New Delhi: World Technologies.

Fehrman, K. R. & Fehrman, C. (2015). *Color: the secret influence (3rd ed).* Upper Saddle River, NJ: Prentice Hall.

Fiore, A. M. and Kimle, P.A. (1997). *Understanding aesthetics for the merchandising and design professional*. New York: Fairchild.

Formlabs (2018). *How to choose the right 3D printing material*. Retrieved March 8, 2018 from https://formlabs.com/blog/how-to-choose-the-right-3D-printing-material/

France, A. K. (2014). *Make: 3D Printing: The Essential Guide to 3D Printers*. Maker Media, Inc..

French, M. (1999). *Conceptual design for engineers* (3rd Edn.). London: Springer.

Gebhardt, A. (2012). *Understanding additive manufacturing - rapid prototyping, rapid tooling, rapid manufacturing.* Cincinnati, OH: Hanser Publishers.

Gemperle, F., Kasabach, C., Stivoric, J., Bauer, M., & Martin, R. (1998, October). Design for wearability. In *Wearable Computers, 1998. Digest of Papers. Second International Symposium on* (pp. 116-122). IEEE.

Gerritsen, F. (1975). *Theory and practice of color: a color theory based on laws of perception.* New York: Van Nostrand Reinhold.

Geršak, J. (2002). Development of the system for qualitative prediction of garments appearance quality. *International Journal of Clothing Science and Technology*, *14*(3/4), 169-180.

Geršak, J., & Marcic, M. (2013). The complex design concept for functional protective clothing. *Tekstil: Journal of Textile & Clothing Technology, 62*.

Giang, K. (n.d). *PLA vs. ABS: What's the difference?*. Retrieved June 14, 2017 from https://www.3dhubs.com/knowledge-base/pla-vs-abs-whats-difference#what-are-abs-and-pla

Gibson, Rosen, Stucker, Rosen, David, & Stucker, Brent. (2015). *Additive Manufacturing Technologies 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing* (2nd ed. 2015.. ed.). New York, NY: Springer New York : Imprint: Springer.

Gilbert, P. U. P. A., & Haeberli, W. (2011). *Physics in the Arts: Revised Edition*. Academic Press.

Gioello, D. A. & Berke, B. (1979). *Figure types and size ranges.* New York: Fairchild Books.

Godoi, F. C., Prakash, S., & Bhandari, B. R. (2016). 3d printing technologies applied for food design: Status and prospects. *Journal of Food Engineering*, *179*, 44-54.

Goehrke, S. A (2016). *Multi-Color, Multi-Material Unprecedented Efficiency: Stratasys' J750 Reinvents 3D Printing* . Retrieved February 8, 2017 from https://3dprint.com/127875/stratasys-j750-multi-material/

Goel, V. and Pirolli, P. (1992). The structure of design problem spaces. *Cognitive Science 16*, 395-429.

GrabCAD (2018). *Guide to Voxel Printing*. Retrieved January 1, 2018 from https://help.grabcad.com/article/230-guide-to-voxel-printing?locale=en

Grant, D. P. (1986). Geoffrey Broadbent on current directions in design methods. *Design Methods and Theories*, *20*(2), 401-408.

Guvendiren, M., Molde, J., Soares, R. M., & Kohn, J. (2016). Designing biomaterials for 3D printing. *ACS biomaterials science & engineering*, *2*(10), 1679-1693.

Haggar, A., & Haggar, A. (2004). *Pattern Cutting: For Lingerie, Beachwear and Leisurewear*. Oxford: Blackwell Publications.

Halloran, J. W., Tomeckova, V., Gentry, S., Das, S., Cilino, P., Yuan, D., ... & Alabi, T. R. (2011). Photopolymerization of powder suspensions for shaping ceramics. *Journal of the European Ceramic Society*, *31*(14), 2613-2619.

Hanks, K., Belliston, L., & Edwards, D. (1977). *Design yourself!*. MBI Publishing Company.

Haralick, R. M. (1979). Statistical and structural approaches to texture. *Proceedings of the IEEE*, *67*(5), 786-804.

Harold, R. M. (2001). An introduction to appearance analysis. *GATFWORLD*, *13*(3), 5-12.

