This is an Accepted Manuscript of an article published by Taylor & Francis in *TEXTILE* on 18/08/21, available online: http://www.tandfonline.com/10.1080/14759756.2021.1955582

A Brief Introduction to Body-Oriented Parametric Design for 3D-Printed Fashion and Textiles

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To cite this article: Mingjing Lin (2021): A Brief Introduction to Body-Oriented Parametric Design for 3D-Printed Fashion and Textiles, TEXTILE, DOI: 10.1080/14759756.2021.1955582

To link to this article: https://doi.org/10.1080/14759756.2021.1955582

A Brief Introduction to Body-Oriented Parametric Design for 3D-Printed Fashion and Textiles

Abstract

This paper presents the introduction to the author's PhD thesis titled, *Interfashionality: Body-oriented Parametric Design and Parametric Thinkign 2.0 for 3D-printed Fashion and Textiles*. The paper firstly introduces the author's research motivation, which is followed by theoretical discussions around and design examples of fashion and textile digitalization, as well as 3 D-printed fashion and textiles. The author then introduces the important implication of parametric design for creating 3 D-printed fashion and textiles. In this section, through analyzing the self-organized conference, *Digital Fashion-3D Printing for Designer*, and through intensive discussions of the origin of parametric design and its adoption in fashion, the author then summarizes the scope of the research. This paves the way for a concrete research question, five research aims, research structure (model of the research) and thesis structure.

Keywords: 3d printing (3DP); parametric design; body; fashion; textiles

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A Brief Introduction to Body-Oriented Parametric Design for 3D-Printed Fashion and Textiles

1. Motivation

I was trained as a fashion designer in China at Tsinghua University, which is famous for its science and technology education. Although courses encouraged students to seek out advanced and digital technologies in design, I was still most inspired by hand-making. Initially, as a BA fashion student, my prior knowledge of textiles was limited due to the division between the fashion and textile disciplines at Tsinghua. As a result of completing several textile induction courses (knitting, weaving, dyeing and crocheting) at Tsinghua, I discovered my interest in conventional textile hand-making processes: hand weaving and dyeing, specifically. Hand-making continued to inspire my MA study (Fashion Design Technology) at the London College of Fashion (2012–2014): I used basketry weaving and dip-dye in my final fashion collection to emphasize the *wabi-sabi* esthetic of the raw edges of the material and the tangibility of the hand-made fabric.

On the other hand, the professional training in garment making (at Tsinghua and the London College of Fashion) highlights a key aspect of fashion design—the visualization and iteration of 3 D shapes through construction, moving from 2 D patterns for 2 D cloth via, for example, draping and toile-making. It was not until I came to the UK to study at the London College of Fashion that I was first alerted to the broader and more imaginative applications of cutting-edge digital technologies in fashion, such as 3 D printing (3DP). 3DP offers a different approach from that of the conventional 2 D/3D/2D interplay of fashion construction: without necessarily making a physical toile, an immediate digital rendering shows the final look of a 3 D garment constructed from a piece of cloth on a computer, and this design can be printed out directly as a tangible material/fabric/garment. Influenced by examples of pioneering designs by Freedom of Creation and Iris van Herpen, I began to explore the possibilities of using 3DP in textiles and fashion design. However, immersing myself in a more futuristic context did not affect my enjoyment and appreciation of traditional approaches. In fact, my knowledge of textile hand-making, such as hand sewing, weaving and dyeing, as well as fashion construction, has influenced and informed new opportunities for digital 3 D making in my practice. For instance, the hand-dyed 3 D-printed textiles[1] of the *Interfashionality* project, the hand-sewn 3 D-printed pleats and the 3 D pleats with an intricate woven structure[2] of the *Fold-the-Interfashionality* project that feature in my PhD research demonstrate that the creativity in my practice emerges not from a separation between modernity and tradition, digital making and hand-making, but from the conflation, mediation or integration of

dissimilar, and even opposing, elements. Throughout the thesis the interactions between different disciplines, such as fashion, textiles, architecture and performance, are key.

Apart from this interdisciplinary feature, cultural exchange appeared gradually based on my experience of living in China and the UK. Even though intercultural dialogue between Eastern and Western design elements, filtered through myself, was not present throughout the entire research, it was embedded in some of my projects and started to increase in importance during the last two projects: "Inter-fashionality," 3 D-printed *Qipao*[3] for physical performance, and "Fold-the-Interfashionality," 3 D-printed pleated costume for Beijing Opera. To certain extent, this cultural aspect reinforces the concept of mediation between opposites, which was generated from the earlier interdisciplinary aspect. Similarly, living and working in Western countries did not mean that I separated myself completely from Eastern culture and esthetics. As a matter of fact, the mixture and hybridity of both cultural elements contributed to the generating of innovation through the blending of dissimilar territories, such as 3DP and Chinese *jingju* from the Inter-fashionality project.

Developing new ideas from these contrasts is thus evidenced in my recent work, such as emphasizing the combination of, and the transition between, warm and cold colors, geometrical silhouettes and exquisite fabric details, hand-making and digital making, within one design. The idea of moving around was best described by Jonathan Openshaw (2015, 11), in conversation with Hans Ulrich Obrist, when he put digital technology into a creative cultural and generational context: The generation born after 1989

> *[…] are deeply inspired by the digital; they often make work that is powerfully physical, using very tactile materials. They oscillate back and forth between the digital and the analogue with total fluidity […] moving as freely between disciplines as they do between media formats.*

My interdisciplinary and intercultural background does not view conflicting notions or an ambivalent attitude in a negative context. Instead, this encourages a fluid thinking in my practice: I have always sought newness from the mediation of opposites. For me, design is not a binary activity, but a spectrum of possibilities. So the journey begins.

2. 3D-Printed Digital Fashion and Textiles

> *'Modernisation' refers to the processes of scientific, technological, industrial, economic and political innovation that also become urban, social and artistic in their impact. 'Modernity' refers to the way that modernization infiltrates everyday life and permeates sensibilities. And 'Modernism' refers to a wave of avant- garde artistic movements. (Breward and Evans 2005, 1)*

Fashion and textile industries have been driven and accompanied by technological innovations throughout global industrial revolutions. British economic historian Arnold Toynbee first introduced the term "Industrial Revolution" into the English language in the early 1880s (Hudson 1992, 11), after which it was applied more widely. The First Industrial Revolution started in the British textile industry during the late eighteenth century. The factory was created as a result of the gathering together of independent weavers, and the transition of production methods from hand-craft to machine making.

