Materializing Data

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craftsmanship
and technology for
ultra-personalization

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EINDHOVEN UNIVERSITY OF TECHNOLOGY

Materializing Data: craftsmanship and technology for ultra-personalization

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Craftsmanship and technology
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PROEFSCHRIFT

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door

Troy Robert Nachtigall

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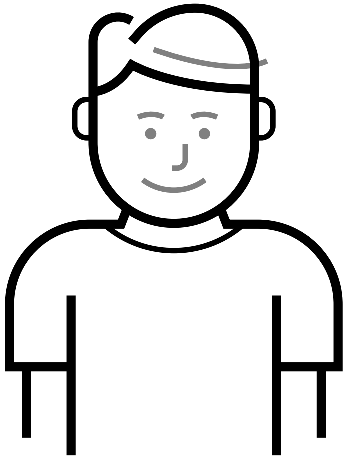
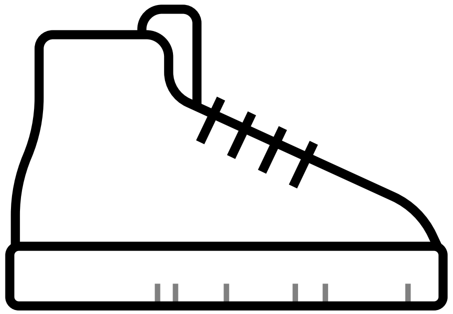
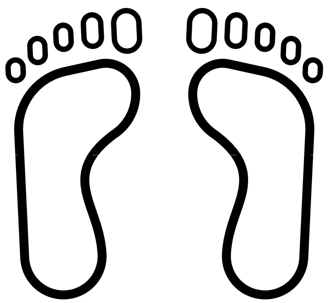
for Aurelio, Arturo and their little brother,

dedicated to the memory of Valérie Lamontagne and Fiore Basile

Table of Contents







1 Introduction and Background

Do you remember throwing away a favorite pair of shoes? Perhaps they were too beat up to go on? Too full of holes. Too broken. Do you remember how well they **fit** you? Do you remember how great they felt when you walked in them? How great they looked? Most of us have had that shoe. Some of us have found it more than once. Finding that shoe is a difficult process. But what if there was a way for those shoes to tell your next shoes about you?

I came to this research wanting to make personalized shoes that would fit your feet, your step, and your style. Not just one pair of shoes, I imagined a whole closet of personalized shoes that were subscribed to through a Netflix-like service. I wanted to 3D-print personalized shoes for you out of a single material, so they could be recycled again and again. There were many ways to approach this problem: scientific analysis of your movements, an analysis of the taxonomy of a specific kind of footwear design, or interviewing many experts such as orthopedists, shoe designers, and trend experts. Recent research into personalization comes primarily from an engineering perspective.

As a fashion designer, I make things that are worn, or as they say in design research, embodied. I have traveled the world to understand how, why, and where fashion is made, and who makes it. Along the way, I developed skills from many domains, many of which were brought to this research project. I found an opportunity in this research to approach it from a craft, in this case bespoke shoemaking, perspective.

What if the personalized, bespoke tradition of shoemaking could be supported by the crafting of data, algorithms, and digital fabrication? Could data be treated as a material? Could data be crafted as a digital material alongside the physical materials? In this dissertation I, along with many talented stakeholders, made shoes and enabled hundreds to make their own shoes. Along the way, I looked at how shoemaking could become a data-driven framework for a product service system of personalized shoes.

I discovered that personalizing shoes also means personalizing the sensors, tools, services, and, systems involved. I discovered that it was possible, without the need for embedded electronics, to make a shoe that makes data for more shoes. I took the designerly role of the craftsperson, and recruited the stakeholders to make shoemaking with data as a system. We made shoes, 3D printers, foot scanners, web apps, databases and the APIs needed to transition the data from analysis to design, manufacturing and use. From a practice of making shoes and shoe systems with data show that the practice of craftsmanship is needed to understand and improve the potential of the emerging technology of digital fabrication.

Emerging digital technologies enabled by data, algorithms, and computation hold new opportunities to make everyday things. Data meets new flexible 3D-printing materials in digital fabrication technology. These technologies and materials have only recently begun to be applied to shoe design and fashion design.

This research stands to benefit everyone who wears shoes. It enables new forms of fit: form, behavior, and aesthetic. New tangible interactivity is made possible by flexible internal structures that respond to movement. Moreover, the shoe has medical implications. In working with orthopedists during this research, an old adage of foot specialists arose: “The shoes you wear in your twenties and thirties will cause the problems of your seventies and eighties.”. If machine learning could be applied to the data of shoes, could shoes be made to avoid knee and hip replacement? While this will take time to be tested, the ability to create data that inform future shoes is here.

If it is possible to personalize shoes with data, what else could be personalized? If a lifetime of shoe can be personalized to a person, how can data allow us to make many things personalized?

1.1 Where Does This Research Come From?

This thesis comes from a practice of shoemaking. I am a designer, I make things (and services and systems). This dissertation is an implicit autoethnography of my design practice. I put my own practice under the lens of research. I used a series of different design methodologies including an exemplar, toolkit, deep exploration, annotated portfolios, and a design game to make shoes (and systems of shoemaking) using digital fabricadtion.

Walk around my lab and you will find a lot of samples. I like to embed knowledge in things I make. Even the trash contains knowledge. Look in my recycling box and you will find the inspiration for many more projects as seen in "The Box of Glorious Failures" (Nachtigall 2018). The process of collecting everything and looking at its meaning lead to the annotated portfolio featured in chapter 7. In the process of the research, the contents of my recycling box were moved into a series of display cases as I came to realize how much knowledge was contained on those samples. This idea is captured by the anthropologist Ingold in the book Making:

> ***"Making, then, is a process of correspondence: not the imposition of preconceived form on raw material substance, but the drawing out or bringing forth of potentials imminent in a world of becoming. In the phenomenal world, every material is such a becoming, one path or trajectory through a maze of trajectories." (Ingold 2013)***

I once listed my profession as "digital artisan, intrepid designer, cunning artificer." I make things. I think through those things. I use those things to show others what I was thinking about. This turns into collections of things. Those collections of things allow me to reflect and understand. Materials, tools, techniques, and data all shed light into the future services and systems. I dream of a future where design uses those systems and services to make many personalized things.

It was in April of 2015 that the idea of personalizing the behavior, form, and aesthetic of a shoe by using 3D printing first became a possibility. I was teaching a course titled 3D Modeling and Wearable Technology at SLEM, a shoe-innovation institute in the Netherlands. I found the Recreus Sneaker II on Thingiverse[1], an online digital fabrication sharing website.

The shoe was not as interesting as the material. Ignacio Garcia, chemical engineer, had been making injection-molded model airplanes in TPE-s, styrenic thermoplastic polyethylene . He realized that it could be extruded as a filament to be 3D printed. 3D-printing a soft and squishy material is not nearly as easy as it sounds.

Ignacio described 3D-printing with Fila Flex, as "trying to push a rope." I traveled to Elda, Spain to spend a few days sharing and learning. We shared shoe designs, shoe knowledge, material knowledge and 3D-printing experience. Two days later we had printed the first version of my project Spike Shoe and variable infill insoles in a soft and flexible material (see Figure 1). That material allowed the creation of areas of a shoe that were hard and soft. It allowed the making of shoes that looked dangerous, but were actually soft.

In our discussions I was introduced to Craftware, a 3D-printing software that made it possible to change the infill, the internal structure of a 3D model. As shown in Figure 1, I captured the moment that controlling the internal structure of the print could program the behavior of the shoe.

1 https://www.thingiverse.com/thing:285404

Figure 1. Images of the insoles and shoes designed and printed with the soft 3D-printing filament at Recreus in the Spanish shoemaking district of Elda. The infill structure created variable softness when worn.

The experience is documented in my studies in digital fabrication course at the Fab Academy[2].

Why FilaFlex worked so well was revealed to me later in an interview with Paul van Hal, a chemist at Philips Lighting. Paul explained TPE/s bing close it is chemically to shoe rubber. Rubber shoe soles are made from styrene butadiene rubber (SBR), a very close "cousin." SBR rubber is far too sticky to travel through the head of a 3D printer, saving me hours of heartache and misery as a filament extrusion machine had already been purchased with that in mind.

My experience with shoemaking and shoemakers starts earlier. I spent over 10 years in Florence as a fashion designer working for brands such as Emilio Cavalini, Dan Ward, Calvin Klein, Hugo Boss, and Jean Paul Gaultier Jeans. I worked in fashion studios near Empoli (a region of Florence famous for fashion and shoe design), then in my own studio in Castello (an area of Florence known for co-working and manufacturing).

For years I lived in the Altro-Arno area of Florence, known for craftsmanship of shoes, furniture, and restoration. Every morning I would walk past the workshop of the Bemer Brothers, fabled bespoke shoemakers, where every morning the window had a new shoe that was freshly minted. I had the opportunity to work with the Bemer family on the project Craft the Leather in 2011 and 2012. Inside his workshop, I experienced how he analyzed the wearer before making the shoe.

In my time spent with bespoke shoemakers in Italy, I noted how they analyze the foot. The shoemaker and apprentices take detailed measurements, inkblots of the foot sole, and touch the foot to see where the bones, calluses, and fatty tissue are. From the moment a client walks in the door, shoemaker observes how the person walks, stands, and sits. They analyze the client's style and the current shoes for signs of wear and tear.

At the same time I co-founded two fab labs (digital fabrication laboratories) and attended the digital fabrication course known as Fab Academy[3]. Fab Academy ties hundreds of Fab Labs around the world together to share knowledge. It was here that the idea started that shoes could be made *en masse* to fit individuals. The personalization possibilities of a shoe-production platform could come together with the distributed manufacturing envisioned by Fab Labs. I only needed to change how shoes are made.

2 http://www.fabacademy.org/archives/2015/eu/students/nachtigall.troy_robert/3D.html
3 https://fabacademy.org/

Figure 2. Screenshot of the ArcInTexETN website, featuring an early sample from this research, used to understand the heel of a personalized shoe.

1.1.1 ArcInTexETN

This research was funded through the ArcInTex European Training Network (ETN) Marie Skłodowska-Curie Action to understand future ways of living (see figure 2). It was an explorative program to understand how art, design, and science could come together to understand the intersection of architecture, interaction design, and textiles. The European Union engaged five universities, two companies, and 15 PhD researchers (designers, architects, artists, and scientists from around the world). While my research was based in TU/e, I spent a semester at the Design Research Lab of the Berlin University of the Arts (UDK), and a semester at Philips Lighting (the company has since changed its name to Signify).

The research included two-week engagements, three times per year, at the aforementioned institutions, as well as the Royal College of Art in London, Heriot-Watt University in Edinburgh, Vilnius Academy of Arts, and the Swedish School of Textiles at the University of Borås. Professors, researchers, practitioners, and critics from architecture, art, textiles, business, research, lighting, and other adjacent fields advised this research over three years. This work is documented at the ArcInTex ETN website[4], and can be seen in the work of other fellows who worked in fiber innovation (Beyer 2019), textile ideation (Castan and Tomico 2018), textile choreographies (Castan and Suarez 2017) digital materials (Mackey et al. 2019), phase change materials (Rešetar and Palz 2019), plant–textile co-design (Keune 2017), kinetic morphologies (Piñeyro 2019), atmospheric modelling (Kapur and Pečiulytė 2018), textile ontologies (Lundberg 2018), sonic textiles (Stasiulyte 2017), and electricity-generating textiles (Gowrishankar 2017).

This network of institutions created the ArcInTex ETN with the following goal:

"The ArcInTex European Training Network (ETN) aims to strengthen the foundations of design for more sustainable forms of living by connecting architecture, interaction design and textiles in a training network for early stage researchers. By deepening the connections between textile, architecture and interaction design the network will explore new expressions of living in an age of technological innovations through the design of adaptive and responsive environments connecting the scales of the body, the interior, and the building."[5]

For the ArcInTexETN project, I was selected to investigate the designing of adaptive and responsive clothing at the scale of the body. I selected shoes as my application domain, but my research fellows explored scales from five-nanometer-thick graphene to planetary space elevators. Their perspectives allowed me to see the shoes through many scales, not only shoes as molecular connections, but shoes as tiny buildings.

1.1.2 TU/e Wearable Senses Lab

My research was performed in the Wearable Senses Lab, run by researchers Oscar Tomico and Stephan Wensveen. The Lab has conducted research into wearable technology, embodied ideation, personalization, service design, craft, sustainability and bringing technology close to the body. The Wearable Senses Lab was known for projects like the generative womens dress project This Fits Me by Leonie Tenthof van Noorden[6] in 2014 and the interactive color changing lingerie Unlace by Eef Lubbers[7] in 2012.

There were four PhD students associated with the Wearable Senses Lab. Martijn ten Bhömer was researching the design of ultra-personalized embodied smart textile services (Bhömer 2016). It is from his work that I developed my understanding of personalization. Kristi Kuusk was researching the qualities of crafts and sustainability (Kuusk 2012), and from her work I further developed my understanding of craftsmanship. Kristi and Martijn were working on the Smart Textile Services research project part of CRISP (Creative Industries Scientific Program). The work of Pauline van Dongen (Smelik 2016) and her thesis on the material aesthetics of technology (Dongen 2019) has influenced my work throughout this research. Pauline and I worked together on Project J (presented in Chapter 5) and has inspired my practice for more than a decade. Additionally, Lianne Toussaint was associated with the lab and deeply informed my understanding of clothing from a technological perspective (Toussaint 2018).