Helson, H., & Lansford, T. (1970). The role of spectral energy of source and background color in the pleasantness of object colors. *Applied optics*, *9*(7), 1513-1562.

Hemphill, M. (1996). A note on adults' color–emotion associations. *The Journal of genetic psychology*, *157*(3), 275-280.

Herpan, I. V. (2015). *Womenswear | Iris van Herpan*. Retrieved November 31, 2015 from http://www.irisvanherpen.com/

Hogg, J., Goodman, S., Porter, T., Mikellides, B., & Preddy, D. E. (1979). Dimensions and determinants of judgements of colour samples and a simulated interior space by architects and non-architects. *British Journal of Psychology*, *70*(2), 231-242.

Hohkraut, U. (2010). Rapid prototyping and jewelry design. *In: B. Katalinic, ed. Annals of DAAAM for 2010 & proceedings of the 21st international DAAAM symposium*, 20–23 October 2010. Zadar, Croatia. Vienna: DAAAM International, 1555–1556.

Hollins, B., & Pugh, S. (1990). *Successful product design: what to do and when*. London: Butterworth-Heinemann.

Howarth, D. (2013). *3D-printed dress for Dita Von Teese by Michael Schmidt and Francis Bitonti*. Retrieved November 8, 2015 from https://www.dezeen.com/2013/03/07/3d-printed-dress-dita-von-teese-michael-schmidt-francis-bitonti/

Howarth, D. (2014a). *3D-printed fabrics by Richard Beckett woven into Pringle of Scotland's ready to wear garments*. Retrieved November 8, 2015 from http://www.dezeen.com/2014/02/17/3d-printed-fabrics-by-richard-beckett-woven-into-pringle-of-scotlands-ready-to-wear-garments/

Howarth, D. (2014b). *Francis Bitonti creates pixellated 3D-printed shoes using cellular automation*. Retrieved November 8, 2015 from https://www.dezeen.com/2014/09/26/francis-bitonti-3d-printed-molecule-shoes-adobe-stratasys/

Howarth, D. (2014c). *Neri Oxman creates wearable 3D-printed structures for interplanetary voyages*. Retrieved November 8, 2015 from http://www.dezeen.com/2014/11/25/neri-oxman-mit-media-lab-stratasys-wearable-3d-printed-structures-interplanetary-voyages-synthetic-biology/

Hull, C. W. (1986). *U.S. Patent No. 4,575,330.* Washington, DC: U.S. Patent and Trademark Office.

Hull, C. W. (1990). *U.S. Patent No. 4,929,402.* Washington, DC: U.S. Patent and Trademark Office.

Hull, C. W. (1993). *U.S. Patent No. 5,236,637.* Washington, DC: U.S. Patent and Trademark Office.

Iancu, C., Iancu, D., & Stăncioiu, A. (2010). FROM CAD MODEL TO 3D PRINT VIA" STL" FILE FORMAT. *Fiability & Durability/Fiabilitate si Durabilitate*, (1).

International Ergonomics Association, J. (2014). *What is Ergonomics*. Retrieved November 29, 2014 from http://www.iea.cc/whats/

Ivanova, K., & Stanchev, P. (2009, July). Color harmonies and contrasts search in art image collections. In *Advances in Multimedia, 2009. MMEDIA'09. First International Conference on*(pp. 180-187). IEEE.

Jenkins, D. L., & Martin, R. R. (1993). Importance of free-hand sketching in conceptual design: Automatic sketch input. *ASME DES ENG DIV PUBL DE., ASME, NEW YORK, NY(USA), 1993, 53*, 115-128.

Jones, J. C. (1992). *Design methods*. John Wiley & Sons.

Jones, J.C. (1970). *Design methods: Seeds of human futures*. New York: Wiley-Interscience.

Jones, J.C. (1984). A method of systematic design. In N. Cross (Ed.), *Developments in design methodology* (pp.9-32). New York: John Wiley.

Jones, P. R. M., West, G. M., Harris, D. H., & Read, J. B. (1989). The Loughborough anthropometric shadow scanner (LASS). *Endeavor, 13(new series)*, 162–168.

Jones, S. W. (1973). *Product design and process selection*. London: Buterworths.