These technological innovations laid the foundations for computational knowledge as it known today. The first form of "computer," Joseph Marie Jacquard's loom, devised in 1880, was predicated on the inseparable relationship between computational knowledge and creative industry. Computer innovation experienced the following key moments: Charles Babbage devised the Analytical Engine in 1839; during World War II Alan Turing designed techniques for code-breaking and Tommy Flowers created the first electronic computer. The Digital Revolution (from the late 1950s to the late 1970s) marked a period of transition from mechanization to digitization. It stemmed from the first American commercial computer, Universal Automatic Computer 1 (Univac 1), produced in 1951 By the US Census Bureau, and spread to the realms of art and design. Whilst computers and code were, by the mid-1960s, primarily considered the stuff of science and technology rather than art, the creative industries witnessed opposite trends; 2 D computer animation has emerged since the late 1960s. One early example can be found in the remarkable Alfred Hitchcock film Vertigo (1958); John Whitney designed the rotating pattern in collaboration with graphic designer Saul Bass. Another landmark event was the 2 D motion graphic film Arabesque (1975), which resulted from IBM's first artist-in-residence project (from 1966).

"Fashion and technology" is a topic that has been discussed through relevant theories and practices. One of the best-recognised discourses has been that of fashion and modernity, first formulated (1985, 7, 8) by Elizabeth Wilson, in which she argues that fashion is a culture of modernity, with an avant-garde that innovates through experimental techniques and transgressive responses toward convention. Wilson and Entwistle (2001, 4) further developed the concept of fashion and modernity by stating that fashion as a social, spatial and bodily practice is influenced by technological innovation.

Fashion can be understood as a version of modernity that is practised on and through bodily spaces. These spaces are both anatomical and social. Culture can be considered as an intersection of the natural and the social. The basis of modernity and fashion within mechanization is well documented (Wilson 2005; Breward and Evans 2005), and I am interested in how the modern age challenges and even revives these theories, especially in respect to contemporary culture that engages with digitalization. Thus, a brief history of digital fashion and textiles will be introduced here, focusing especially how 3DP has influenced fashion and textiles within this modern digital context.

2.1. Fashion and Textile Digitalization

The history of fashion and textiles in the context of digitalization is an "enigmatic" progression (Clarke and Harris 2012, 9). Differing from the term "Digital Revolution," which indi- cates a period of time when analogue electronic technology and mechanical devices evolved into digital electronics, "digitization" refers to the process of conversion from image, word, voice or any other non-digital objects into digital format (Bloomberg 2018), whilst "digitalization" indicates the widespread use of digital technologies in daily life, making it more of a social phenomenon than one based on physical actions (Brennen and Kreiss 2016, 1).

Sarah Clarke and Harris (2012, 14) explain digitalization as a social and historical progression in relation to fashion and textiles by assigning three different categories of activity: capturing the look of code, acknowledging the fusion of technology and craft and imagining the future under the scope of digitization. At the pre-developed stage of digital art (from the mid-'60s to the late '90 s), designers and artists tried to find out what the "code" or other technological elements looked like, and how this could be applied to their work. Eley Kishimoto designed the graphics for Hussein Chalayan's Spring/Summer collection in 1996, and Alexander McQueen designed the circuit pattern for Givenchy in the 1999–2000 Autumn/Winter catwalk show garments.

Further exploring the materiality of code, Clarke and Harris argue that, in the context of fashion and textiles, the integration of technology and craft gave birth to new vocabularies and esthetics in creativity. As such, both digital and hand-made aspects are embraced by contemporary design (Clarke and Harris 2012). The last point they make is that, in the light of technological development, digitalization can be understood as a means of building a freely imaginary sphere where various boundary-testing projects cross digital and material formats: for instance, digitally designing graphics then materializing them through printing the patterns onto a piece of textile, or digitally testing material properties on a virtual human model prior to production. Fashion and textiles are an important medium in which to express this mixed virtual and material culture in design.

The above inventions inspired me to envisage how what I will call the "3 D real world" (physical and tangible objects) and 2 D digitalization (designs that appear on a screen or that are created by a computer) mutually relate and creatively transform each other. For example, code appears in the tactile design of Eley Kishimoto, Hussein Chalayan and Alexander McQueen. Pushing this sensibility further, later inventions include Philip Delamore (2004) making the most of 2 D/3D software for engineering images for textile print and surface exploration (2004). This also involved developing multiple media for generating the illusion of two and three dimensions. The 2 D concept, in terms of how to use 3 D CG (computer graphics) to make imagery and surface decoration, was examined in detail by Jane Harris (2000) in her doctoral thesis. I thus question how cutting-edge digital technology, through the progression of the Industrial Revolution and digitalization, revives the concept of 2 D and 3 D inter-conversion. 3 D printing is one of these.

2.2. The Beginning of 3 D Printing in Fashion and Textiles

3DP produces objects by adding material point by point and layer by layer, and some refer to it as additive manufacturing (Gibson, Rosen, and Stucker 2015) or rapid prototyping (Vanderploeg, Lee, and Mamp 2017). The early form of 3DP, particularly Stereolithography (SLA), was developed in the 1980s by material