This research also contained two secondments. A semester was spent in the Design Research Lab[8] of the Berlin University of the Arts where many workshops around digital craftsmanship were held. A semester was also spent working with Philips Lighting.

1.2 Personal Inspiration, Motivation, and Background

My practice comes from many disciplines and experiences. Here I share a few of those that were fundamental to this thesis.

I spent the summer vacations of 2002 and 2005 excavating a small section of an ancient Roman military base five meters into the ground. It was there that I would find a woman's shoe that would change how I thought about design. The shoe had been buried for nearly 1,800 years,

4 www.arcintexetn.com

5 http://www.arcintexetn.eu/

6 http://leoniesuzanne.com/thisfitsme.html

7 https://www.eeflubbers.com/unlace.html

8 https://www.drlab.org/

but as it was unearthed you could see the clear footprint of the person who wore that shoe two thousand years ago. It was in the shed over the morning cup of tea that I would be exposed to the idea that archaeologists could gather immense amounts of data from the ancient Romans by looking at their shoes (Greene 2016 and 2019).

In 2012 I was in studio Bemer when I witnessed Mario take a wearer's shoe from their foot and analyze it to understand how that shoe was used. The way the bespoke shoemaker gathered data with his hands and eyes was incredible. The shoemaker was feeling the foot, looking at the current shoes and watching the user walk while annotating in a personal system.

In 2013 I started teaching wearable technology for shoes at SLEM based upon previous experience with wearable technology and soft sensors (see Figure 3). At the same time, I was completing Fab Academy, a course by Neil Gershenfeld of MIT and the WAAG society of Amsterdam, I traveled with the director of SLEM to meet with the only person who had successfully printed a soft and flexible sole. For there the next year I would 3D-print day and night to develop the digital fabrication technology to realize a complete shoe.

In 2015, the Spike Shoe, seen in Figure 4, was shown at Salone del Mobile in Milan. SLEM[9] is unfortunately closed now, but for the years it existed it was the bright point of shoe innovation worldwide and attracted some of the world's best shoe designers. I went from having conversations with shoe craftsmen in Florence to discussing the shore values, how hard something feels, of specific materials with the head of research and development of Nike. One thing was clear, making shoes around data would not be easy.

1.2.1 Background and Identity

It is commonly understood that craftsmanship embodies the embodied expertise of the craftsperson. That is to say that the craftsmanship is the sum of all the craftsperson's experiences of making. Craft requires hours of practice. Like many designers, I came into the research with years of practice. I think it is important to unpack that practice because this research is in a way an autoethnography of my own craftsmanship. In this research I am both the designer and researcher: my design is the research. Design and craftsmanship don't spring up overnight,. They require years of practice. In social science, anthropologists have adopted a practice of making subjectivity statements (Preissle 2008, 844). In the following part of this section I describe the ways in which my past experience enabled the performance of this research.

Early Years

It would be easy to start this in New York City where I studied fashion design, but my making and design started far earlier. I was raised in Wyoming and South Dakota, spending much of my time on a ranch far away from anything. The kind of place where people made what they needed, or traded with their neighbors. I was taught to sew at the age of seven due to a lack of interest in animal husbandry and crop rotations. The county fair, a rural american festival, was the highlight of the year.

I found my identity in competitions of fashion design, canned vegetables, and artistic projects. When I was thirteen I made a full wardrobe of my own clothes and set up a bulletin board service (BBS), a very early version of a website, with a friend. My lifeworld was a sewing machine and a computer, and that built the foundation for a life as a designer.

Figure 3. Shoe by Bob Han and electronic textile workbooks made in my class on wearable technology for shoes with Rhode Island School of Design at SLEM.

Wyoming is full of compelling nature, but is also full of abandoned nuclear missile silos. The Intercontinental Ballistic Missile program has been upgraded twice. It left massive underground city-like structures. I would venture into these abandoned spaces spending hours traveling ten stories underground before hitting the water table. We never found the end, what we did find was ARPANET.

ARPANET was created in the 1960s and was an early instance of networked computing (Bing 2011). In practice, this meant a 100-meter-long underground room full of transistor tubes, a few of which could still be seen. A fascination with how such a system was made lead me to study networking in my free time in high school.

Figure 4. Spike Shoe, designed with Nicolene van Enter, designed and printed at SLEM. Model Sharieta Berghuis

Engineer

Growing up in Wyoming left me with a lot of time on my hands, together with my friends from Science Olympiad (an after-school activity for hardcore nerds), we made our own BBS in 1992. I remember when email would take a week to arrive. This steadily lead to programming on a Unix BSD operating system and a fascination with the internet, shared with the friends I ran around in abandoned missile silos with. This also lead me into an enjoyment of mathematics. I have never met another fashion designer who completed took a course on calculus at the university level.

In 1999 moved to New York City to work as a field engineer at the end of the first internet bubble. We managed servers for some big companies which allowed me into the depths of the data centers that run the internet. It was there that I learned the power of data and how it moves.

Fashion Designer

I spent quite a few years as a fashion designer. Four past experiences in fashion design directly inform my research.

My first internship in fashion design was designing backpacks for the largest handbag manufacturer in the USA. I worked in the Empire State Building where I would draw handbags in Adobe Illustrator and email the drawings to a contractor in China. If those drawings were completed by noon the bag would be back on my desk by 5 p.m. the next day. This was impressive, given the flight time. The disconnect between the drawing and the manufactured bag made an impression.

My second internship experience was with the fashion brand I.C.R. vs. Deth Killers of Bushwick. I was taking freshly made clothing and making it look twenty years old, by hand. This meant washing new things with stones and sand, screen-printing poorly, scratching new leather with sandpaper, and shooting jeans with a shotgun. Most of the clothing was sold at a members-only store in Japan where the membership came with a private cell phone just to let you know when things arrived. It seemed to be based on the fictional brand "Gabriel Hounds" from the novel Pattern Recognition (Gibson 2003). People loved it. I learned that personalization can be a lived-in experience. Sometimes people want to put on a new set of clothing and feel like they have always owned it.

The third experience occurred while designing for Hugo Boss at Studio Mauro Taliani, I learned a secret about the fit of the men's clothing. Instead of tailoring the garments, the design team would buy very used military clothing from every army and moment in history possible. The more the garment was used, the better. These garments would be used to make the patterns for new garments (a technique known as "rubbing," frowned upon by many designers, though employed by most). I learned that in this process the garment would feel more lived in when manufactured new, or rather, the imprint of the wearer is left upon the garment and can be passed on.

The final fashion experience was as a knitwear designer for Emilio Cavalini. Beyond the usual role of sketching, designing, and prototyping, I glimpsed the relationship between the data and material. I learned to transform my technical illustrations into instructions for a Santoni knitting machine by generating the machine code. Technicians (who have their own form of craftsmanship) would run my machine code on a large knitting machine turning the code into tubular textiles. What would exit was far from a finished product, this tube was often three times longer than

10 http://etextile-summercamp.org/2016/

11 https://moulinsdepaillard.wordpress.com/les-moulins-de-paillard-2/

the finished product. I would run the textiles to the nearby dye factory, deliver the dyed textiles to the sewing lab floor, and help direct the production. I even learned to take garments through packaging and logistics. I then watched my friends buy and wear the clothing. What I learned in this experience was the to think holistically about the process with a glimpse of how data was transformed into material.

In each of these examples, I see a form of data that is transmitted by email in the handbags, as a narrative in the I.C.R. vs. Deth Killers of Bushwick, as a form of physical fit of the garment at Hugo Boss, and as code-into-knit with Cavallini. In this thesis, I only use data like the Hugo Boss example, but I am fascinated with other forms of wearer data including contextual, psychographic, conversational, technographic, sociographic, and demographic. Additionally, I look at the data-flow that makes the object and how it is transformed in the process (like the handbags).

Wearable Technologist

My personal experience with wearable technology (also known as "wearables") starts by zig-zag-stitching speaker wire to a garment controlled by a "555" timer integrated circuit to blink LEDs. While I did many projects in my undergraduate work at the Fashion Institute of Technology of the State University of New York, they were largely misunderstood. My wearables pieces became a hobby to my fashion-design practice until I founded my own studio and started doing projects that found their ways into exhibitions and eTextiles Summer Camp (Hertenberger et al. 2014). As a designer I worked on kits with the wearables company Plug&Wear. I co-founded the research group W4IT (Wearables for Italy). As a wearable maker, I have taught hundreds of wearable workshops, like the one shown in Figure 5. An example of this can be seen on the website of SparkFun[12].

Maker

The love of making as a child never left. When the maker movement, a loose conglomeration of individuals interested in digital fabrication, congealed in 2007, I quickly reached out to others like me. In 2011 I co-founded the Fab Lab Firenze (Florence) and then Fab Lab Tuscany[13] in Cascina in 2013. This lead to Fab Academy[14], a digital certification course taught by Neil Gershenfeld of MIT. I completed the course in 2015 and have been an external mentor and teacher for the new course on textiles. I have hosted workshops and presented designs. The fundamental ethos of the Maker movement can be summarized as "Make, learn, share."

Craftsperson

Living in Florence from 2002 to 2015 taught me about craftsmanship. Craftsmanship in my chosen discipline of fashion design was always about making things with technology that question the discipline itself. Long before laser cutters and 3D printers were commonplace, I was using these technologies to prototype zipper pulls and button covers using service houses literally halfway around the world; New Zealand, to be specific.

Craftsmanship would lead me to be a part of Craft the Leather[15] 2012 and 2013. Craft The Leather is a yearly week-long event where ten of the best designers from design schools worldwide

12 https://www.sparkfun.com/news/512

13 http://fablabtoscana.it/

14 http://www.fabacademy.org/

15 http://www.pellealvegetale.it/en/activities/craft-the-leather-consortium/

come to Tuscany to learn how to work with vegetable-tanned leather. It was there that I met many of the best craftspeople, tanners, and designers of leather worldwide.

In my practice as a designer, I learned a secret that is contained in the language used by the craftsmen. The Italian craftsmen say "*fatto bene*," which translates as "*made well*," in the place where English uses "*properly*." "*Fatto bene*" carries an understanding of doing something well alongside an appreciation that others do it differently. Each craftsperson is expected to find their own way of making the thing.

Another example is the phrase "*pay attention*." My experience in Italian is that they use the phrase "*fai attenzione*" which translates to "make attention." Attention is something that is created, not paid for. Craftsmanship in Florence is making attention and doing something well, in your own way.

In 2007, for a course on design creativity, I made a personal manifesto of craftsmanship adapted from The Book of Five Rings (Miyamoto 1645) to illustrate the breadth that I draw from.

Craftsmanship is the understanding a person gains from practising a craft while:

- **Understanding how the materials, tools, and techniques work in reality.**
- **Appreciating the art form,**
- **Knowing the principles of the craft,**
- **Showing awareness of the science,**
- **Knowing which rules can be bent and which can be broken,**
- **Being aware of what is not obvious,**
- **Being careful with the details,**
- **Being honest with the material,**
- **Appreciating that others do it differently.**

Shœmaker

Shoemaking found me in fashion design. My experience with the graphical layout program Adobe Illustrator allowed me to not only make the illustrations for fashion hardware but to digitally fabricate the objects themselves. This started with laser cutting and gradually lead to 3D printing. Many of these pieces were details for the shoes created for the collections and I found myself working on many details of the shoe. I would end up opening my own studio around this idea and worked with many companies like Fendi and Calvin Klein using new technologies.

Like many Florentines, I moved into the countryside surrounding Florence, to a small town called Fucecchio. In Fucecchio I found myself surrounded by lifelong shoemakers who had worked for high-end fashion brands. Many of these people retired early, as they had already started working at 14 years old. These shoemakers were a wealth of knowledge as at any moment I could run to the bar, often carrying a shoe with me, and ask an expert how they would do something.

Florence is a capital of craftsmanship and is full of many of the most skilled craftsman and the people who research them. I passed hours with many craftspeople as friends and colleagues in Florence discussing the tools, techniques, skills, knowledge, and know-how of many disciplines. These discussions were not only about craft today, but craft over three thousand years of history stretching back to how the ancient Etruscans made things.

Figure 5. Participants of the Presence and Pressure: Sensing on the Body workshop given at eTextiles Summer Camp 2016[10] at the Paillard Centre d'Art[11].

Educator

Alongside my practice in a design studio in Florence, I lectured at universities about digital fabrication of fashion and other related design subjects. This started with lecturing on fashion technology and digital fashion design at the IUAV University of Venice (Frisa 2015, 6). This soon included lecturing at the University of Rome, Sapienza in digital fashion design and digital fabrication. I also taught at the Institute of European Design (IED) Florence, where my workshop Alta Digitale, Alto Artigianato (Italian for "High Digital, High Artisanship") became the vision statement of the campus, I also had the distinct pleasure of lecturing a course called Eco Design at the ISIA Firenze.

This resulted in traveling to the Netherlands to teach wearable technology and 3D printing for shoe design at SLEM. It was there that the majority of my early work in shoe printing was undertaken as Technical Director. In these explorations, everything we knew about shoes was thrown out. My students and I returned to thinking about footwear as pockets for the feet that provide expression and short-range mobility. Doing so allowed us to start rethinking about what is human locomotion and the expressions of feet in motion leading to a new vision for the future.