Kalita, S. J., Bose, S., Hosick, H. L., & Bandyopadhyay, A. (2003). Development of controlled porosity polymer-ceramic composite scaffolds via fused deposition modeling. *Materials Science and Engineering: C, 23*(5), 611-620.

Kalmus, J. (2013). *Knickers are downloaded as couple produce underwear on 3D printer*. Retrieved November 8, 2015 from http://www.thejc.com/news/uk-news/114142/knickers-are-downloaded-couple-produce-underwear-3d-printer

Khurana, P. (2007). *Introduction to fashion technology*. Firewall Media.

Kira (2016). *3DTie launches 3D printed necktie collection for the 21st century man*. Retrieved June 14, 2017 from https://www.3ders.org/articles/20160423-3dtie-launches-3d-printed-necktie-collection-for-the-21st-century-man.html

Koberg, D. and Badnell, J. (1973). *The universal traveller: A companion for those on problem-solving journeys*. Los Altos, CA: William Kaufmann.

Koenig, B. (2012). *Color workbook* (4th ed.). Upper Saddle River: Pearson.

Koslow, T. (2016). *Stratasys and threeASFOUR Unveil 3D Printed Oscillation Dress at NYFW 2016*. Retrieved July 28, 2017 from https://3dprint.com/149732/stratasys-threeasfour-nyfw/

Kwallek, N., Woodson, H., Lewis, C. M., & Sales, C. (1997). Impact of three interior color schemes on worker mood and performance relative to individual environmental sensitivity. *Color Research and Application, 22,* 121–132.

LaBat, K.L. & Solkolowski, S.L. (1999). A three-stage design process applied to an industry-University textile product design project. *Clothing and Textiles Research Journal*, 17(1), 11-19.

Lamb, J.M. and Kallel, M.J. (1992). A conceptual framework for apparel design. *Clothing and Textiles Research Journal* 10(2), 42-47.

Landau, E. (2017). *'Space Fabric' Links Fashion and Engineering.* Retrieved March 5, 2018 from https://www.jpl.nasa.gov/news/news.php?feature=6816

Landers, R., & Mülhaupt, R. (2000). Desktop manufacturing of complex objects, prototypes and biomedical scaffolds by means of computer-assisted design combined with computer-guided 3D plotting of polymers and reactive oligomers. *Macromolecular Materials and Engineering*, *282*(1), 17-21.

Lauer, D. & Pentak, S. (1995). Design basics, 4th edition. Ft. Worth, TX: Harcourt Brace College Publishers.

Lawson, B. (1980). *How designers think*. London: Architectural Press.

Lawson, B. (2006). *How designers think: the design process demystified*. Routledge.

Leach, N., & Farahi, B. (2017). *3D-Printed Body Architecture*. New York, United States: John Wiley & Sons.

Leech, D. J. (1972). *Management of engineering design*. London: John Wiley & Sons.

Leggett, G. (2013). *Color vs. Appearance*. Retrieved March 5, 2017 from Quality Magazine https://www.qualitymag.com/articles/91148-color-vs-appearance

Leichman, A. K. (2015). *World's first fashion collection printed at home*. Retrieved July 28, 2017 from https://www.israel21c.org/worlds-first-fashion-collection-printed-at-home/

Levkowitz, H. (1997). *Color theory and modeling for computer graphics, visualization, and multimedia applications* (Kluwer international series in engineering and computer science ; SECS 402). Boston: Kluwer Academic.

Lewis, W.P. and Samuel, A.E. (1989). *Fundamentals of engineering design*. New York: Prentice Hall.

Lipson, H., & Kurman, M. (2013). *Fabricated: The new world of 3D printing*. John Wiley & Sons.

Liska, R., Schuster, M., Inführ, R., Turecek, C., Fritscher, C., Seidl, B., ... & Lichtenegger, H. (2007). Photopolymers for rapid prototyping. *Journal of Coatings Technology and Research*, *4*(4), 505-510.

Lopes, A., Navarrete, M., Medina, F., Palmer, J., MacDonald, E., & Wicker, R. B. (2006, August). Expanding rapid prototyping for electronic systems integration of arbitrary form. In *17th annual solid freeform fabrication symposium, University of Texas at Austin, Austin, TX, Aug* (pp. 14-16).

Loy, J., & Canning, S. (2016). Clash of Cultures: Fashion, Engineering, and 3D Printing. In *Creative Technologies for Multidisciplinary Applications* (pp. 25-53). IGI Global.