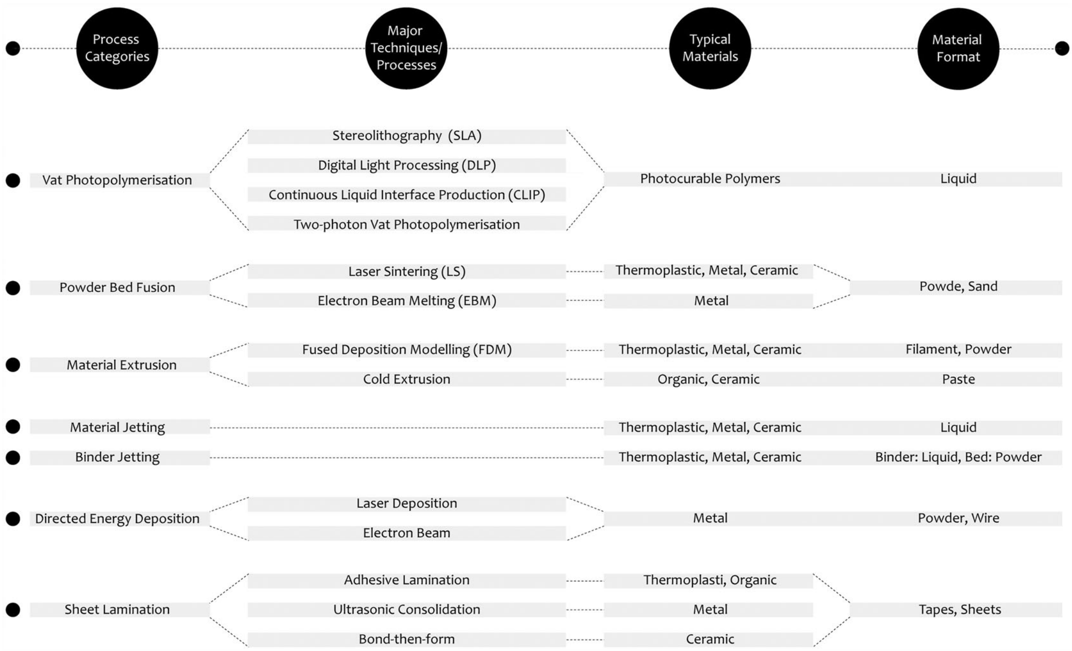

Figure 1
Major additive manufacturing categories and materials.

scientists and engineers, including Jean Claude André, Alain Le Méhauté and Olivier de Witte at the University of Lorraine (France), as well as Chuck Hull of 3D Systems Corporation (United States), who has a background in engineering physics and is acknowledged as the first holder of the US SLA patent (US4575330). It is regularly used in product and architectural design as a rapid prototyping method (Gibson, Rosen, and Stucker, 2015). There are seven families of additive manufacturing process categories, according to the International Organization for Standardization and the American Society for Testing and Materials (ISO/ASTM 52900) in 2015, and major additive manufacturing categories, techniques and materials, based on the study by Gibson, Rosen, and Stucker (2015), can be demonstrated as Figure 1.

In 2008, the patent for the important technique of fused deposition modeling (FDM) expired, which then enabled 3DP to become established at a commercial level within a relatively short time (Lipson and Kurman 2013). One noteworthy example is the domestic printer Makerbot, which has lowered the price of the FDM 3D printer by as much as 90 per cent (Wray 2014). No longer just a laboratory experiment, 3DP now covers several realms, including fashion, jewelry, medical and dental product development, architecture, industrial design and aerospace engineering. Scholars (Rifkin 2011; Marsh 2012; Lipson and Kurman 2013; Barnatt 2016) have defined 3DP as a manufacturing method that is an innate driving force behind the "Third Industrial Revolution" and research in the 3D market shows aggressive growth, as reported by Wohlers (McCue 2016). Klaus Schwab and Nicholas Davis have even predicted that 3DP will trigger the Fourth Industrial Revolution through its "economically feasible low-volume production, fast prototyping, and the decentralization and distribution of manufacturing" (Schwab and Davis 2018, 343).

3DP opens up a discussion of what can be seen as the new materiality in digitalization. It reduces the object-making to only two phases, designing the digital file using a three-dimensional computer-aided design (CAD) and printing, as opposed to other production methods, such as ones typical in manufacturing—subtractive or molding casting processes (Friedland 2016)—in which careful examination of the geometry and process is needed to control things like fabrication order, tools for different material production and material binding methods (Gibson, Rosen, and Stucker 2015). Thus, the work involved in more traditional mass production, based on manual production, has been reduced. Fashion production can use subtractive manufacturing, since it often involves cutting patterns out of fabric and re-assembling them. Textile production, on the other hand, is usually considered as an additive process, since many textiles, such as knitting or weaving, are constructed by adding more and more materials. In this sense, textiles and 3DP manufacturing are very alike: they both imply a way of designing, fabricating and even thinking about things additively. It is thus the starting point for my endeavor to bring the textile aspect, such as design and construction, into 3DP, so "3 D-printed textile and fashion" or "3 D-printed textile for fashion (purposes)" are frequently used phrases/terms to describe my projects, rather than just "3 D-printed fashion" or "3 D-printed textiles." Fashion and textiles go hand in hand, forming the subject of this research.

Although 3DP technology is not yet widespread in the fashion and textiles field (Sun 2015), designers and scholars have picked up this technology and observed its growing significance for future fashion and textile development (Van Den Berg, Van Der Hof, and Kosta 2016; Sun and Zhao 2017; Kwon, Lee, and Kim 2017). Like other great inventions, 3 D-printed fashion and textiles started with small ideas and avant-garde experiments. Back in the 1990s, a Dutch industrial engineer, Jiri Evenhuis, created the very first 3 D-printed fabric (Perepelkin 2013). In 2000, Janne Kyttanen and Evenhuis co-founded Freedom of Creation, a research-based design company, to continue to develop 3 D-printed wearable pieces, and a series of fully functional and flexible 3 D-printed "chain link" structured fabrics were created.

These early creations could be considered as singular and innovative fabric development, and I believe that the beginning of fashion's engagement with 3DP starts properly with the work of Dutch designer Iris van Herpen. Because the concept of fashion and modernity indicates (Wilson 2005, 9) that fashion, on the one hand, is associated with the clothing of our everyday life; on the other hand, it engages with trends and mass popularity in which avant-garde creations, like van Herpen's designs, influence, infiltrate and, to some extent, inspire others' practices. Also, from a technical perspective, after 2008 the FDM technique was no longer patented, and many consumers have benefited from accessing this technology more easily through the increasing availability of commercial 3 D printers. This thus gives many designers the opportunity to learn about 3DP and apply it in design. Therefore, more and more designers, such as Catherine Wales, Katya Leonovich and Xuberance, started to use this technology in fashion after 2010 when van Herpen showed the first 3 D-printed haute couture piece "Crystallization" during Amsterdam fashion week.

There are other reasons why van Herpen's work became more appealing than the fabric designed by Kyttanen and Evenhuis and could reach broader audiences. Taking the practical aspect into consideration, when the price of 3DP was extremely high, in the early 2000s, it seemed more valuable for designers to use this technology to develop more complicated and unique shapes that were tailored to this technique rather than simple geometries that could be produced by alternative methods. The chain-like structured fabric devised by Kyttanen and Evenhuis consisted of separate flat 3 D-printed pieces draped over a mannequin. It showed less potential for creativity because it lacked variety in terms of its elements and inspirational design concept. This structure could easily be compared with the plastic mesh that we frequently see, constructed using similar linking structures. The question is why would people wear a piece of 3 D-printed fabric made by the chain-like structure, which, in fact, might be easier to produce by well-established manufacturing methods, such as injection molding or extrusion molding for plastic? In comparison, Van Herpen collaborated with Daniel Widrig to design more intricate and complex geometries, which beautifully translate the crystallization process into a highly imaginative shape that is almost impossible to make by alternative methods. This conceptual fashion piece might not even have existed without access to technologies like 3DP and parametric modeling that have emerged within the last decade (see Section 3).