1.2.2 My Vision of the Future

Past experience in fashion, shoes, engineering, and making led me to ask the question: What if your shoes made data about how well they fit you, for all your future shoes? What if your shoes told us how your foot shape is changing? What if your shoes told us how they felt when walking? What if your shoes told us how they projected an image of who you are into the social life that is fashion? Shoes would be far different.

Not only could designers predict how long the shoe would last on a material level, but how long the shoe would last on a stylistic level. What if the material itself contained the extra data? What would happen with that shoe if you had to bring it back to retrieve that data? Would we recycle the shoe just because we had a pile of shoes lying there? I suspect that we would. While this was too much for a single PhD thesis, I hope the small steps made here someday result in something much larger that can address the more wicked questions of fashion, style, and sustainability.

The things we make with mass-manufacturing systems still carry the hallmarks of being streamlined in two world wars (Leslie and Noble 2006). But what if things in our everyday life could be the interfaces and data sources, like those in “tangible bits” (Ishii and Ullmer 1997)? The wear and tear seen in the leather and soles of our shoes could be used to reflect on our movement and activities as a form of “slow technology” (Hallnäs and Redström 2001) in the near future. I believe that we can craft those objects and answer the question of how to make a world where our everyday things are programed with materials that integrate into a computational system.

Design holds a future where we designers make individual things for individual people on the large scale thanks to digital fabrication. Computation has brought us to a point that we can calculate the form, behavior, and aesthetic of a shoe for the time and place it will exist. When I made my version of the Dutch clog that changes form when walked on, I was looking to that future, shown in Figure 6.

There is a possibility for fashion to be generated with data about as a social community as an expression inside of that community. Moreover, the system can go beyond shoes. I see a future where the relationship with the fashion designer is based upon that designer understanding wearer personally and designing things for individuals. The relationship is personal and data-driven enabling it economically. It is from this vision of the future that the research began.

1.3 Why Should This Research Happen Now?

A colleague described my work as “folding the barely possible into the now.” This research is happening now because of a combination of emerging digital technologies: new flexible filaments, a democratization of 3D printing (thanks to the expiration of patents), a new interest in 3D printing on the part of the fashion industry (Vanderploeg et al. 2017), and a growing desire from people to have things made near where they live.

The research required physical materials that could be soft or hard depending on their 3D-printed geometry, which could be controlled with data. Many others have been looking at similar interaction at the same time as this research. A few key examples are “Understanding Metamaterial Mechanisms” (Ion et al. 2019) which describes making movements, actions and reactions. “Giving form to computational things: developing a practice of interaction design” (Vallgårda, 2014) provides framework for understanding how things interact by changing over time. “Personal Fabrication” (Baudish and Muller, 2017) details techniques for designing interactive behavior in 3D printed objects, and “The Design Space of 3D Printable Interactivity” (Ballagas et al. 2018) defines a design space of interactions and what technologies can produce them with specific examples.

Figure 6. My version of the Dutch clog that deforms with the foot as the wearer runs. Made at the SLEM, Waalwijk 2015.

As seen in the papers above, this research could have been done from a manufacturing engineering perspective, but that is not my practice. I brought bespoke shoemaking practices and created ways to put the craftsmanship and technology together. What resulted was a system for iterative personalization. In the early 2010s, the idea of thinking through things took hold. Ingold expresses it as an idea of trajectories:

What then is the relation between thinking and making? To this, the theorist and the craftsman would give different answers.

> ***“It is not that the former only thinks and the latter only makes, but that the one makes through thinking and the other thinks through making. The theorist does his thinking in his head, and only then applies the forms of thought to the substance of the material world. The way of the craftsman, by contrast, is to allow knowledge to grow from the crucible of our practical and observational engagements with the beings and things around us (Dormer 1994; Adamson 2007). This is to practise what I would like to call an art of inquiry. (Ingold 2013, 6)***

The idea was elegantly described for design in Prototypes and Prototyping in Design Research

(Wensveen and Matthews 2014) as a *"vehicle for inquiry"* where the *"Research contribution is tied to the process of crafting the artifacts."*

Craftsmanship enables looking at personalization from a different perspective. Craft has been shown to create knowledge in Thinking through Craft (Adamson, 2007). Craftsmanship in my practice meant more than making 3D models of shoes. Craftsmanship required developing the mathematics that described a shoe, making 3D printers, creating feet pressure scanners, hacking filament sensors, creating new web architecture, and wearing shoes. CoDesign asked a question in 2008: "Who are the new hybrid researcher-designers? Can we learn how to identify people with the most promise? What abilities, skills, mindsets and worldviews will they need?" (Sanders and Stappers 2008). This thesis attempts to help answer this question.

This PhD research was also needed because new possibilities for using data as a material were emerging when we started in 2015. Moreover, research into theory on mass personalization existed but very little was available on how practice informs personalization theory. That is to say, examples of someone opening up their own design practice of making something as traditional as shoes with digital fabrication were rare (Piller et al. 2012).

It was also the right moment for 3D-printing, and shoe printing was an emerging technology. 3D-printed shoe projects that predate this research include Nike[16] in 2013, New Balance[17] in 2015, and the Nylon 12 series by United Nude (Burrus, 2014). There was a high heel shoe with springs printed in the foot bed by Freedom of Creation and Pauline van Dongen[18.] There was also work exploring 3D-printed running shoes from barefoot cultures printed by then student Rene Mendel for the thesis of Catherine Willems (Willems 2015). As this research progressed there were many other projects that developed the space at the same time including Adidas Carbon[19] in 2017, Under Armour[20] in 2016, Nike[21] in 2016, Feetz[22] 2015, and United Nude by Francis Bitonti[23] in 2015.

Additionally, previous work at the Wearable Senses Lab of the Eindhoven University of Technology inspired this research and gave it a place inside the lab's research program. My work is not easily identifiable as textile, but if you look closely at 3D printing, it can be seen as hundreds of layers of textile stacked upon each other. The nozzle of the printhead looks very much like those used to make synthetic and artificial yarns and threads. The practice of making clothes out of specific fibers to make cooling and warming effects can be extended into 3D printing, with a trick or two.

16 https://3dprintingindustry.com/news/nike-has-just-done-it-first-3d-printed-football-cleat-5941/
17 https://gearjunkie.com/new-balance-3d-printed-spikes
18 https://www.3dsystems.com/blog/foc/high-heel-shoes-by-pauline-van-dongen
19 https://www.theverge.com/2017/4/7/15216724/adidas-3d-printed-sneaker-futurecraft
20 https://www.engineering.com/3DPrinting/3DPrintingArticles/ArticleID/14595/Under-Armour-Debuts-Futurist-Shoes-with-3D-Printed-Midsoles.aspx
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22 https://www.telegraph.co.uk/finance/newsbysector/retailandconsumer/12041816/Feetz-to-bring-bespoke-3D-printed-shoes-to-market-in-2016.html
23 https://www.designboom.com/design/francis-bitonti-3d-printed-shoes-united-nude-mutatio-3d-systems-09-09-2015/

1.4 What This Thesis Is and Is Not

This thesis uses craft and technology simultaneously to produce a form of trans-disciplinary knowledge. Slow technology offers that the crafting of technology leads to understanding the expressions of that technology. "Craft is in many ways a form of technology envelopment and it is interesting to see new forms of crafts emerging in an answer to challenges as to master new technology as a means of expression" (Hallnäs 2015). Additionally, what is the craftsmanship that a practice of this kind would develop?

This research is about fashion design, in that fashion designers (including myself) dream of a past when everyone wore personalized clothing and accessories handmade by skilled artisans. This idea is a myth: personalization in its crafted forms of tailored, bespoke, and soft weft clothing has always been available to those with financial means dating as far back as the ancient Romans (Greene, 2016). Nevertheless, what if this fabled age of mass personalization could be made real?

This research is a designerly exploration into an ultra-personalized product service system that is informed by craft which operationalizes new technology. The bespoke traditions of shoe personalization are integrated with the technology. Implicit, bespoke traditions of shoemaking are merged with explicit tangible expressions of data. As a result, the possibilities of personalization broaden as craft and emergent digital technology inform each other.

This research addresses emerging digital technologies (Dutton et al. 2006), such as soft 3D printing, body scanning, embedded computation, and laser cutting. It does not address many emerging digital technologies like blockchain, autonomous driving, or neuromorphic hardware. The research deals with artificial intelligence and machine learning only in that the data in parts of what is presented here is made in such a way to make it easy to eventually integrate with those technologies.

This thesis is not about the specific structures created to make the variable density flexibility in shoes. This is available in my works "Sole Maker: Towards Ultra-personalised Shoe Design Using Voronoi Diagrams and 3D Printing" (Feijs et al. 2016), and "Exploring Mechanical Meta-Material Structures through Personalised Shoe Sole Design" (Amorim et al. 2019). Others have also addressed the making of specific structures for shoes in 3D Printing Shoes (Bitonti 2019, 18) and AAD Algorithms-Aided Design (Tedeschi 2014). With my background, motivation, vision, and approach established, I will next discuss the structure of the dissertation.

1.5 The Structure of the Thesis

This dissertation is structured around a cumulative series of papers that form an expansive Research Through Design (RtD) (Krogh et al. 2015) thesis. In each paper, research questions are posed, findings presented, a reflection is often made, and conclusions drawn, which lead to more questions.

The research contributes tools and techniques for personalization with data and a new understanding of the relationship between data and materials. An expanded theoretical model is offered with a series of challenges and learnings. The thesis concludes with recommendations for the future of digital fabrication for ultra-personalization.

Following is a brief summary of each chapter:

Chapter 1 introduces the challenge, explains my background, lays out a structure, and posits a research question. I related a deep part of my background, discussed my personal practice, and related to similar communities. This included experience in fashion, shoes, wearable technology, digital fabrication, material, and coding. The background is made to show how expansive RtD is my modus operandi, and the focus in this research was to put that practice under a microscope. In this way, I was able to analyze my digital-fabrication practice and understand how it could be applied to research and made operational.

Chapter 2 situates the challenge. How I understand craft, technology, and personalization in my practice, the work of others, and the difference between those is established. I outline my argument for a new craftsmanship.

Chapter 3 presents the methodology: expansive RtD and craftsmanship. I then situate the challenge in fashion design, shoe design and digital fabrication. This is followed by a portfolio of the practice of the research. This included the Project J shoe, the ONEDAY shoe toolkit, the Solemaker projects, and the UPPSS game including shoes made by the students. These projects result in research in Chapters 4–8.

Chapter 4, Project J, describes the making of fully bespoke personalized shoe using data of the foot form, the footstep behavior, and the social aesthetic. Working with a well-known Dutch fashion designer, a generative fashion designer, and many others, I digitally fabricated the high-heeled shoes. I detailed the making process of using off-the-shelf software over four iterations to create one pair of shoes for a single event. (Yes, it was very much like the story of Cinderella.) This was a direct application of craftsmanship in shoemaking, generative modeling, 3D scanning, and 3D flexible printing. It was also an exemplar of what I wanted personalization to be. The project concludes with design considerations needed to negotiate a parametric digitally fabricated shoe in Project J. This is presented as the case study “Towards Ultra Personalized 4D Printed Shoe” (Nachtigall et al. 2018a).

Chapter 5 looks to understands personalization done by the wearer as a toolkit with the ONEDAY Project described in the paper “ONEDAY Shoes: A Maker Toolkit to Understand the Role of Co-Manufacturing in Personalization” (Nachtigall et al. 2019c) in. I set out to investigate not only how to make a toolkit for personalized shoes, but also how others personalize shoes in the fabrication process. The ONEDAY toolkit showed that when a person wants to make their own shoes, they engage in the craftsmanship of shoemaking, where personalization often occurs. From the interviews and social media posts of the shoemakers, it was found that personalization is important to the social and psychological needs of the makers. Surprisingly, participants who said they would personalize the least ultimately personalized the most.

Chapter 6 describes a project, Solemaker, that investigates creating and using data to make shoes. I wanted to understand the data that was needed and how it was created, changed and manipulated in software. User data and co-design is used to create a system in Solemaker which is presented in the paper “Encoding Data and Materials for Iterative Personalization” (Nachtigall et al. 2019b). This included in iterative subprojects:

SoleScan – A foot scanner that translated the footstep into pressure and 3D data.

Solemaker.pde – Design software that allows for stakeholder co-design and hardware modifications (or prosthetics, as they came to see them) that use data to generate a shoe-soles with variable density structures.

The Edge – Design software that adjusts the upper (top part of the shoe) to laser cut leather (or similar material) to the size of the generated sole in Solemaker.pde.

Solemaker.io – A web platform and database that allowed Solemaker.pde (rewritten in Java Script as Solemaker.js), Solescan, and the Edge to function as a system.