Lu, J. M., & Wang, M. J. J. (2008). Automated anthropometric data collection using 3D whole body scanners. *Expert Systems with Applications*, *35*(1), 407-414.

Lyons, P., & Moretti, G. (2004, June). Nine tools for generating harmonious colour schemes. In *Asia-Pacific Conference on Computer Human Interaction* (pp. 241-251). Springer, Berlin, Heidelberg.

Makerbot (n.d.). *Tough PLA* [data sheet]. Retrieved February 12, 2018 from https://download.makerbot.com/filament/tough_pla_datasheet.pdf

Martins, S. B., & Martins, L. B. (2012). Ergonomics, design universal and fashion. *Work: A Journal of Prevention, Assessment and Rehabilitation*, *41*, 4733-4738.

Matisons, M. (2015). *Cosmetic Surgery Prep Using 3D Systems' 3D Printed Models Causes Paradigm Shift*. Retrieved October 20, 2015 from https://3dprint.com/101197/3d-systems-mirrorme3d/

McIntyre, P. (2006). Creative practice as research: „Testing out" the systems model of creativity through practitioner based enquiry. In *Speculation and Innovation: Applying practice led research in the creative industries.* Queensland University of Technology, Brisbane.

McLaughlin, S. (2006). Valuing insight and judgment: A hermeneutic perspective on the development of validating contexts for practice-based research in design. In *Speculation and Innovation: Applying practice led* *research in the creative industries*. Queensland University of Technology, Brisbane.

MCor Technologies (2014a). *MCor Iris.* Retrieved November 10, 2015 from http://mcortechnologies.com/3d-printers/iris/

MCor Technologies (2014b). *Why True Colour 3D printing capability matters*. Retrieved from https://s3-eu-west-1.amazonaws.com/mcortechnologies.com/wp-content/uploads/2014/07/Why-True-Colour-3D-Printing-Matters.pdf

Medland, A.J. (1992). *The computer-based design process* (2nd Edn.). London: Chapman & Hall.

Mendoza, H. R. (2014). *Noa Raviv Shows Off Her Amazing 3D Printed Fashion*. Retrieved October 1, 2015 from http://3dprint.com/12682/3d-printing-fashion/

Micom (2014). *The Difference Between True Color and Perceived Color.* Retrieved July 1, 2017 from https://www.micomlab.com/wp-content/uploads/2014/06/True-Color-vs-Perceived-Color.pdf

Middendorf, W. H. (1969). *Engineering design*. Boston: Allyn and Bacon.

Molitch-Hou, M. (2014, September 23). *Orbit 1 Electroplating Device for 3D Prints to Hit Kickstarter in January.* Retrieved February 13, 2016 from http://3dprintingindustry.com/2014/09/23/orbit-1-electroplating-device-3d-prints-hit-kickstarter-january/

Moller, A. C., Elliot, A. J., & Maier, M. A. (2009). Basic hue-meaning associations. *Emotion, 9*, 898–902.

Morton, J.L. (1998). *Color Logic*. Colorcom.

Mullen, T. (2011). *Mastering blender*. John Wiley & Sons.

Murdock, K. L. (2012). *Autodesk 3ds Max 2013 Bible* (Vol. 799). John Wiley & Sons.

Murray, D. C., & Deabler, H. L. (1957). Colors and mood-tones. Journal of Applied Psychology, 41(5), 179–283.

Murray, L & Lawrence, B. (2000). *Practitioner-Based Enquiry: Principles for Postgraduate Research*. London: Falmer Press.

Myers-McDevitt, P. J. (2004). *Complete guide to size specification and technical design*. Fairchild Publications.

Navarrete, M., Lopes, A., Acuna, J., Estrada, R., MacDonald, E., Palmer, J., & Wicker, R. (2007). *Integrated layered manufacturing of a novel wireless motion sensor system with GPS*. TEXAS UNIV AT EL PASO WM KECK CENTER FOR 3D INNOVATION.

Navinchandra, D. (1991). *Exploration and innovation in design: towards a computational model*. New York: Springer Science & Business Media.