But there continues to be problems in terms of increasing complexity and wearability in 3 D-printed fashion, especially the fact that the wearer would be restricted in 3 D-printed couture and might not be able to move their bodies as they could when

Figure 2
Standard stages of 3 D printing.

wearing softer fabric, such as the "Crystallization" dress (2010) and the "Skeleton" dress (2011) designed by van Herpen in collaboration with Daniel Widrig and Isaie Bloch, respectively. I began to question whether factors relating to the human body, especially body shape and body movement, were considered less in these designs? If so, what is the reason behind this?

3. The Scope of the Research

There are generally at least five stages involved in the design and production process of 3DP (Gibson, Rosen, and Stucker 2015; Vanderploeg, Lee, and Mamp 2017; André 2017) as shown in the Figure 2.

Designers are continually engaged with the first and last stages, designing the object using software and the post-treatment of objects. These two stages reflect how designers and their design process impacts on the application of 3DP in both digital and material aspects, specifically computer software and tactile approaches.

Specifically, while there is a significant amount of scientific literature (mostly written by engineers and/or materials scientists) on the tangible (technical and material) aspects of 3DP (Van Den Berg, Van Der Hof, and Kosta 2016; André 2017), very few articles have appeared in the literature which discuss fashion and textile practitioners' attitude toward the emotional attachment to, and interaction with, 3 D-printed materials in the design process. Similarly, within the last five years, academic conferences on 3DP and/or additive manufacturing have been dominated either by broadly themed events[4] across science, technology, engineering and/or design or by themed events[5] focusing on areas other than fashion and textiles. Within the broadly themed conferences, fashion and textiles are mainly sectional, such as the first 3 D-printed fashion show organized by Materialize during the RAPID 2012 Conference and Exhibition and the 3 D-printed fashion and textile showcase/presentation during 3 D Printing and Design Symposium 2017 organized by Digital Hack Lab at the University of Hertfordshire, and the International 3 D Printing Fashion Show at the World 3 D Printing Technology Conference and Expo 2015 in Cheng Du, China. To my knowledge, there was no independently organized academic conference that specifically discussed the application of 3DP in fashion and textiles before the conference I organized on the May 19th, 2016. Also, commercial, personalized/bespoke and sustainable aspects of 3 D-printed fashion and 3 D body scanning, aspects that relate to the fashion/apparel industry, have been much studied by researchers, including Sun (2015), Bougourd and Delamore (2007), and Peng, Sweeney, and Delamore (2012). In this PhD research I have been curious about how experimental and conceptual fashion practices (the context outlined at the beginning of this chapter), based on my experience, influence and tackle the crossover between digital and material culture.

I therefore organized a conference titled *Digital Fashion: 3 D Printing for Designers* on May 19, 2016 at the Royal College of Art in order to discuss avant-garde practices. I wanted to choose five presenters from various non-fashion backgrounds, and encouraged them to explain their idea of the interface between digital technology and fashion, because this would help me to reflect on my practice and identify differences.

3.1. Conference Report

3.1.1. Content of the Conference

I invited five speakers to the conference: Fergal Coulter, from Nottingham Trent University, an engineering researcher in 3 D Printing on inflated substrates and dielectric elastomer artificial muscles; Behnaz Farahi, from USC School of Cinematic Arts, an architect researching into 3 D-printed body architecture; Troy Nachtigall, a researcher from the ArcInTexETN network studying 3 D-printed footwear and wearer behavior; Filippo Nassetti, a designer from Zaha Hadid Architects interested in using parametric modeling and generative design making wearables, and Oliver Smith, a 3 D printing design consultant from Stratasys Strategic Consulting. Claire Pajaczkowska, the RCA Senior Research Tutor in Fashion and Textiles, gave the opening address. At the end, Clare Johnston, RCA professor and senior research fellow, chaired a panel discussion on the questions around interdisciplinary collaboration, 3 D printed fashion and the barriers of this technology.

3.1.2. Presentation 1: Parameters from Nature— Filippo Nassetti

Nassetti's architectural background did not limit his interest in body-scale wearables. Nassetti stated that his research focuses on bio-digital synthesis and prosthetics by projects. These can be separated into a two-stage transformation: translate a biological process to digital coding, and then turn the coding into body-related fabrication, mainly through 3 D printing. Nature for him is not an image or pattern, but a dynamic system filled with paths and processes. The key word for parametric design is "grow," which indicates the nature of digital fabrication that builds geometry from codes and data. With coding languages, the design could be translated into something generatively and digitally grown. The main tool for his practice is Processing, which is open-source coding software, and GH, which is plug-in for architectural software—Rhino—for designing parametric models.

3.1.2. Presentation 2: Parameterizing the Market—Oliver Smith

Stratasys is one of the world's leading 3 D printing companies. This company has previously collaborated with fashion designers such as Iris Van Herpen and threeASFOUR. One of the best-known products of Stratasys was the Object 500 Connex3, which was an industrial machine that could print full colors and materials of programmed softness. Apart from presenting a fundamental industry and commercial report, two other aspects Smith shared related to this research directly. 3 D printing is challenging traditional fashion design and mass production systems. 3 D printing allows designers to design and manufacture their own extremely complex designs. The industry 4.0 explains that this industrial revolution is the result of digital development. In fashion, it is similar to an era of artisan or hand-made production, when there were no clear lines between designers and tailors. Needless to say, 3 D printing is a superior craft industry in that it produces extremely complex objects with different geometries without extra cost, using low-volume production and achieving highly customized products. In this way, 3 D printing brings new digital opportunities of personalization to the traditional French fashion system, in which fashion is an avant-garde prototyping activity by individuals. Another aspect is the value of material development in 3 D printing. 3 D printing has both pros and cons in terms of the way it produces things layer by layer. There are limitations to the materials. The reason for this is that the building material should either be joined with other binding materials or joined via chemical reactions, such as temperature change or UV light curing.

3.1.3. Presentation 3: Parametrizing the Wearers' Behavior—Troy Nachtigall

Nachtigall has researched into how technological materials could solve problems that appear in the mass production of the fashion industry. He is specifically looking into 3 D printed flexible shoes that are fitted for feet and movement. The parametric modeling here is used as a way to design the perfect personalized, fitted shoes. A valuable result is that certain parametrized designs result in different behaviors by the wearer.