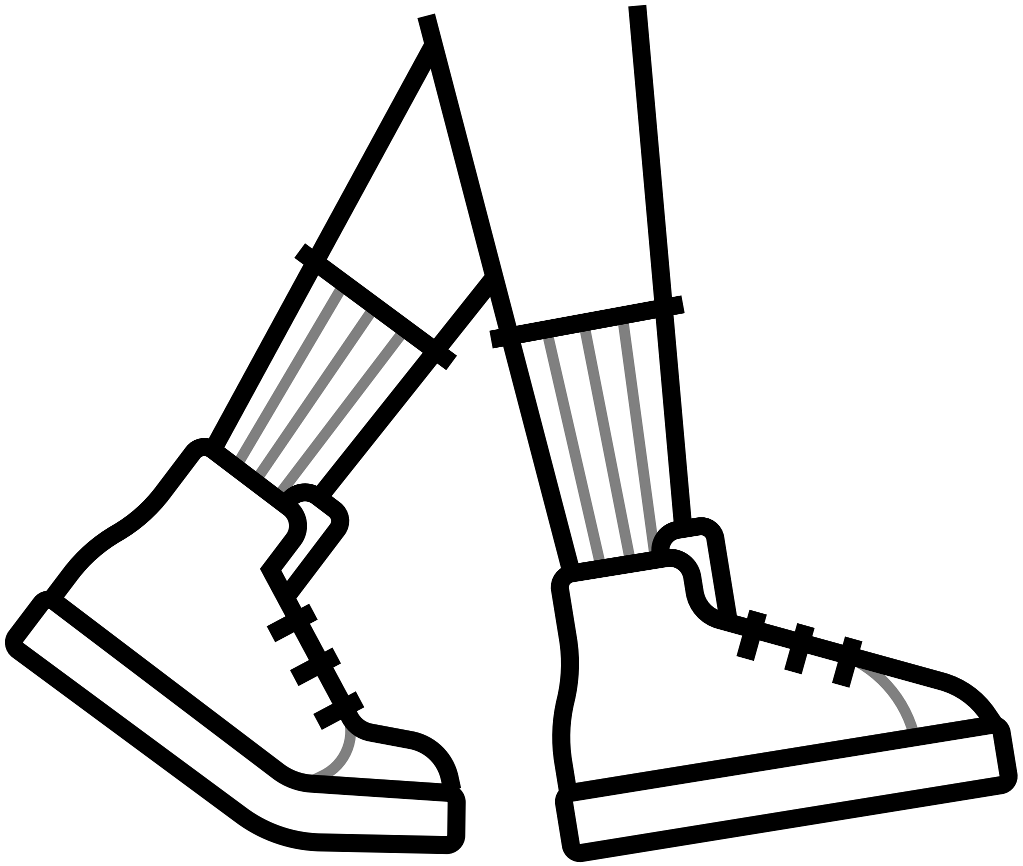
EVA Moccasin – A second generation of the Solemaker shoe that makes data while being worn while creating a more personalized aesthetic.

Chapter 7 is an analysis of the practice described in Chapter 6. This analysis included unpacking the data material relationship of 272 artifacts, sorting (or as I called it, “boxing”) those artifacts into an annotated portfolio, expanding the theoretical model into a theoretical ultra-personalized product service system (UPPSS) model. This resulted in a complex picture of practice but allowed an expansion of the theoretical model, making it operational to designers engaged in the design of an ultra-personalized product service system.

Chapter 8, extends chapter 7 by confronting methodology in the paper “Unpacking Solemaker for a system of UPPSS” (Nachtigall et al. 2019a). In Chapter 8, the knowledge is generalized as digital craftsmanship by creating a design game based upon the previous research. The ONEDAY kit from Chapter 5 is used alongside a design game that synthesizes the design consideration from Chapter 5, the challenges and learnings from Chapter 6, and the UPPSS theoretical model from Chapter 7. I deploy the game and toolkit with students from industrial design who made their own personalized shoes and UPPSS. Data (and data as a material) is difficult for designers. The design games show that once designers are better with data, what comes next is interesting. I found that knowledge transference is aided by an embodied experience and that the UPPSS design game helps abstract that knowledge to scale it up into a Product Service System (PSS) (Tukker 2004). I also found that there are limitations and that transferring stakeholder roles become blurred in the process. The conclusions of Chapters 7 and 8 are then generalized into a design game used in the undergraduate course Digital Craftsmanship, presented in “From Personal to Ultra-Personalized” (Nachtigall et al. 2019d) at the EKSIG ’19 conference.

Chapter 9 presents contributions in the form of an expanded UPPSS model, a detailed exploration of using craft to make a product service system for personalization, a reflection on the data-material relationship and a series of challenges that need to be addressed in the craftsmanship of an UPPSS. This is followed by a discussion on how this might affect shoemaking and possibilities for the future.

All together these chapters are used to answer a research questions that is presented in the next section.



1.6 Research Question

This research poses the question

> ***"How to craft ultra-personalized products, services, and systems through emerging digital technologies?"***

This was operationalized in practice by asking "*Can I use data to make a personalized shoe?*". To answer this I looked to bespoke shoemakers who already do this, implicitly. They look at old shoes, touch feet and watch people walk. From this individual analysis, the bespoke shoemaker creates a shoe to the form, behavior and aesthetics of the person.

Over four years of practice-based research, I went as deep as I could into personalizing shoes with data aided by the help of skilled makers, podiatrists, interaction designers, computer scientists, electronic engineers, design researchers, and many others. During the practice the question grew into: *"Can I use data to make a personalized shoe that generates more data for future shoes?"*

Chapters 4–8 address individual research questions that represent the process of expanding the knowledge that occurred in the research:

Chapter 4: RQ: Can a shoe be personalized using current digital fabrication technologies?
Finding: Yes it can, but it requires negotiating design considerations, great amounts of effort, and several stakeholders.

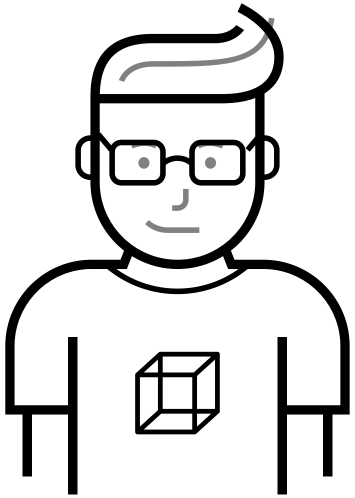
Chapter 5: RQ: Will a wearer personalize their shoe if they make the shoe themselves?
Finding: Yes they will, depending upon the quality of the tools and materials.

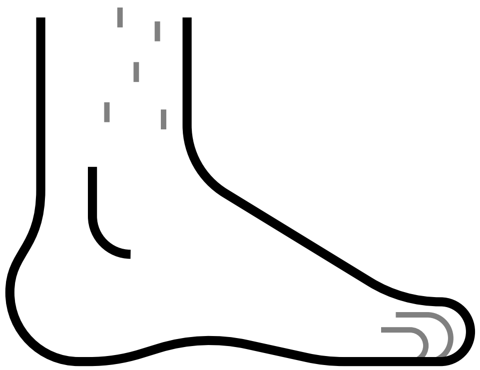
Chapter 6: RQ: Can shoes be ultra-personalized with the wearer's data?
Finding: Yes they can, and the same 3D-printed structures can make data for more shoes.

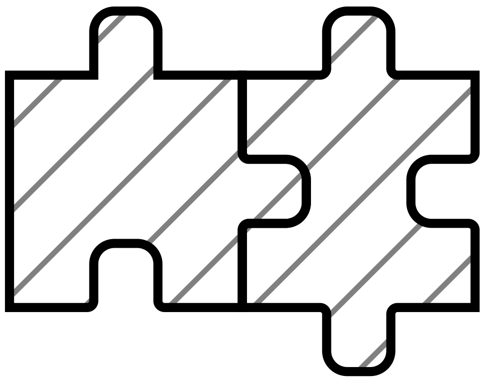
Chapter 7: RQ: Can reflecting on the conceptually rich artifacts improve theory?
Finding: Yes, the artifacts can be annotated in groups and used to inform theory.

Chapter 8: RQ: Can the knowledge be transferred to others using a design game?
Finding: Yes, the knowledge is transferable to varying degrees.

These chapters are followed by conclusions drawn from looking at craft and craftsmanship of using data as if it is a material in chapter 9. In the next chapter, the challenge of craft, technology and personalization are addressed to bring us closer to the projects detailed chapter three.







2 The Challenge of Craftsmanship for Personalization

Mass manufacturing has long embraced the idea of **ubiquity**. Everyday things are made to fit as many people as possible. This can be seen as especially true in computational artifacts. Software allows computers and phones to be used by nearly everyone everywhere. Yet Bill Buxton, senior designer at Microsoft, has proposed a new design idea for computing: ubiety. **“There’s meaning in place. It’s the condition and respect of place or location, local relationship and whereness”** (Buxton 2019).

This idea of *ubiety* or specific "*whereness*" is important to my understanding of personalized shoemaking. Ubiety is close to the far more popular word ubiquity. Both words come from the latin root *ubi-* or "*where*." *Ubiquity* being "*the fact of appearing everywhere or of being very common*" (OED 2017). *Ubiety* being "*the condition of being in a definite place*" (OED 2017). I would add to the OED definition of "*ubiety*" the idea of "being very specific," as the words are antonyms. Ubiquitous computing is the idea that computers provide information and services whenever and wherever "takes into account the natural human environment and allows the computers themselves to vanish into the background" (Weiser 1991, 104). This is the situation most of the world lives in today with smartphones. Bill Buxton wants us to ask, what is ubietous computing?

How does this apply to shoes? In this research I propose that to design shoes to be scalable and personalized as in an ultra-personalized product service system (UPPSS) requires data and craftsmanship. Data is in many respects ubiquitous and drives the scaling of production that potentially allows for personalization for many. However, personalization is very specific and requires a craftsmanship that can make products bespoke or ubietous. In ultra-personalization, I see a duality of craftsmanship and technology (see Figure 7) as ubietous and ubiquity. This leads to many questions: What does it mean to craft a bespoke shoe made of data? What is the craftsmanship of a ubietous shoe made for place (and time) of the user who wears it? How can data be crafted into a product service system that enables personalization at scale?

The answer to these questions revolves around the ideal of material. The embodied craft changes a material. In order for craft to exist, an embodied practice is performed in a specific moment on a specific material. It is ubietous. Craft can not exist without a deep relationship of a material to the embodiment of practice that happens in a specific place and time. Without the material, craft as an embodiment of practice is just the waving of hands in the air. (Which may indeed be a craft in itself but I would prefer to call it dance.)

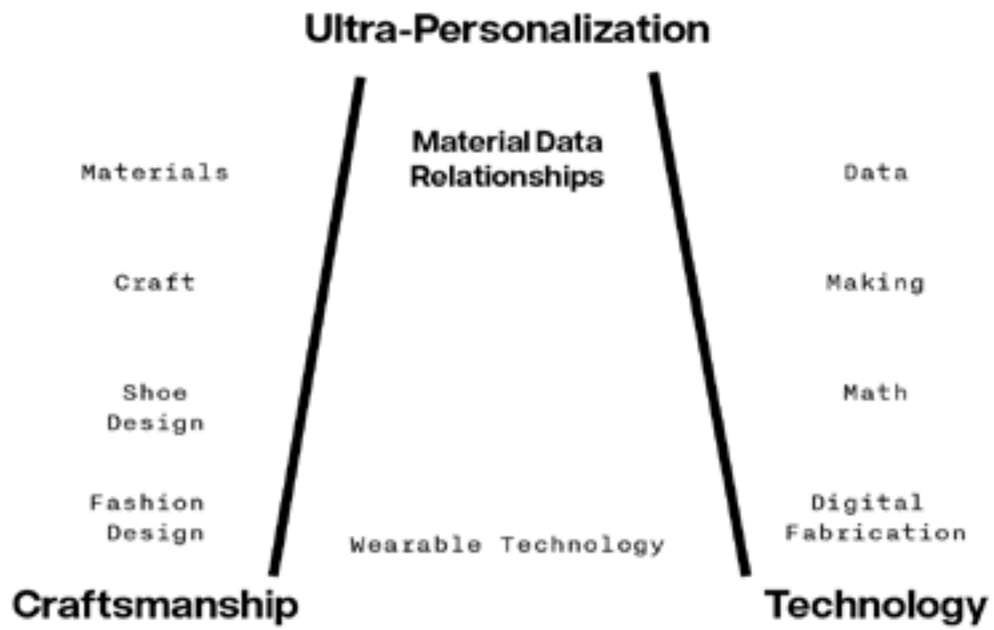


Figure 7. Ultra-personalization realized through the crafting of emergent digital technology.

The material being crafted need not be physical. Digital materials provide a possibility to craft data in the form of a video projection or concert. Embodied craft can make a thing, i.e. a shoe, or it can make data, i.e. a techno song. Emerging digital fabrication technologies like the 3D printer allow the crafting of data and thing simultaneously. Data can be used to craft a generated thing (like a shoe) that is an expression of embodied practice in relationship to a digital and physical material. Data can be crafted by a digital craftsperson to make a specific physical thing as the craftsperson embodies the 3D printer as if it were a hammer. The data is part of a system of algorithms and databases that transform the data into practice at the correct moment. New forms of craftsmanship that embody the embodied practice of the digital craftsperson who crafts the data emerge as the data is embodied into a system that makes ubietous products. I see an embodied understanding of personalization in the form of craftsmanship and a material approach to data.