NCS (2017). *How the NCS system works.* Retrieved March 3, 2017 from http://ncscolour.com/about-us/how-the-ncs-system-works/

Nervous System (2013). *Kinematics-Nervous System*. Retrieved November 31, 2014 from http://n-e-r-v-o-u-s.com/

Nervous System (2014). *Kinematics Dress.* Retrieved March 15, 2018 from https://n-e-r-v-o-u-s.com/projects/sets/kinematics-dress/

Newsome, S. L., Spillers, W. R., & Finger, S. (Eds.). (2013). *Design Theory'88: Proceedings of the 1988 NSF Grantee Workshop on Design Theory and Methodology*. Springer Science & Business Media.

Nurre, J. H., Connor, J., Lewark, E. A., & Collier, J. S. (2000). On segmenting the three-dimensional scan data of a human body. *IEEE Transactions on Medical Imaging, 19*(8), 787–797.

Ocvirk, O., Stinson, R., Wigg, P., Bone, R., & Cayton, D. (2002). *Art fundamentals: theory & practice* (9th ed.). New York: McGraw-Hill.

Orlando, J. Y. (1979). Objectifying apparel design. In *Combined Proceedings, Association of College Professors of Textiles and Clothing, Eastern, Central and Western Regional Meetings*, 127-132.

Pahl, G., Beitz, W., Feldhusen, J. & Grote, K.H. (2007). *Engineering design: a systematic approach* (3rd ed.). London: Imprint: Springer.

Palmer, J. A., Yang, P., & Davis, D. W. (2000). *Rapid prototyping of high density circuitry*. Society of Manufacturing Engineers.

Parraman, C., Walters, P., Reid, B., & Huson, D. (2008, February). Specifying colour and maintaining colour accuracy for 3D printing. In *Three-Dimensional Image Capture and Applications 2008* (Vol. 6805, p. 68050L). International Society for Optics and Photonics.

Peleg, D. (2017). *The process*. Retrieved July 28, 2017 from https://danitpeleg.com/

Petrick, I. J., & Simpson, T. W. (2013). 3D printing disrupts manufacturing. *Research Technology Management*, *56*(6), 12.

Petrovic, V., Vicente Haro Gonzalez, J., Jorda Ferrando, O., Delgado Gordillo, J., Ramon Blasco Puchades, J., & Portoles Grinan, L. (2011). Additive layered manufacturing: sectors of industrial application shown through case studies. *International Journal of Production Research, 49*(4), 1061-1079.

Pipes, A. (2004). Introduction to design. Upper Saddle River: Prentice Hall.

Ratto, M., & Ree, R. (2012). Materializing information: 3D printing and social change. *First Monday*, *17*(7).

Rayna, T., & Striukova, L. (2016). From rapid prototyping to home fabrication: How 3D printing is changing business model innovation. *Technological Forecasting and Social Change*, *102*, 214-224.

Reader's Digest (1997). *Reader's Digest Complete Guide to Sewing (8th edition).* New York: Reader's Digest.

Regan, C.L., Kincade, D.H. and Shelden, G. (1998). Applicability of the engineering design process theory in the apparel design process. *Clothing and Textiles Research Journal* 16(1), 36-46.

Reiss, D. S., Price, J. J., & Evans, T. S. (2013). Sculplexity: Sculptures of Complexity using 3D printing. *EPL (Europhysics Letters)*, *104*(4), 48001.

Rifkin, J. (2012). *The Third Industrial Revolution: How the Internet, Green Electricity, and 3-D Printing are Ushering in a Sustainable Era of Distributed Capitalism*. Retrieved September 3, 2015 from http://www.worldfinancialreview.com/?p=2271

Russo, M. (2006). *Polygonal Modeling: Basic and Advanced Techniques*. Jones & Bartlett Learning.

Sachs, E. M., Haggerty, J. S., Cima, M. J., & Williams, P. A. (1993). *U.S. Patent No. 5,204,055*. Washington, DC: U.S. Patent and Trademark Office.

Saito, M. (1994). A cross-cultural study on color preference in three Asian cities. *Japanese Psychological Research*, *36*(4), 219-232.

Schmid, U., & Mecheels, J. (1981). Forces Acting on Textiles and Clothing Seams as Functions of Body Movements and Cut of Garment, Melliand Textilber. *Engl. Ed*, *10*(3), 314-320.