3.1.4. Presentation 4: Parametric Design and Science—Fergal Coulter

From a scientific point of view, Coulter gave a presentation on engineering a machine for printing silicone with a parametrically inflated structure. Although his work is not fashion related, it helps me to make a comparison between art-based and science-based research. Compared with research in art, his science-based research focuses more on solving the problems, which differentiate it from a speculative research method. This presentation is also valuable, as it enriches the ways we think of 3 D printing. He had the idea of changing the print platform to a spherical one, turning the model and the extruder printing onto the model. With the help of the parametric modeling tool, GH, the pattern could be printed onto the model. As Fergal stated, interdisciplinary collaboration is what has been driving his research.

3.1.5. Participation 5: Parametrizing Future Humans—Behnaz Farahi

Behnaz Farahi was trained as an architect and is a current PhD student in interactive body architecture. Her work is related to wearable technology and 3 D printing. Her most recent and influential piece is "The Caress of the Gaze," in which she embedded a camera in a garment to capture viewers' facial expressions: the garment will react based on different facial data. A comparison between her work and my previous practice, Bond, shows that we both used facial recognition technology, 3 D printing and auxetic structures. Although we use similar technologies and concepts to create future humans that possess other functions, her work is superior to mine. However, the printer is a multi-material and multi-color one, and the auxetic structure was seamlessly translated into a fabric, while the facial recognition device is perfectly hidden in the garment. This makes me really think about the advantages that I have, over architecture, in terms of designing a body-related project. This is how I see both the body and garments, as three-dimensionally moving, natural things, and shows how I value the translation between 2 D and 3 D. From her work, there is less interaction the garment, body shape and body movements. As a fashion designer, I really value how our bodies are formed by nature and how our limbs and body can interact, change and influence garments. I really admire her work in bringing other senses to the garment, but I will endeavor to bring natural movement and interaction to clothes.

3.1.6. Interview Questions Put to Behnaz Farahi

Q1: We know that you are an architect and interaction designer, exploring the possibilities of interactive environments and their relationship to the human body. Would you like to give us some general information about yourself? Your education, your work experience and design interests?

Q2: You are currently a PhD student as well; how do you feel about being a researcher rather than a designer? Do you think these conflict?

Q3: If you could describe your main works in a few words, what are they?

Q4: You were talking about the interaction between the human body and the environment; you were also talking about the architect and fashion, so what is your definition of fashion?

Q5: There is also a traditional way of defining fashion, which applies to its functional, practical, washable qualities, etc. How do you define your work? Is that a part of fashion, textiles, installation works, wearable technology?

Q6: Could you please introduce the most exciting work you have created so far? Is it The Caress of the Gaze? How were you inspired to create it? What was the technology used for this work? What are the difficulties you experienced during the process?

Q7: When and why did you begin to be interested into 3 D printing? What does this technology mean to you and to other designers?

Q8: What was the shift that 3 D printing enabled, from your experience?

Q9: From your perspective, in order to spread the use of 3 D printing widely, what is the most effective way to tackle the problems encountered in material, structure, fabrication or application?

Q10: Why is 3 D printing attracting so many other major designers' attention?

Q11: Do you think 3 D printing or other digital approaches to fashion will replace certain traditional ways of making?

Q12: How do companies and start-ups see the opportunities in the latest innovations?

Q13: Do you think there will be distinctive Fashion? Do we really need 3D printing for fashion?

3.1.7. Interview Questions at the Conference Panel Discussion (Addressed to Filippo Nassetti, Troy Nachtigall, Oliver Smith, Fergal Coulter)

Q1: Collaboration. Have you found working with 3 D printing requires interdisciplinary knowledge?

Q2: How has the world of fashion influenced your thinking in relation to 3 D printing? Has it been useful in giving you limitations and boundaries, and what is your experience of these?

Q3: What are the problems and barriers facing 3 D printing? Material, structure, application, touch, wearability and feeling of the material? How could the 3 D printed material behave next to your skin?

Q4: Brands use 3 D printing: is this generally for technological purposes alone, or to draw attention as branding?

3.1.8. Conference Reflection

The presentations covered many aspects of 3 D printing: the fashion industry, materials and engineering sciences, digital modeling innovation and interactive smart materials. The conference highlighted the strong relationship between fashion and parametric design. The parameters of 3 D printing can be understood as both parametric design and also cultural attitudes toward the 3 D printed fashion phenomenon. For all of the 3D designers above, the concept of a human and technology interface plays a vital role in their work, but because of their different backgrounds, they explain this concept distinctively. What fashion practitioners understand better are intimate spaces and bodily relations with external systems, such as clothing and technology, whereas an architect might focus on the larger-scale interactions between the whole body and space. As for engineers, the interface is possibly understood as how humans operate machinery. To understand the intertextuality requires multi-faceted knowledge across several disciplines. However, when fashion designers design with 3 D printing, they tend to collaborate with other designers, who are more fluent with modeling tools. This makes me think that I should carry out an investigation into modeling, especially parametric tools. This could potentially differentiate my approach from other designers' toward 3 D printing, especially in terms of the transformation from digital data/algorithms to tangible materials. The parametric then is not only limited to specific parametric design methods; it might expand to include a broader sense of thought and creativity.

Parametric design is a technique to design 3 D printable objects by algorithms; however, from the cases above, it can be seen that there is certain logic in creative design and manufacturing in a highly developed digital age that is able to create things from data, to design the output through input and algorithms and to link the data with the human body. Here I propose that this concept should be seen as "parametric thinking," that links algorithmic design, fashion design (pattern cutting) and the body together, in respect to the materials made by textiles. There needs to be more investigation into this hypothesis in both its theoretical and practical aspects.

3.2. Summary of the Conference Report

From the conference report, I concluded that there needs to be more investigation into (1) the important role of parametric design (2) the awareness of the human body in 3D-printed and body-related projects (3) the possibility of adopting (1) and (2) to create a concept of "parametric thinking." First, fashion and textile practitioners are often challenged by using 3D CAD programs (Sun 2015), which are primarily designed for other disciplines such as architecture and product design.

As can be seen from the outer circle in Figure 3, all five participants mentioned parametric design/technology to a certain extent: Filippo Nassetti took parameters from nature and transferred them into algorithms for designing wearables; Fergal Coulter used parametric design tools for scientific and engineering development; Troy Nachtigall parameterized wearers' behavior through 3 D-printed shoes; Oliver Smith situated parametric designs in interdisciplinary and societal changes by explaining many commercial and experimental examples of 3 D-printed wearables; Behnaz Farahi used parametric design in a futuristic context to predict human behavior. As shown from the inner circle (parametric design and parametric thinking) and the curved arrows in Figure 3, while Nassetti and Coulter continue to push the limits of parametric design in technological contexts, Nachtigall, Farahi and Smith extend the use of parametric design into a broader understanding of the human body, future humans and society, respectively.