2.1 Previous Attempts at Mass Personalization

The literature discussing personalization shows that personalization is typically researched by production engineers driving toward ubiquitous systems. This is as seen in "Design for mass personalization" (Tseng et al. 2010), "Industry 4.0: a way from mass customization to mass personalization production" (Wang et al. 2017) or "Product Design for Mass-Individualization" (Koren et al. 2015). While these systems drive towards a ubiquitous system, there is little consistency around the definitions of personalization, customization, individualization or other topics that should be considered ubietous.

This is true in the domain of footwear, where many practitioners and researchers make little distinction between personalization, customization and individualization, as seen in the examples such as "The Next Revolution in Mass Customization: An insight into the sneaker market" (Baena Gracia and Winkelhuis 2016) where the words are used interchangeably. Sometimes personalization is seens as adding a person's name onto a finished object[24] at other times systems go as far as "Open-Architecture Products" (Koren et al. 2013) where the engineering system runs all possible combinations to generate parametric forms.

Tseng et al. (2010) also showed that considering customers as individuals opens new dimensions for product design based upon personal taste, traits, needs and experiences. Personalization is often seen as a question of production and manufacturing. This can be seen in the push towards robotic and data enabled manufacturing commonly referred to as "Industry 4.0" (Wang et al. 2017). Another popular approach is NASA's digital twinning process where virtual models are aligned to physical models which is moving into everyday manufacturing (Tao et al. 2018). Personalization is beginning to be driven by the analysis of data, as used in machine learning (Yang 2018).

However, I argue more than data is needed for personalization. Craft provides an opportunity to make specific data into a form of personalization. It revitalizes the thing and location relationship by considering local materials, local history, and local data along by integrating their specific qualities. In the context of UPPSS as the possible next form of mass personalization, I see the need for bringing data together with craftsmanship.

24 https://www.faz.net/aktuell/wirtschaft/unternehmen/mass-customization-massenware-nach-mass-11900853.html

2.2 If Data is Ubiquitous, Craft is Ubietous

As motivated in Chapter 1, the bespoke shoemaker of Florence makes a shoe for a specific person who spends their life walking the cobblestone streets of Florence in one of the most sophisticated places in the world. Florentine shoemakers such as Ferragamo and Bemer have drawn upon traditions and craftsmanship that goes at least as far back as the ancient Romans. This research takes a deep inspiration from these shoemakers which is addressed in Chapters 4–6.

Mass-Manufacturing is a ubiquitous process. Things are made to roughly fit as many people as possible. This is fine for those in the middle of that fit, but ignores those who are not. In shoes this means sizes. Mass Manufactured shoes production typically starts with an executive who analyzes a spreadsheet of past sales (typically broken down by material in my past experience) and creates a brief of what styles of shoes need designed. The designers create a series of drawings of new shoes that fulfill the brief while being significantly new enough to be seen as desirable while still carrying the form language of the brand and style. Spec sheets are created with details about the design.

From there, developers are given the drawings and spec sheets and begin prototyping the shoes in a medium size. Shoe forms known lasts are used to construct around predetermined shoe styles. Former Nike designer Mike Friton points out that these forms are rarely updated and are often based on forms that are decades old as detailed in the film Shoespriacy[25]. Once a medium size is realized the patterns are graded to realize the other sizes. These are manufactured *en masse* and distributed all over the world. Users buty these shoes and eventually throw them out where they biodegrade, often over thousands of years.

On the other end of shoes are personalized shoes made by an artisan who makes single pairs for single people. This is commonly commonly known as "bespoke" shoemaking. In shoemaking, "bespoke" is defined as the making of something for a specific person after they have requested it to be made (Ball and Rollinson 1935). A bespoke shoemaker often watches a person walk and looks at their personal style. A footprint is taken in water or ink and the circumference of the foot is measured in several key places. The Artisan then constructs the shoe not only to the form of the foot, but to the behavior and aesthetic of the foot by using different kinds of leather, rubber and steel. The shoe supports the specific movement and style of the wearer while being made to their specific feet forms.

The shoes made in this research do not yet reach the level of quality of bespoke that the Florentine bespoke shoemakers. Yet the performed research shows that using data as if it is a material is possible. In this research it was realized that the digitally fabricated material of the shoe could also make more data. That data could be used to make the next pair of shoes even more personalized, much like the relationship of the bespoke shoe maker and their repeat clientele. Data made in the material of the shoe opens new frontiers and definitions of personalization.

2.2.1 But What is Craft and How Does It Make a Bespoke Shoe?

The Oxford English Dictionary defines "craft" as a noun as "an activity involving skill in making things by hand: the craft of cobbling," and as a verb "exercise skill in making (an object), typically by hand: he crafted the chair lovingly" (OED 2018). The mention of cobbling, or repairing shoes, should not be overlooked. Sennet would argue craft is "'a basic human impulse, the desire to

25 https://www.shoespiracy.tv/

do a job well for its own sake" and provide examples of open source software in The Craftsman (2008), while Frayling would argue in On Craftsmanship "design and craft are not just something you do to things, they are something that happens in a cultural and economic context; and where there's a sense of stimulating industry rather than criticising it or even serving it" (Frayling 2012, 91) .

Frayling (2012) also looks at craft also as defined by the artifact being produced. Here are a few from a long list that inform this research.

> ***Crafts can be made with machines and maybe even by them, if numerically-controlled technology goes on improving;***
>
> ***Crafts can be made with synthetic materials, in all colours of the rainbow;***
>
> ***Crafts can be made in limited production; Crafts can be designed by one person and made by another (as they often were, in fact, in the original Arts and Crafts period);***
>
> ***Crafts can provide designed prototypes for industry;***
>
> ***Crafts can be high fashion, and still be well made, although they needn't be;***
>
> ***Crafts can be transient***
>
> ***(Frayling 2012, 119)***

This research also places "craft" separate from "making." This view is argued in "Material Is the Mother of Innovation": "Craft is about making but making is not necessarily craft." (Kuijpers 2019). Kuijpers demonstrates that craft holds a human–material relationship that requires understanding in the craftsperson. Can this relationship be applied to data be used to make ubietous systems of personalization?

There are many interpretations of what craft is by these and other authors. But this research looks at craft through the lens of ubiety discussed above. Craft is the ubiety found in each experience of embodied practice. Craft occurs when something is made and the detail of the experience is unique. Sometimes craft is done by hand, sometimes with a 3D printer (which in this research is like a third hand), sometimes it is in the beating of the buttons of keyboard to make code, sometimes it is walking in a shoe day after day. In craft I see the action of the hand or machine as a practice and specific to what is being crafted.

But What Has to be Crafted?

The obvious answer is "shoes," but that is only half the story. In order to answer the research question of "How to craft ultra-personalized products, services, and systems through emerging digital technologies?", I argue that data needs to be crafted. As a designer I am in the practice of crafting materials to make things. How does a designer treat data as a material in order to craft it? Let's first look at a few others that are using materials and data to craft things.

The decision to use a craft perspective to address the data and technology of personalization was inspired by others working with the idea of "hybrid craft," a term that has come to mean the bringing of craft and technology together. Hybrid craft is found as human 3D printing by following a laser pointer in "Being the Machine" (Devendorf and Ryokai 2015). Other recent HCI work into personalized craft includes the making of knitting (Rosner and Ryokai 2009), bookbinding (Rosner and Taylor 2011), leatherworking (Tsaknaki et al. 2014) and interactive Decoration (Benford et al. 2017). Craft is also found in "Hybrid Reassemblage" (Zoran and Buechley, 2013) which materializes and dematerializes objects on in the movement and behavior of objects with 3D-printed interactivity (Ballagas et al., 2018). What all of these examples share is a digital (data) quality alongside the physical qualities of the material.

Diane Becker describes a "living material" as one that adapts its shape, color and texture through use (Becker 2018). These have also been called active materials by Ingold (Ingold 2009). These materials change with use and forces the designer to think about the lifetime of the material. This research addresses how these kinds of materials may be data. The key is that these active and living materials can also include some form of data.

2.3 Material

Materials are traditionally something physical as defined by the OED materials are "the matter from which a thing is or can be made". (OED 2018). Recently other designers who collaborated in the projects found in Chapter 3 have developed similar ideas that materials may be non-physical things. Pauline van Dongen has come to understand technology as a material that is designed with (Dongen 2019) by means of post-phenomenology (Rosenberger and Verbeek 2015). Loe Feijs, designer and mathematician, sees algorithms as a material for making art and fashion (Feijs, 2018).

Long before this research, Ishi and Ulmer establish that bits are something that can be touched in the Tangible Bits project (Ishii and Ulmer, 1997), "Bits flowing through the wires of a computer network become tangible through motion, sound, and even touch." If the data can be touched can it be crafted? Computational composites takes an even firmer stance on the subject and argues that the computer is just the streaming of electrons through logic gates, data and computation are just language used to describe the behavior (Vallgårda and Redström, 2007). They go on to argue that the result is a not even a metaphor. Data as a material is elaborated upon even further in The Stuff of Bits (Dourish, 2017) "software and digital information—the ultimate "virtual" objects, the poster children for the triumph of bits over atoms—have a material dimension in the interactional processes of their construction and use." In fact, Dourish would not go so far as to call data a material, but would speak of the materialities of information.

The materialities of information are those properties of representations and formats that constrain, enable, limit, and shape the ways in which those representations can be created, transmitted, stored, manipulated, and put to use—properties like their heft, size, fragility, and transparency. (Dourish 2017)

Whether or not data is actually a material is an open question. What needs to be established here is that in this research, data is treated as a material. It is something that can be crafted and that opens up new doors to craftsmanship—even a new form of craftsmanship.

For example, using algorithms as a tool allows the craftsmanship of a system where:

Large amounts of movement data can be transformed into a series of parameters needed to generate a personalized shoe design.

That generated shoe design can be a code that tells a 3D printer where to move deposit material in manufacturing.

A database can remember how the shoe was generated to a specific person. This can be saved so later and compared to how the shoe changed with use.

The shoe can be monitored for performance, comparing the current state versus the profile. Data is generated from the physical shoe allowing for more shoes.

Treating data as a material is not a new thing. Other researchers have been looking at how material changes over time and how that process is recorded as data. Skylar Tibbits used “multi-material prints with the capability to transform over time, or a customised material system that can change from one shape” or “self-assembly programmable materials” (Tibbits, 2014) to make 4D materials. Add the idea of “temporal form” (Vallgårda et al. 2015), where things change over time and making a mechanical computer reemerges, maybe even as shoes.

Data-enabled design (Bogers et al. 2016) treats data over the lifetime of the product as a design material used to make new things. Meta-material structures (Ion, et al., 2016), use a programing interface to craft 3D-printed flexible 2.5D structures to create mechanical door handles and shoe tread are 3D printed with mechanical properties such as door handles and shoe treads. Ion and team has also recently come to understand the design of such structures in “Understanding Metamaterials” (Ion et al., 2018) that allows the user to describe the behavior over time.

Programmers often see code and its algorithms as things as well. It is through the concept of “abstraction” presented in Physical Computing (O'Sullivan and Igoe 2004, xxiii), that code and algorithms become a driver for interaction. “Turtles for Tessellation” (Feijs and Hu, 2013) explains how data can be used to drive digital fabrication. The algorithms needed to describe objects like shoes hold their own challenges. Order in Space (Critchlow, 1969) is a deep lesson on the mathematical art form of voxelization (3D pixels) and deep explanation of form. The symmetry of nature algorithmically described in Symmetry Discovered (Rosen, 1975), along with the limiting groups described in Geometric Symmetry (Lockwood and Macmillan, 1978), and the understanding of faces in Curiosities of the Cube (Rannucci and Rollins, 1977) provide a basis of mathematical theory to describe shoes.

Emerging digital technologies including digital fabrication, algorithms, computation (Dutton et al., 2006) are the tools to make with data. It was imagined 20 years ago that these would lead to personalization “By giving computers the means to manipulate atoms as easily as they manipulate bits, we can bring the same kind of personalization to the rest of our lives” (Gershenfeld, 1999, 64). Twenty years later, this vision remains only partially fulfilled. I argue this is because the craftsmanship of data as a material is not yet fully understood.

2.3.1 A New Craftsmanship of “Data as a Material”?

In the previous section, “craft” is defined as the ubiety found in each experience of embodied

practice in the previous section. But what is craftsmanship? Sennet interprets craftsmanship as skill that is developed and acquired when practicing a craft (Sennet, 2008), which agrees heavily with the Oxford English Dictionary (OED) “Skill in a particular craft” (OED, 2018). Yet, it is commonly understood in research that craftsmanship embodies the embodied expertise of the craftsperson. Expertise in this case is recognizing the ubiety in the unique experience of craft. This may be a tacit or implicit experience in craft. In this research, “craftsmanship” is the aggregate of ubietous experiences embodied as a capacity of the craftsperson to address a future specific instance with ubiety.

Ingold supports this as well when he argues that craftsmanship is a “rhythmic process of making, like a metronome, but with improvisation” (Ingold, 2009), or “Craftsmanship is a repeated, attentive practice that looks at different ways of doing even simple actions” (Ingold, 2009). But what of those experiences did not only reside in the craftsperson? If data is a material (or a composite of it), could a system be created to remember specific experiences in the form of data? What would that mean to personalization? Polanyi described the tacit nature of experience as “we can know more than we can tell” (Polanyi 1966, 4). Can a system know more than it can tell?