Schon, D.A. (1990). The design process. In V.A. Howard (Ed.), *Varieties of thinking: Essays from Harvard's philosophy of education research center* (pp.110-141). New York: Routledge.

Scribano, F., Burns, M., & Barron, E. R. (1970). *Design, Development and Fabrication of a Personnel Armor Load Profile Analyzer* (No. C/PLSEL-75). IIT RESEARCH INST CHICAGO IL.

Sedhom, R. V. (2015). 3D Printing and its Effect on the Fashion Industry: It's More Than Just About Intellectual Property. *Santa Clara L. Rev.*, *55*, 865.

Setchell, J. M., & Wickings, E. J. (2005). Dominance, status signals, and coloration in male mandrills (Mandrillus sphinx). *Ethology, 111,* 25–50.

Soldat, A. S., Sinclair, R. C., & Mark, M. M. (1997). Color as an environmental processing cue: External affective cues can directly affect processing strategy without affecting mood. *Social Cognition, 15,* 55–71.

Stecker, P. (1996). *The fashion design manual*. South Melbourne [Vic.]: Macmillan Education Australia.

Stewart, M. (2002). Launching the imagination. New York: McGraw-Hill.

Stone, N. J., & English, A. J. (1998). Task type, posters, and workspace color on mood, satisfaction, and performance. *Journal of Environmental Psychology, 18*, 175–185.

Stratasys (2018a). *Materials safety data sheets* [safety data sheet]. Retrieved January 8, 2017 from http://www.stratasys.com/en/sds?families={954F7CD3-261E-46FC-8B45-8A55AD2D3DCC}

Stratasys (2018b). *Stratasys J735 and J750*. Retrieved January 1, 2018 from http://www.stratasys.com/3d-printers/j735-j750

Stratasys (2018c). *Vero* [data sheet]. Retrieved January 8, 2017 from http://www.stratasys.com/-/media/files/material-spec-sheets/mss_pj_vero_0318a.pdf

Stucker, B. R. E. N. T. (2012). Additive manufacturing technologies: technology introduction and business implications. In *Frontiers of Engineering: Reports on Leading-Edge Engineering From the 2011 Symposium, National Academies Press, Washington, DC, Sept*, 19-21.

Suh, N. P. (1990). *The principles of design* (Vol. 990). New York: Oxford University Press.

Sundstrom, E., & Sundstrom, M. G. (1986). *Work places: The psychology of the physical environment in offices and factories*. CUP Archive.

Takala, R., Keinonen, T., & Mantere, J. (2006). Processes of product concepting. In *Product Concept Design* (pp. 57-90). Springer London.

Taylor, A., & Unver, E. (2014). 3D Printing-Media Hype or Manufacturing Reality: Textiles Surface Fashion Product Architecture.

Technology & Living Resource Depository: B. Fashion Design Basics (2011). *Booklet 3: Fashion Design Basics*. Retrieved December 27, 2017 from Education Bureau, Technology Education Section of the Curriculum Development Institute Web site: http://edblog.hkedcity.net/te_tl_e/category/1-resources/12-fashion-clothing-and-textiles-strand/121-compulsory-part/b-fashion-design-basics/

The 3Doodler. (2014). *The 3Doodled Seashell Lace Dress: The 3Doodler.* Retrieved October 10, 2015 from http://the3doodler.com/3doodled-seashell-lace-dress/

The Economist (2011). Print me a Stradivarius. *The Economist, 398* (8720), 77.

Thompson, R. (2011). *Prototyping and low-volume production*. London: Thames & Hudson.

Town, C. (2014). *Multi-material fashion range made using 3D printer*. Retrieved October 17, 2015 from http://www.themalaymailonline.com/features/article/multi-material-fashion-range-made-using-3d-printer

United Kingdom Council for Graduate Education, Frayling, C., & Burgess, R. G. (1997). *Practice-based doctorates in the creative and performing arts and design*. UK Council for Graduate Education.

Unver, E., Swann, D., Bailey, R., Govindarajan, I., & Dollan, F. (2013). The Art of 3D Sculpted Printing: Royal Coat of Arms Case Study.