Apart from parametric design, the second aspect concluded from the analysis was that these presenters were likely to prioritize their professional knowledge (architecture, materials science, footwear, commercial 3DP), over a consideration of the human body and/or its interaction with 3 D-printed garments/textiles. Even human body-related 3DP practices were mentioned, fashion aspects related to the human body were rarely discussed by these speakers: how does a body move together with the 3 D-printed garment; how could garment construction and pattern cutting influence the process of making and designing 3D-printed fashion and textiles; what does the 3D-printed material feel like when you touch it, and will its tangibility also impact on the making and designing process and outcome?

Thus, although parametric design is commonly understood by the conference participates as a technique to use algorithms in the design process, the cases above propose the idea that there is certain logic in creative design and manufacturing in a highly developed digital age that is able to

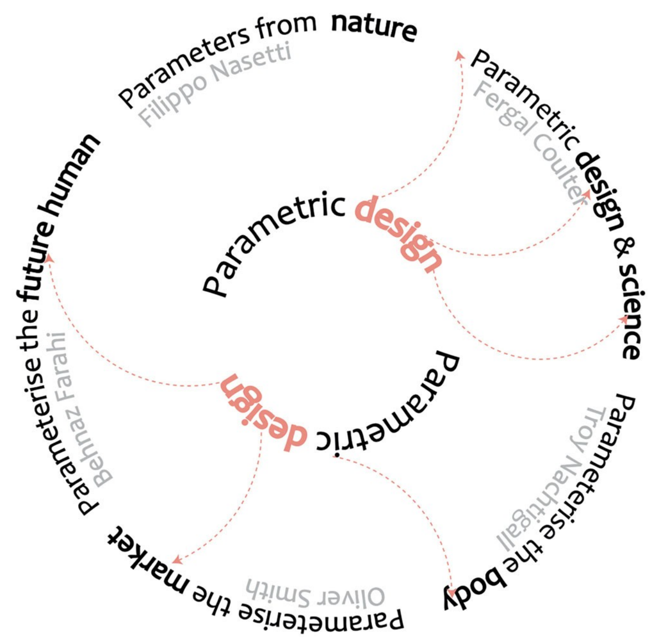

Figure 3
An analysis of the conference "Digital Fashion: 3 D Printing for Designer."

create things from data, to design the output through input and algorithms and to link the data with the human body. Even though I was not sure whether any literature existed on parametric thinking at that time, the conference was the critical moment when I began to propose that this logic should be seen as "parametric thinking," and that it might link algorithmic design, fashion knowledge (pattern cutting) and the body together in respect to textile construction. This invited me to investigate further into this hypothesis in both its theoretical and practical aspects.

3.3. The origin of parametric design and its adoption in fashion

There are four terms, *parametric modeling*, *parametric tools*, *parametric design*, and *parametric thinking*, that need to be clarified in order to avoid potential confusion.

Parametric modeling is a technique of digital modeling defined as designing complex geometry from data, numbers and algorithms (Frazer 2016) through computer-programmable and/or algorithm-based tools. These tools, often in the format of computer programmes, software and software add-ons, are considered as parametric tools. For example, these include Processing,[6] Grasshopper,[7] eVe/Voronax,[8] Freeform Origami[9] and Rigid Origami.[10] In contrast to shaping geometry by cutting and adding other geometries, as with a conventional modeling system (Woodbury 2010), parametric modeling is a way of designing and modeling algorithm-based geometries, which can be changed, defined or encoded by parameters and variables. Parametric modeling enables significant capability and typological variety in design generation and modification simply by altering parameters rather than re-coding or re-modeling (Mohammad 2012; Oxman 2017; Alalouch 2018).

This design method and the resulting design output produced from the parametric modeling technique and parametric tools can be explained as parametric design in this research. As a design approach, parametric design means to establish the relationships/logics by algorithm ("a set of principles encoded as a sequence of parametric equations" (Mohammad 2012, 4)) between parts of the design, and to create/modify a design through changing the relationships of the algorithm, rather than designing the specific shape. When parametric design refers to design output, this indicates not only a digital format (design rendering) produced by a computer, but also physical forms, if the digital design is eventually materialized—for instance in Zaha Hadid's Soho Galaxy building. Parametric design is not an entirely new territory for architectural design (Zarei 2012). The ancient pyramids and Gaudi's remarkable Sagrada Família were early examples of designs based on mathematics. However, it was not until the 1980s that computational parametric design was used in architecture (Phillips 2012). The last decade has witnessed parametric modeling being used regularly in architectural design (Davis 2013). Parametric design is currently a very fashionable phenomenon in architecture and has a long history in this field compared with parametric design in fashion; however, with the help of the new fabrication tool 3DP, and influenced by avant-garde practitioners such as Nervous System and Julia Koerner, fashion designers have recently started to create parametric wearable design, such as the works of threeASFOUR designed in 2015 and 2016, and most of the designs that Iris van Herpen created since 2010.

Fashion designers and architects commonly collaborate because of their interests in shapes and space. The immediacy of production of the scale of fashion allows architectural forms to be created within a shorter time, and with the help of 3DP, a large number can be produced immediately (Robinson 2015, 41). Some architects are even involved with the fashion industry. Zaha Hadid has a fashion label producing parametric accessories. Footwear brand United Nude was launched by architects Rem D. Koolhaas and shoe designer Galahad Clark. 3 D-printed fashion, unsurprisingly, follows the same pattern as other avant-garde fashions. For the majority of the cases I studied, fashion designers collaborated with, or were supported by, an architect. All of Iris van Herpen's collaborators—Neri Oxman, Julia Koerner, Daniel Widrig, Isaie Bloch and Niccolò Casas—came from architectural or computational design backgrounds, and parametric modeling tools were used to produce most of their work.