Additionally, craftsmanship often happens in small communities. Craftspersons often group together, in physical locations like the lab, and now also digital one where a culture is created. These communities form conversations around tools and techniques and often a consensus around technology. There is often also a consensus around which technology that is not used. Science fiction writer Neal Stephenson introduces the word “*amishtics*” in the novel Seveneves to describe deliberately not using technology. Craftspeople congregate and differentiate around technologies.

In “Craft quality of design” (Badrzell et al. 2012), interviews with craftspeople look not only at the tools and materials, but also at the background, community of makers and the relationship of that community to society at large. In this thesis, it is important how craftsmanship is defined by the place, time and relationships that the craftsperson has to that place and time.

In practice, craftspeople make their own tools as well. Ingold argues that the technology of the tools in craft practice change the understanding of the craft (Ingold 2013, 122–123). If data is a material to be crafted, then new tools and techniques are needed to make the shoes. If craftsmanship is remembering the experience as expertise then services and systems are needed.

2.4 Ultra-Personalized Product and Services

Finding a way to describe “bespoke” in terms of data instead of shoes was a difficult process. I needed a way to describe the specific tools, techniques, services and systems needed to craft shoes with data. Mass customization, mass personalization and mass individualization all reflect an engineering approach to making products. Early in the research it was already clear that data was important to a crafted system. In “Going Digital”, Stolwijk and Punter (2018) define an UPPS as having two categories “(1) Products in which personal data is obtained before use and (2) products in which the data is obtained during use.” Obtaining data from a product in use enables the line seen in Figure 8 to connect the output of a UPPS into an input for future products. This enables a shift in thinking from product design (Clark et al. 2014), to an ultra-personalized service (Bhömer et al. 2015), and then a Product Service System (PSS) (Tukker, 2004).

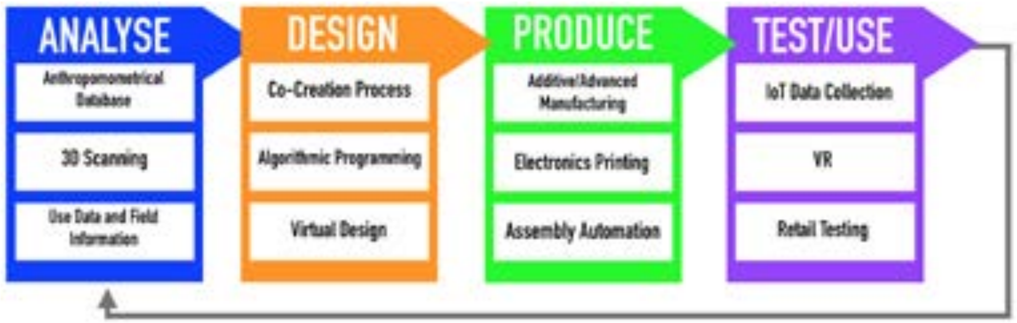


Figure 8. UPPS model extracted from the presentation by Bart Ahsmann from the smart industries project and UPPS Field Labs.

In his research, ten Bhömer uses describes ultra-personalization as "using and making data from an object or service" (Bhömer, 2016), based upon "end-user based design of innovative smart clothing" (McCann, 2009). The Creative Industries Fund NL[26] established several field labs for ultra-personalized products and services[27] (UPPS) in 2016 (Ahsmann, 2016). These field labs were dedicated to the smart industry initiative where digital manufacturing is combined with network-centric technologies concentrating on fashion and health personalization. The focus was on emerging digital technologies such as mobile, 3D scanning, simulation, printed electronics, 3D printing, and laser cutting.

This research builds upon the UPPS theoretical model (Ahsmann, 2016) to compare the practice of this thesis to theory. "Borrowed theories (or concepts) are often used both to inspire new designs and to articulate existing ones" (Gaver, 2012). As shown in Chapter 7, the theoretical model didn't fully explain the practice.

The UPPS Model allowed a way to consider the holistic complexity needed to realize a system that fully engaged data as a material and established a relationship of the data and material that lead to the conclusions of this thesis. Additionally, it provides the framework to show that craftsmanship is a necessary part of making the next generation of the system, UPPSS, work.

For craftsmanship, the research draws upon fashion design, shoe design, crafting and materials. For emerging digital technology, I draw upon digital fabrication, mathematics, making and data science. This emerging digital technology specifically used are as 3D printing, 3D scanning, capacitive sensing, the maker movement, and the use of algorithms.

2.5 Digital Fabrication to Craft an UPPSS

Daniel Southwick, in his PhD thesis Expertise in the Age of Digital Fabrication, traces the foundations of digital fabrication to its origins in numeric control of the 1950s and the craftsmanship it was born out of (Southwick, 2019). Craftsmanship is shown to be at the foundation of digital fabrication. This craftsmanship has been taken up by the maker community who are creating new expressions of digital craftsmanship.

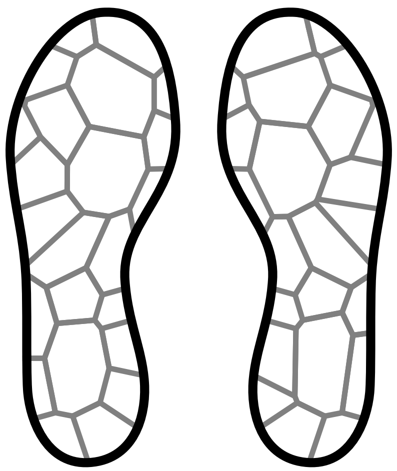
Many see digital fabrication as only the making of plastic toys with the 3D printer. Yet, many modify their 3D printers to enable them to print with new materials, print larger volumes or add CNC technologies (Mota, 2011). There is an increased interest in the texture, internal structures and overall behavior of 3D-printed objects, as described in "Personal Fabrication" (Baudisch and Muller, 2017). Many of the researchers and makers extend their interests beyond fabrication, and become interested in the machines, the materials (the filaments), the software and business models.

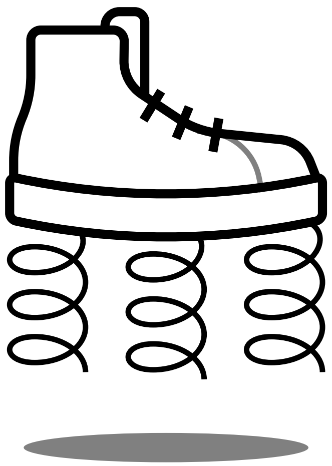
This research was conducted with tools that are available in any one of the 1,200 digital fabrication spaces worldwide noted in FabLab – a new space for commons-based peer production (Liotard, 2017) using the tools found in a Fab Lab[28]. These tools in 2014 included 3D printers, laser cutters, CNC mills, vinyl cutters and electronic equipment. Neil Gershenfeld, head instructor of Fab Academy, defines the goals of the Fab Lab as sustainable production, sustainable consumption, skills, education, creativity and the democratization of manufacturing (Gershenfeld, 2012).

Making and modifying of the digital fabrication tools was a must. This comes from a tradition of makers, a loosely organized group of individuals gathered around digital fabrication technologies (Tanenbaum, 2013) gravitating around Maker Faires (Meissner, 2019). The values of first-hand making and distributed learning of the Fab Academy are expressed through courses and a common set of tools found at Fab Labs worldwide, such as 3D printers, laser cutters, CNC mills, and vinyl cutters. During this research, the maker movement has grown to include biological and textile tools (Papavlasopoulou et al. 2017). This research adopts the Gershenfeld goals as it embraces the social, technological and economic aspects of the making.

When crafting with digital fabrication technology the technology takes on new interpretations. The 3D printer is no more than a hot glue gun in the hands of a dexterous and prodigiously perfectionist robot that draws and draws layer upon layer. This is a hand that cannot improvise, and the robot is only capable of the sparsest conversation skills, responding to commands to slow down, heat up and spit out more glue. It knows nothing of surprise, error correction, or satisfaction of a job well done.

26 https://www.clicknl.nl/
27 https://www.upps.nl/
28 https://www.bit.ly/fabinventory





3 Methodology, Context, and Portfolio

Design is making things, services, and systems, but the important thing is design is making. My approach to making is best summarized in a report to the European Union about the research “Troy has a very strong passion for experimental explorations through digital modelling in design. This is evident in his highly practice based experimental research approach and his ceaseless stamina for where continuous experiments are needed.”(P4, D4.4, D21, 2018). In this chapter the method, context and most importantly a **portfolio** of the things that were made in this research are elaborated.

3.1 Methodology

Practice-based research has been shown to create knowledge when the practitioner has sufficient background in the subject and documents the process in order to make the context explicit or discussable (Nimkulrat, 2007). Moreover, artifacts in RtD contain the knowledge and are contextually rich (Gaver and Bowers, 2012). In this dissertation the practice and resulting artifacts are presented in a cumulative collection of papers of five papers published at key conferences and a portfolio of projects that generated artifacts. Placed together they show how the understanding of craft for personalization changed over time. The cumulative method has been shown to be effective in the thesis Enabling through Design: Explorations of Aesthetic Interaction in Therapy and Hare (Marti, 2012).

The theoretical framing of this thesis is rooted in research through design (Frayling, 1993). I use a practice-based approach to look at the combination of craftsmanship and technology in the context of an ultra-personalized product service system. This research took the time (and space) to make and reflect upon the crafted design work. Allowing time and space to let knowledge to develop and seeing without immediately judging has been shown to be advantageous in How to do Nothing (Odell, 2019).

Similar successful PhD thesis have used RtD to address similar questions in “Crafting Sustainable Smart Textile Services” (Kuusk, 2016) and “Designing Embodied Smart Textile Services: The Role of Prototypes for Project, Community and Stakeholders” (Bhömer, 2016). More specifically this thesis uses expansive RtD which “articulates the identification of an area as-yet uncovered with the ambition to reveal its qualities” (Krogh, et al., 2015). Examples of expansive RtD being applied in a thesis can be found in Rights Through Making: Skills for Pervasive Ethics (Trotto, 2011) and Fictional Space In Participatory Design Of Engaging Interactive Environments (Dindler, 2010).

There are limitations to this methodology. It is mostly derived from firsthand experience in a specific application domain. Yet the understanding created here is supported by others such as “Understanding Craft-Based Inquiry in HCI” (Frankjaer and Dalsgaard, 2018) and “Materializing Fashion” (Braithwaite, 2014), which both take ethnographic approaches.

Additionally, the UPPSS game shows how the knowledge was transferable to industrial design students. There is a limit to how generalizable the knowledge may be. The research was not unlimited, as pointed out in Chapter 7. A multinational shoe company with a larger budget may have different results. I would like to test that theory. Yet, I used the considerable resources of this research to the best of my abilities.

Together, these papers show how a system of a product–service was crafted. The papers track the process of making the UPPSS and the craftsmanship involved. In each paper, the understanding of the research shifts slightly as knowledge was created over time in the process. The limitation being that understanding of that knowledge to the moment in time it was published and this may differ slightly with the final description of the understanding created.

Each paper uses its own specific methodology, detailed in the paper. But those methodologies are all informed by a previous research. Working by myself, and with others, and watching others use my work comes from “Designing for, with or within: 1st, 2nd and 3rd person points of view on designing for systems" (Tomico et al., 2012). The projects use prototypes as a "vehicle for inquiry" (Wensveen and Matthews, 2014), and are inspired by Ingold's concept of "the art of inquiry" (Ingold, 2013). The research aim of many of the papers was to develop research products (Odom et al., 2016) situated in the wearer's everyday life as slow technology (Hallnäs and Redström 2001, Odom et al. 2012, Hallnäs 2015).

The resulting research products, samples, errors, and alternatives come together as conceptually rich artifacts (Gaver, 2012) that are analyzed in an annotated portfolio (Gaver and Bowers, 2012) and address theory from an informed perspective (Höök and Löwgren, 2012). Together, the papers show how to design for UPPSS.

The practiced-based research illustrated in Figure 9, is based upon the expansive research through design illustration in "Ways of Drifting" (Krogh, et al., 2015). It is based upon the explanation of drifting; "drifting or pursuing alternative opportunities in the vicinity of one's work is an embedded way of arriving at relevant and high quality work." (Krogh, et al., 2015). This map was drawn at the end of the research to describe the knowledge created from the past four years. The map highlights the projects and papers important in the practice of this research. At the same time it illustrates how a designer often does lots of work and looks for the meaning inside of it. Left out of this thesis was a speculative film Ahti about a dystopian design future roaming the solar system walking on stars made in Berlin[29]. There were 3D-printed luminaires with Philips Lighting[30]. There was a patent for 3D printing on dye sublimation paper (in press). There are publications about pockets (Nachtigall and Andersen, 2018), wearables research (Nachtigall et al. 2018), and mechanical metamaterial structures (Jose et al. 2019).

The complete richness of this practice is impossible to capture in theory, but it can inform theory (Binder and Redström, 2006). While the papers from the work serve to share the knowledge generated from the work. As a craftsperson I believe that the knowledge is embedded in the artifacts themselves. The portfolio below shows the results of the research as practice in which much of the knowledge is embedded. But before the portfolio, the context of the research is discussed to situate the research in the practices of fashion design, shoe design and wearable technology.

3.2 Framing the Context of the Design Practice

In this section the practices of fashion design, shoe design and wearable technology are presented as the context of practice for this design research.

3.2.1 Fashion Design

This research considers fashion design to be the practice of designing clothing that is literally embodied (Tomico and Wilde, 2016). It is important to understand the process of fashion design in order to understand an UPPSS for shoes.