Valdez, P., & Mehrabian, A. (1994). Effects of color on emotions. *Journal of Experimental Psychology: General, 123,* 394–409

Vance, A. (2011, January 12). The Wow Factor of three-dimensional Printing. *The New York Times*, p.B10.

Varotsis, A. B. (n.d.). *Introduction to Material Jetting 3D Printing.* Retrieved January 11, 2018 from https://www.3dhubs.com/knowledge-base/introduction-material-jetting-3d-printing

Veppumthara, S. (2013, December). 3DOODLER: BRINGING YOUR DOODLES TO LIFE. *Whitman Science Magazine*, *2*(1), 12.

Vidimče, K., Wang, S. P., Ragan-Kelley, J., & Matusik, W. (2013). Openfab: A programmable pipeline for multi-material fabrication. *ACM Transactions on Graphics (TOG)*, *32*(4), 136.

Walsh, A. (2014). *ALEXIS WALSH - Spire Dress*. Retrieved June 14, 2017 from www.alexiswalsh.com/spire

Wang, C. C. L., Chang, T. K. K., & Yuen, M. M. F. (2003). From laserscanning data to feature human model: a system based on fuzzy logic concept. *Computer-Aided Design, 35,* 241–253.

Watkins, S. (1995). *Clothing: The portable environment* (2nd ed.). Ames: Iowa State University Press.

Watkins, S. M. (1988). Using the design process to teach functional apparel design. *Clothing and Textile Research Journal* 7(l), 10-14.

Wertheimer, M. (1959). *Productive thinking.* New York: Harper and Row.

Wexner, L. B. (1954). The degree to which colors (hues) are associated with mood-tones. *Journal of applied psychology*, *38*(6), 432.

Wicker, R. B., & MacDonald, E. W. (2012). Multi-material, multi-technology stereolithography: This feature article covers a decade of research into tackling one of the major challenges of the stereolithography technique, which is including multiple materials in one construct. *Virtual and Physical Prototyping*, *7*(3), 181-194.

Wiegersma, S. and Van der Elst, G. (1988), "Blue phenomenon: spontaneity or preference?", *Perceptual & Motor Skills*, Vol. 66 No. 1, pp. 308-10.

Winter, R., Griffiths, M. & Green, K. (2000). The academic qualities of practice-based PhD? *Studies in Higher Education* 25(1), 25-37

Wohlers, J. (2013). *MakerBot Explorers | Francis Bitonti's New Skins*. Retrieved November 31, 2014 from http://www.makerbot.com/blog/2013/09/06/makerbot-explorers-francis-bitontis-new-skins/

Wolfe, M.G. (2012). *Fashion!* (6th ed.). Tinley Park, Illinois: Goodheart-Wilcox Company.

Wong, K. V., & Hernandez, A. (2012). A review of additive manufacturing. *ISRN Mechanical Engineering*, *2012*.

Wynn, D., & Clarkson, J. (2005). Models of designing. In *Design process improvement* (pp. 34-59). Springer London.

Xiao, K., Sohiab, A., Sun, P. L., Yates, J. M., Li, C., & Wuerger, S. (2016, October). A colour image reproduction framework for 3D colour printing. In *Advanced Laser Manufacturing Technology* (Vol. 10153, p. 1015318). International Society for Optics and Photonics.

Yap, Y. L., & Yeong, W. Y. (2014). Additive manufacture of fashion and jewellery products: a mini review: This paper provides an insight into the future of 3D printing industries for fashion and jewellery products. *Virtual and Physical Prototyping*, *9*(3), 195-201.

Zamiska, P.P.M., Cole, J., Lu, H., & Weise, W. (2013). *LITERATURE REVIEW 3D PRINTER*. Retrieved March 18, 2016 from http://me495.engr.siu.edu/F13-3DPR/LiteratureReview.pdf

Zeagler, C. (2017, September). Where to wear it: functional, technical, and social considerations in on-body location for wearable technology 20 years of designing for wearability. In *Proceedings of the 2017 ACM International Symposium on Wearable Computers* (pp. 150-157). ACM.

Zeisel, J. (1984). *Inquiry by design: Tools for environment-behavior research.* Cambridge: Cambridge University Press.

Zhang, Y., Yin, C., Zheng, C., & Zhou, K. (2015). Computational hydrographic printing. *ACM Transactions on Graphics (TOG)*, *34*(4), 131.