However, architects and fashion designers seem to pay attention to different aspects of the human body in architectural and garment design: an architect might consider the circulation of the human body, the surrounding spaces and the larger building scale, while as a fashion designer, I care more about the details, the dynamics of the body, the material covering the body and the intimate relationship between the body and the material. The fundamental difference in design focus is reflected in the different approaches to a body-related project: the human body tends to be treated as a static whole when architects design clothing/body-related projects using digital tools: they are less concerned with the body's dynamics and its interaction with tangible materials. For instance, architect and computational designer Alessandro Zomparelli developed the Tissue add-on for Blender, which could grow a Lattice structure along the (body) surface. Playing around with ideas on a digital form of the human body (mannequin) is adequate for early idea exploration and demonstration when designers do not need to produce real objects. However, a real human body is much more than a static surface, and it is often prioritized in my practice, especially in terms of the dynamics of body movement, body shape and physical interaction with materials. In contrast to architectural practices, which might well consider large-scale buildings, the interior space and the area of human activity, my motivation for wearable design has always been driven from the corporeal body to the in-between space between skin and material, to the material details, to the outside world.

Does parametric design have a positive future in fashion? Parametric design is already being used in fashion (Oxman and Gu 2015), and its advantage fundamentally lies in designing imaginative geometries. Some of the geometries, such as studio Xuberance's generative geometry, are almost impossible to build without parametric modeling. But there are also essential differences in terms of how parametric design is applied in fashion compared with its application in architecture, and some of these might be considered drawbacks. For architecture, "inarticulate, undefined, and too difficult to construct" (Phillips 2012) were the drawbacks of applying parametric design in actual bulidings. In contrast, a human-scale project can benefit from these features. It can be seen from examples in the book *3D-Printed Body Architecture* (Leach and Farahi 2017) which calls designers' attention to smaller-scale architecture and human-interactive architecture when using parametric tools and technologies such as 3DP.

Developing from the inspirational concept of parametricism, coined by Patrik Schumacher in 2008, in which he argues that cutting-edge computational and parametric tools could benefit architectural design within the growing volatility of urbanization (Schumacher 2016), parametric thinking has attracted the attention of many architecture scholars and practitioners in recent years (Anderson et al. 2011). Beyond being a novel tool and approach for creating complex geometries, parametric modeling, parametric tools and parametric design are beginning to contribute to emerging ways of thinking (Oxman and Gu 2015, 1; Alalouch 2018, 163) in architectural design: parametric thinking. Parametric thinking is a term first defined by Karle and Kelly (2011, 109), that as a "way of relating tangible and intangible systems into a design proposal removed from digital tool specificity, and establishes relationships between properties within a system. It asks architects to start with the design parameters rather than preconceived or predetermined design solutions." To be more specific, by adjusting the measurable parameters/variables of a parametric definition/equation, various designs, and thus educational outputs, can be created relationally in architectural education (Karle and Kelly 2011, 110, 112). The advantages of parametric design lie in creating variety and alteration with less effort, as well as novel and complicated architectural designs (Alalouch 2018, 164). Parametric thinking is thus distilled from this design approach and can be described as relational thinking, a method of thinking and a type of methodology (Karle and Kelly 2011, 109–111) for enabling architectural students to generate a range of design opportunities by correlating different kinds of content (design, making, technique and contextual study) rather than separating them. Similarly, Sanguinetti and Kraus (2011, 39–47) have also supported parametric thinking as methodological thinking from the perspective of architectural phenomenology. They proposed that parametric thinking offers architects a novel methodological approach to visualizing tacit design intentions (based on designers' sensory experiences, such as those of hearing, touch and vision) into explicit algorithms to be tangibly materialized as design outputs. Mohammad (2012, 8) suggested that strengthening computer-aided parametric design in architectural practice can yield a new model of thinking, parametric thinking, which transforms designers' use and exploration of advanced digital tools into new knowledge of creation and innovation in design.

Researchers including Sanguinetti and Kraus (2011, 39), Mohammad (2012, 3) and Oxman and Gu (2015, 1–6) have all addressed the possibility of linking parametric thinking with design thinking in the field of architecture. Rivka Oxman (2017) carried out an intensive study on theories and models of parametric design thinking (PDT), and situated PDT as continuing and developing as a mode of design thinking. PDT was defined by Oxman and Gu (2015, 2) as involving architects in thinking abstractly, mathematically and algorithmically, in addition to offering fundamental architectural knowledge, while applying parametric tools into their design.

Therefore, current studies above point to two facts: first, parametric thinking is distilled from transferring the practice of parametric design into a mode of thinking—more precisely a methodological approach; and second that this methodological thinking is mainly discussed by architectural scholars within the field of architecture. Although parametric thinking was instigated by architects, researchers have called for a more in-depth and broader understanding of this term in an interdisciplinary (Oxman and Gu 2015, 5) and material (Moussavi 2011; Alalouch 2018, 176) context. I then began to question, researching from a fashion and textiles background, what the differences would be when applying parametric tools to developing 3 D-printed textiles for fashion from my own design process, design outcomes and thinking? How do I understand parametric thinking as a research methodology[11] based on my practice? How can 3 D-printed fashion and textiles practice yield an adaptation of the concept of parametric thinking?

4. Aim and research structure

The studies above show that in pioneering 3 D-printed fashion projects, there is a tendency toward a lack of awareness of the human body from the point of view of both 3 D modeling (software) and materials development, which potentially leads many current collaborative 3 D-printed fashion practices to be too rigid/static, such as in their use of stiff materials, resulting in a "shell-like structure" (Klein 2015). Taking a phenomenological approach,[12] the research fundamentally explores whether the human body can inform new possibilities of both the digital and the material aspects of 3 D-printed fashion and textile design. How could my understanding of the corporeal body from a fashion perspective contribute to new formations of 3 D-printed design and parametric thinking?

The thesis structure (Figure 4. Thesis structure, the model of the research (the animation of the Figure 7 is in Supplementary Appendix 2) is as follows.