Fashion happens in an ongoing seasonal process where design is an ongoing transformational process rather than a conceptual process. Ingold would call this the "interstitiality of design" (Ingold, 2009). It is important to note how fashion designers think seasonally. They return over and over again to similar forms yet find new ways to do it each season, often creating 70 different outfits every collection. This is very different from the technology culture that makes two kinds of

29 http://urn.kb.se/resolve?urn=urn:nbn:se:hb:diva-13880
30 https://www.tailoredlightingcreations.com/

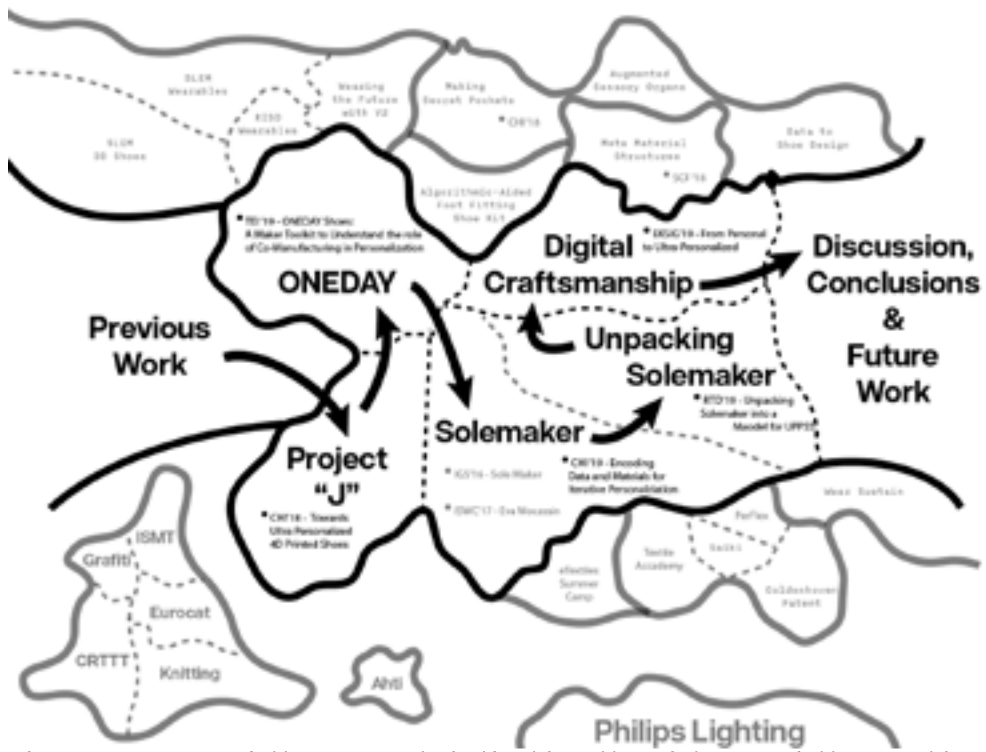


Figure 9. A map of the research indicating the richness of the practice while highlighting the path taken in this dissertation.

phones in four colors once a year. Fashion design is not a culture of the project, but a culture of seasonal collection. Yet in this, fashion remains a material practice "The steps in the designers' creative process show the emergence of fashion through the transformation of ideas and materials." (Braithwaite 2014).

Fashion is complex. It is both physical and meta-physical at the same time (Thornquist 2014). Garments, accessories, trends, style come together and fall apart organically. Working as a fashion designer is a practice of living one to five years in the future from when the objects of fashion are designed. The process of making a single garment is complex. Fibers are spun into yarns (or threads) that are often plyed together. These yarns and threads are woven, knitted or layered into textile. The textiles are cut and sewn into garments and zippers, buttons, and other hardware is added. Along the way things are washed, dyed, and coated several times. Additionally, there are hundreds of exceptions: leather, full-fashioned sweaters and zero-waste garments to name a few. Yet this is only a single garment in a collection typically consisting of around 140 garments.

Fashion design, like industrial design, remembers an age of craft production that was mostly replaced by mass manufacturing in the 1880s. Fashion design held on to the idea of personalization in the tailoring of Savile Row, haute couture of Paris, and the mystique of Italian-made clothing. Fashion designers are taught to not emulate these forms of personalization early in their education, and are gently walked into the stark realities of mass manufacturing. Fashion remains dominated by a mass-manufacturing system, but is also the heart of personalization.

Others understand fashion in many ways, as described by "Materializing Fashion" (Braithwaite, 2014). Fashion can be seasonal trends and changes (Loschek, 2009). Fashion is an industrial system and social phenomenon (Bourdieu, 1994). It is a systemic cycle of appropriation of dress (Kawamura, 2004). Fashion as a system creates new designs for seasons with designers, retail buyers and fashion editors informing consumers (Chapman, 2011). Fashion is moving to a bi-weekly drop cycle and Instagram is disrupting the editorial process of fashion in monumental ways by accelerating trends.

In this disruption it is often not "newness" that fashion designers adopt, instead designers often adapt and mash up past designs (Svendsen, 2006). Even though the look and trend of fashion rapidly changes actual innovations in fashion design move slowly. An example of this is the idea of "fit" in movement. Even though fashion is presented in movement on the runway it is often designed on headless stable forms called mannequins. Yet the idea of designing for the body in movement has been researched (Linqvist and Thornquist, 2015) and expanded into architecture as seen in "'Layering up' soft materiality" (Castan and Tomico, 2018).

A definition of "fashion design" requires recognizing the need for social adaptation, and realizing objects that facilitate those interactions requires a more holistic view. The social function of fashion where people associate with (or differentiate themselves from) others around them (Simmel, 1957). Simmel sees fashion as a complex domain based upon social cohesion and segmentation.

Fashion is the imitation of a given example and satisfies the demand for social adaptation; it leads the individual upon the road which we all travel, it furnishes a general condition, which resolves the conduct of every individual into a mere example. At the same time, it satisfies to no less a degree the need of differentiation, the tendency towards similarity, the desire for change and contrast, on the one hand by a constant change of contents, which gives to the fashion of today an individual stamp as opposed to yesterday and of tomorrow …" (Simmel, 1957) As such, fashion can be seen as a complex system with the qualities of complexity: emergence, transition and resilience (Feijs and Toeters, 2018).

3.2.2 Footwear and Shoe Design

Shoe design is an ideal place to study the craftsmanship of emerging digital technology. Gershenfeld holds that "shoes are in fact an ideal platform for computing. You almost always have your shoes with you; you don't need to remember to carry them along when you leave the house in the morning.." (Gershenfeld, 1999, 51). What if craftsmanship holds the key to programming materials as part of computational system? Would that be a "platform for computing"? Approaching data as a material by bringing electronics to the shoe was part of the approach. But I brought an understanding of craftsmanship that comes from designing for fashion brands in Florence Italy as well.

Footwear is the application domain of this research. Shoes are a good application domain for several reasons.

1. **Footwear easily communicates the need for personalization, coming from a long history of personalization.**

2. **The terminology of footwear is easier to understand for readers outside of the domain than that of, say, knitwear.**

3. **Shoes are an almost ubiquitous human experience in the need for short range mobility.**

In everyday footwear, there is a high importance placed on fit (Curwen and Park, 2014) that is easy to communicate. The form of the shoe must fit the foot. The type of the materials must fit the activity performed in the shoes. The aesthetics of the shoe must fit the social situation. These types of fit are experienced by all. In this research data in the form of parameters, is used to generate shoes algorithmically. This parametric approach to create interactive behavior is supported by other recent shoe research including "The Parameters Required to Support a Woman in Motion" (ten Bhömer 2019).

Today's shoes generally consist of a sole (usually everything under the foot), and an upper (usually everything over the top and sides of the foot). This division is commonly understood to be driven by different material needs. There are a multitude of techniques for creating and attaching soles and uppers which are generally documented in the six-volume series Boots and shoes: Their Making, Manufacture, and Selling (Ball and Rollinson, 1935), as well as the more than two million footwear patents filed since 1845.

For the sake of definition, I consider shoes to be clothing based upon the technological definition of clothing established by Toussaint, "As a direct appendage to the skin, clothing replaces our organic 'protective buffer' with one that envelopes, yet is external from, the body" (Toussaint, 2018, 80). Braithwaite (2014) holds a similar understanding in "Materializing Fashion". This definition allows a perspective on shoes that matches the ideas of "fit" as understood within fashion designs, which drives this research.

In practice there have been previous startup ventures into digitally fabricated shoe manufacturing alongside this research. The company Feetz[31] had just launched a 3D-printed shoe service and the company Sols[32] was launching 3D-printed insoles. Shoe design is not a large field, and I had the pleasure to meet high-ranking members of both companies. Both companies were working in the idea of a shoe made to fit the persons form and movement, known as the "perfect fit" context (Burrus, 2014). Both companies received tens of millions of dollars in investment and both companies failed after spending tens of millions of dollars in investment. I would argue that this likely occurred due to a concentration on technology and a neglect of craftsmanship.

However, I am interested in designing for the lifetime of the shoe, not only up to the manufacture. Moreover, I don't look exclusively at the mass manufacturing of shoes, but at many kinds of shoemaking, from bespoke to distributed manufacturing. I explore what it could mean for shoes to make data to inform many more shoes. This is much like the software cycle of apps as described in Chapter 6.

Considerations of personalization in shoe design are often occupied by the incredible variety of possible foot shapes, but there are also questions about the shoe-wearer's behavior, such as: How is the foot moving? How is the weight being distributed? When and where do the feet strike? What is the effect of the shoe on the foot? Who is wearing the shoes? Where is the wearer going? What is the wearer doing? The human foot is an area complex with data as the foot contains more bones and ligaments than anywhere else on the body (Cheung and Zhang, 2006). Yet, even

31 https://3dprintingindustry.com/news/feetz-3d-shoes-3d-printed-custom-shoes-becoming-norml-44934/
32 https://3dprintingindustry.com/news/sols-custom-3d-printed-insoles-introduced-43k-physical-therapists-41639/

with this understanding the vast majority of shoes are still sized based on one single parameter: length.

This research is deeply inspired by shoe designer Salvatore Ferragamo, who made bespoke shoes in Hollywood in the 1920s. While Salvatore made beautiful shoes, he was frustrated that his shoes hurt the wearer's feet. While shoemaking in California, he took courses in anatomy at the University of Southern California. Known for extreme material choices like steel, jute, and cork, Ferragamo built a shoe repair shop into a business that made hundreds of customized shoes per day based upon more than 350 patents (Belfanti and Merlo, 2016). It was innovation in fit and materials alongside an incredible aesthetic that enabled Ferragamo to build a shoe empire.

3.2.3 Wearable Technology as the Starting Point.

This research draws from wearable technology and the sub genres such as eTextiles (Perner-Wilson et al. 2011, Buechley and Perner-Wilson 2012), smart textiles (Cherenack and Van Pieterson 2012), techno fashion (Quinn, 2010) and a dialogue with that community, for example, in the 2013 "eTextile Swatchbook Exchange" (Hertenberger et al. 2014).

Craft is important to "wearable technology" and is argued to be "the practice of electronics building in the context of other crafts" (Buechley and Perner-Wilson, 2012). It is also understood that "the wearable computing vision implies that people in the future will wear personal computers in the same sense that we wear clothing, in order to facilitate context dependent interactions with the world and the people in it" (Berzowska, 2005). Toussaint describes wearable technology as "garments and accessories (as distinct from tools, instruments, or devices) that combine the functionalities of technology with the aesthetic, expressive, critical and/or communicative role of fashion" (Toussaint, 2018).

Shoes and wearable technology have always gone together. The first wearable computer was a shoe (Mann, 1997). Shoes have been of great interest to the HCI and tangible-interface community. The cover of the seminal book When Things Start to Think (Gershenfeld, 1999) is a shoe. The book provides a common assumption that computation requires a processor, and that the processor has to live inside the thing (with the sensors, actuators and batteries). Gershenfeld discussed the nature of computing in terms of limitations of costs. Yet this research asks, what if the computation lies in the material itself?

Wearables have been around for more than 50 years (Mann, 1997), but the current understanding of crafting wearables begins around 1997 with the inception of the International Symposium on Wearable Computers (ISWC) which included smart fabric and wearable computing (Post and Orth, 1997). Over the past twenty years the role of textiles has grown into HCI as seen in such as "Wearable Computers, Reactive Fashion, and Soft Computation" (Berzowska, 2005b), "Designing Dynamic Textile Patterns" (Worbin, 2010) and "Crafting Technology" (Buechley and Perner-Wilson, 2012).

Is it possible for computation to be part of a shoe that has no processor, wires or electronics? "Wearable technology" was originally thought of as wearing computers on the body, but wearable technology becomes about computation in this work. Computation is often thought of as complex agent networks of finance that collapse a global housing market, but computation can be as simple as the abrasion of the shoe sole against the sidewalk. Computer scientists define computation differently by applying a Turing test, but it is useful for design to think of computation differently when crafting.