Embracing ambivalence has inspired me to always seek out the possibility of joining/mediating conflicts in order to achieve a creative outcome in my practice. Chapter II

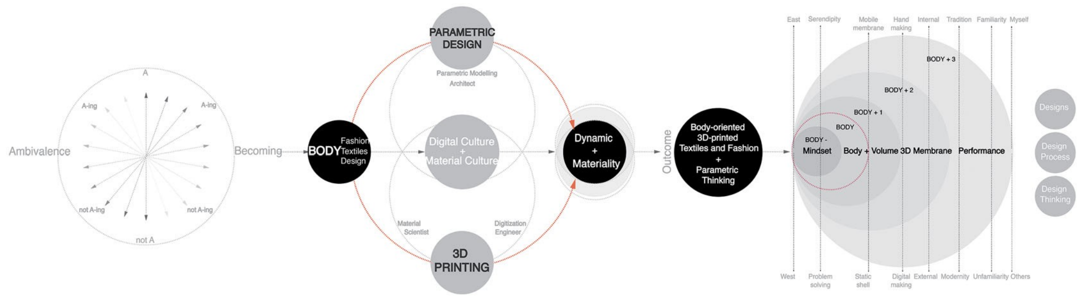

Figure 4
Thesis structure, the model of the research.

provides a chronological contextual review of the development of 3 D printing and 3 D printing for fashion and textiles. The Deleuzian concept of "becoming" (Chapter IV) and its latent acknowledgement of Razinsky's notion of ambivalence provide a literature base that supports creativity associated with the concept of mediation between opposites. I also contextualize other avant-garde designs and my own practice within this concept in order to demonstrate how I embrace ambivalence in 3 D-printed fashion and textiles development. Here, cutting-edge parametric tools (such as Processing and Grasshopper) and 3DP technology (such as multi-material printing) are used to epitomize the creative transitions/transformations between opposing elements such as material softness and hardness or immobility and mobility. Two collaborative projects, "Inter-fashionality" (Chapter V) and "Fold-the-Interfashionality" (Chapter VI) are the main case studies, scrutinizing the human body's decisive role in the innovatory mediations between opposites from both a digital software and materials development perspective. Essentially, I am proposing that fashion and textiles designers could use our knowledge of complex body shape and body movement, as well as the experience of materiality, to bring an intricate/fluid understanding of 3DP fashion construction and textile pattern. The research question is thus divided into the following two aspects (the red circular lines in Figure 4):

1. Can the body inform new dynamics through parametric design, which is used regularly in architecture and other disciplines?
2. Can body-oriented 3D-printed textiles bring new possibilities for materials from a fashion design perspective, rather than from that of materials science or engineering?

The research aims to:

1. Employ my hands-on experience and examine pioneering design in the field of 3D-printed fashion and textiles to interrogate the ambivalent phenomenon of digital fashion. This includes a further investigation on how creativity is linked to the ambivalence embodied in the application of cutting-edge technologies.
2. Develop new forms of 3D-printed design by implanting fashion and textile design knowledge in to 3D modeling, material making and 3DP.
3. Innovate the techniques of 3D-printed fashion and textile creation. It contains, but does not limit to, developing new algorithm/parametric design, producing new ways of making, and/or using new materials in fashion and textiles practice.
4. Experiment 3D-printed design outcomes through their interaction with the human body, while recognizing textile fluidity and fashion performativity.
5. Generate a methodology, a new adaptation of "parametric thinking," which enfolds 3DP, parametric design, fashion and textile expertise in both theoretical and practical senses, for use in fashion and textile design research.

The originality thus lies not only in the new algorithms[13] and designs[14] for 3DP, but also in the different interpretation of parametric thinking[15] in fashion and textiles all of which potentially make the research innovative, from design practice to new fabrication, production and even new models of thinking.

This research offers benefits for fashion and/or textiles researchers who are interested in the area of 3DP, parametric design and parametric thinking. It could also be of use to researchers and practitioners from other disciplines, such as architects, product designers, computer engineers and/or materials scientists/ engineers, who are exploring how 3DP, parametric design and/or wearable technology relate to the human body, particularly the relation between body shape/movement and wearing materials. There might be individuals who are interested in certain aspects of the research: for instance, the notion of ambivalence and Deleuzian "becoming" in a digital fashion context, performance as a fashion and textile research method, or parametric thinking as research methodology, generating new design ideas by embracing oppositional elements. I also welcome audiences to discuss/ challenge the idea of embracing cultural differences and exchanges in digitalization, such as combining Chinese qipao and jingju with 3DP, which, as a technology used in fashion and textile design, has so far been developed mainly in a Western design context.

Notes

1. These refers to the textile creation, which can be found from the 5.3 section in the author's PhD thesis (Lin 2020) titled, *Interfashionality: Body-oriented Parametric Design and Parametric Thinking 2.0 for 3D-printed Fashion and Textiles* (https://researchonline.rca.ac.uk/4527/)
2. The structure refers to the parametrically design and 3D-printed pleats, which can be found from the author's 6.3.1 SECTION in the PhD thesis titled: *Interfashionality: Body-oriented Parametric Design and Parametric Thinking 2.0 for 3D-printed Fashion and Textiles* (https://researchonline.rca.ac.uk/4527/)
3. The qipao/cheongsam is a type of traditional Chinese garment that was originally designed to be wide and loose. It is one of the only traditional forms of dress that have survived the transition to modern dress without losing most of its traditional characteristics (Li 2014, 9), and it is still popular on many occasions today. The period from the 1920s to the 1940s marked the qipao's remarkable transition from being cut from purely flat pattern pieces to dimensional construction in its pattern-cutting (Li, Zhu and Sun 2014).
4. Such as Formnext, TCT, Rapid. Tech þ FabCon 3.D, Global Additive Application Summit, 3D Print Expo, The International Conference on Additive Manufacturing & 3D Printing, IN(3D)USTRY and Inside 3D Printing.
5. Such as 3D Printing Electronics Conference, Additive Manufacturing for Medical Devices 2019, Additive Manufacturing for Aerospace and Space, Annual Conference on 3D Printing & Bio- printing in Healthcare, 3D Metrology Conference, AM Ceramics 2018, International Congress on Welding, Additive Manufacturing and Associated Non-destructive Testing, Automotive 3D Printing Conference.
6. It was used in the 4.2.2 section in the author's PhD thesis titled, *Interfashionality: Body-oriented Parametric Design and Parametric Thinking 2.0 for 3D-printed Fashion and Textiles* (https://researchonline.rca.ac.uk/4527/)
7. It was used in the 5.3 section in the author's PhD thesis.
8. It was used in the 5.3 section in the author's PhD thesis.
9. It was used in the 6.1.2 section in the author's PhD thesis.
10. It was used in the 6.1.2 section in the author's PhD thesis.
11. Using *Parametric Thinking* as a research methodology was intensively discussed in the 3.3.2 SECTION of the author's PhD thesis.
12. The phenomenological approach is an overall research approach for this PhD research, and it was discussed in the Chapter III of the author's thesis.
13. It was presented in the 7.2.2 section of the author's thesis

14. The new design was defined as Parametric Design 2.0 in 7.2.3 section of the author's thesis.
15. The research generated a new model of thinking Parametric Thinking 2.0 in 7.2.1 SECTION of the author's thesis.

Supplemental material

Supplemental research materials for this article can be accessed here.

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