What happens if the electronic processor is removed from the shoe? This changes the electronic idea of wearable technology as electronics in shoes into a systemic process of computation. The idea is close to the idea of Gershenfeld, but without the electronics:

> ***"… shoes are in fact an ideal platform for computing. You almost always have your shoes with you; you don't need to remember to carry them along when you leave the house in the morning. There's plenty of space available in a shoe for circuitry—no companies are yet fighting over access to your shoes, but they will. When you walk, watts of power pass through your feet and get dissipated in abrading your shoes and impacting the ground; it's possible to put materials in a shoe that produce a voltage when they are flexed, which can be used as a power source. With realistic generation efficiencies of a few percent there's plenty of energy available for a low-power computer. Instead of lugging around a laptop's power supply and adapters, and feeding it batteries, you just need to go for a walk every now and then, and feed yourself." (Gershenfeld 1999, 52).***

In the next section I describe a series of projects that lead to cycles of personalization using data.

3.3 Portfolio

The following portfolio has a descriptive goal to describe what happens, and serves as a context. In each paper this is transformed into tools, techniques, theories, and findings. This serves as a description of what was done. The results of this research are expressed best in the artifacts produced. These are artifacts with dynamic properties. Holding and wearing is part of understanding the artifact. This is difficult to do in print but I include photographs and descriptions of the projects and artifacts here. I encourage readers of this thesis to visit TU/e or myself to touch and embody these artifacts. The plural "we" is used because the projects were done in with additional stakeholders as noted in each project.

Figure 14a. Printing a sole on our handmade 3D printer, a Prusa i3 made with Laura Genovesi and Salvatore Balestrino of opensourcehardwear.it
b. (page 45) Bart Pruijmboom wearing Solemaker shoes as SLEM in Waalwijk. Photo by Bart van Overbeeke

3.3.1 Project J

Project J was a project to create a bespoke shoe for a public figure to be worn at the public event known for its fashion design. Based upon past 3D printing of sneakers project, it was the first high-heeled shoe that I 3D printed. This was based upon the wearer telling us that she only wore high heels. In the project 3D scanning, 3D printing, generative geometry, 3D animation and topological analysis were used, see fig. 9.

Project J was a collaborative project with Pauline van Dongen, Leonie Tenthoff van Noorden, Lilian Admiraal, Joe Hammond, and Jet Bussemaker. The project is well documented in the video Project J[33] and on the blog Dezeen[34].

In the project, we 3D scanned the client's foot in the air and while standing (loaded and unloaded). We observed the client walking in shoes and barefoot. Next, the software detailed in chapter 4 was used to design and generate a shoe based upon the data, as shown in Figure 10. Over four iterative prototypes, the design considerations of the shoe were negotiated to arrive at a high heel that was comfortable, supportive, and attractive.

Classic shoemaking requires a last (an internal model of the foot, much like a dress form). The pattern and the sole are developed from this last. Even bespoke shoemakers like Salvatore Ferragamo used specific lasts for their clients. As the shoe was constructed digitally there was no last, moreover, shoes are typically made with a number of materials. As we could control the density of the flexible material we were working with, we created the entire shoe out of a single material, as shown in Figure 11. This was driven by sustainability.

Project J served as the exemplar of the analysis, design, manufacture, and use of a 3D-printed shoe, as shown in Figure 11. This project occurred before I was exposed to the UPPS model and lead to my using it as it most closely matched the practice and process of Project J. The printing of the shoes was live streamed[35]. Additional hardware and software details are available[36].

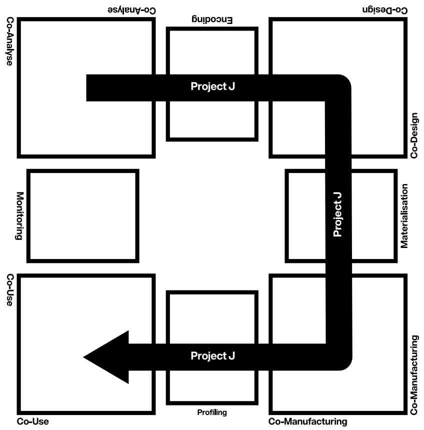


Figure 9. Project J in relation to the UPPSS Model

33 https://vimeo.com/142735987

34 https://www.dezeen.com/2015/10/20/troy-nachtigall-pauline-van-dongen-leonie-tenthof-van-noorden-3d-printed-high-heels-more-comfortable-than-normal-shoes/

35 https://www.youtube.com/watch?v=_kd6wxkUWE0

36https://github.com/troykyo/ProjectJ

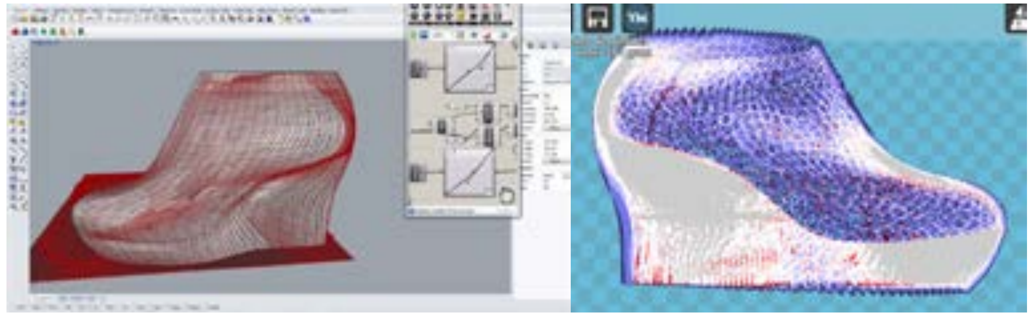


Figure 10. Geometry generation in Grasshopper for Rhino and internal geometry analysis in the G-Code generating slicer program Cura.

Figure 11. (Top Left) Jet Bussemaker wearing the completed shoes with coordinated outfit next to (Top Right) prototypes needed to realize the final shoes. (BottDetail of the final flexible, 3D-printed, personalized shoe.

3.3.2 ONEDAY Shoe Toolkit

The ONEDAY ShoeKit[37] was a project to explore personalization performed in the manufacturing process, see figure 12. The project aims to create a simple yet dynamic shoe kit that could be personalized into any number of shoe styles, as shown in Figure 13. The toolkit was offered via the crowdsourcing platform Kickstarter[38], and more than 300 shoe kits were shipped to six different continents. Two years later, participants were asked for an interview about the shoemaking process. As a toolkit, ONEDAY serves as an example of how to design a toolkit for personalized results.

ONEDAY differs from most shoemaking technologies because of the fact that the shoes are assembled by the wearer themselves in most cases. In most manufacturing, shoes were made to specific standards. ONEDAY as toolkit was created so that making the shoe allowed for personalization. The toolkit imitates a bespoke shoemaker who often develops a model that is then personalized to the individual. There is an expectation of what the final shoe would look like in the mind of the wear before beginning.

ONEDAY was designed as a toolkit to look at manufacturing and personalization that can happen therein, as shown in Figure 13. In the process, elements of design and use were also integrated as the toolkit was designed for personalization and the wearer was interviewed after two years when the shoe was expected to be at the end of life. The toolkit was designed at SLEM with Roderick Peters and the students of the SLEM shoe academy.

ONEDAY is an example of how a toolkit can enable personalization in manufacturing. As RtD, making a toolkit that enables personalization is described in depth in the paper. ONEDAY explores how production can be done by multiple people in a cooperative manner.

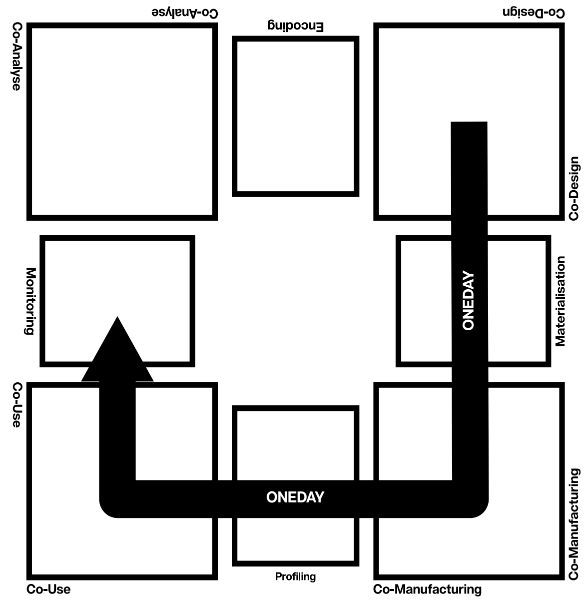


Figure 12. ONEDAY in relation to the UPPSS Model

37 http://onedayshoe.com/
38 https://www.kickstarter.com/projects/149634110/oneday-sneaker-kit/description

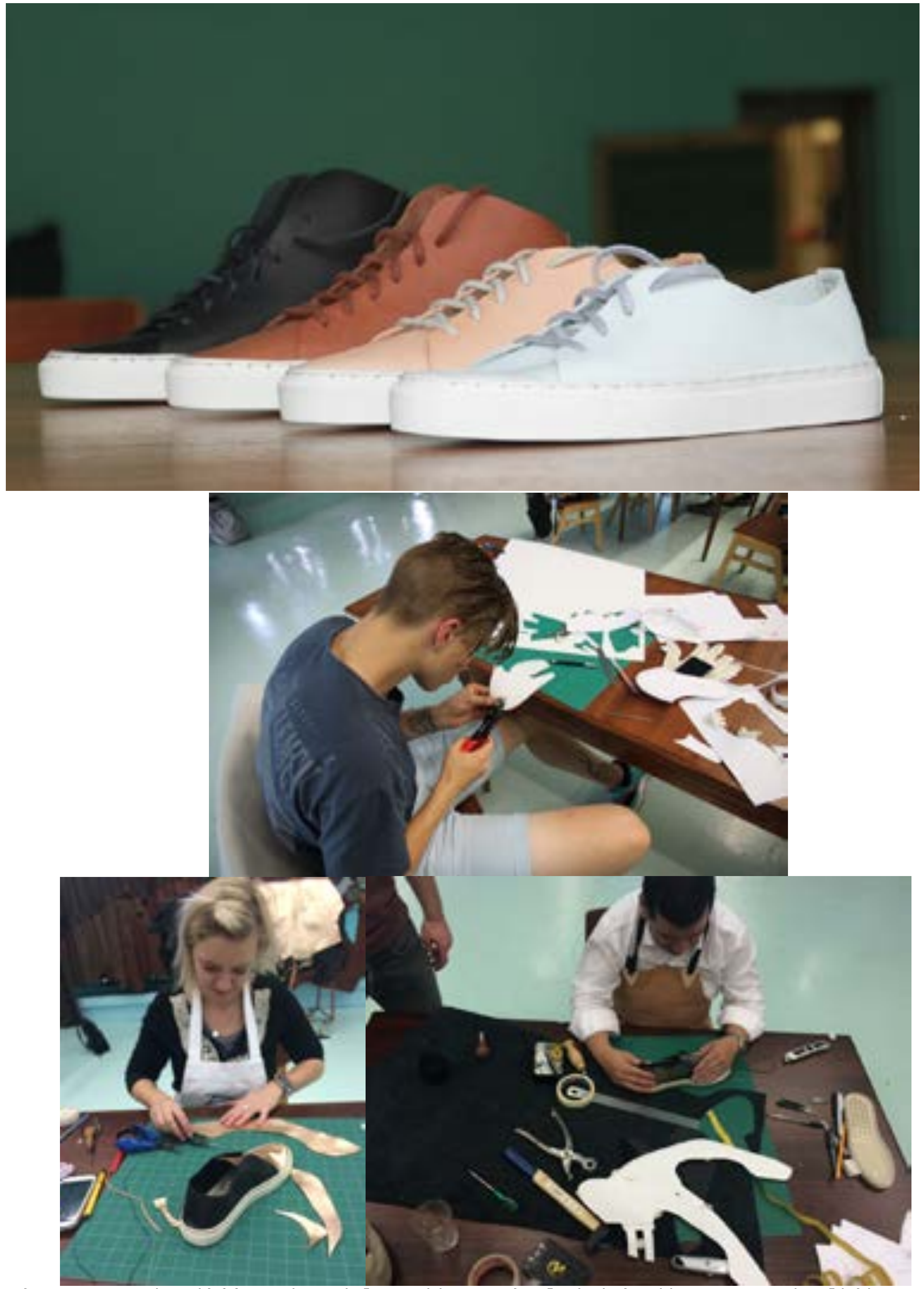


Figure 12. The different models patterns included in the ONEDAY toolkit Followed by pictures of students at SLEM helping develop the toolkit

3.3.3 Solemaker

Solemaker is an umbrella of five projects that all came together, see fig 14. Altogether 272 samples were generated from 2015 to 2018. Four pairs of wearable shoes were realized. There Loe Feijs, Admar Schoonen, Bart Pruijmboom, Eva Klabalová, Henry Lin, Erwin Hoogerwoord, Fiore Basile, Nik van Sleeuwen, Rueben Lekkerkerker, Sigríður Helga Gunnarsdóttir, and Maximiliaan Morres all worked long hours not only on the individual projects but on the integration of the projects into the larger Solemaker system.

In an artisan shoe system, the shoemaker constructs a sole from a base pattern piece or patterns specifically drafted to the wearer's foot. Industrial shoemaking starts with a last in a size EU 39. CAD/CAM software or manual methods are used to model the sole from a shoe last. All other sizes are graded from the median EU 39. In Solemaker the shape of the individual foot is entered into a computer user interface (UI). The tread pattern is created by a stakeholder with the help of templates as needed. The sole is then generated to G-code (a digital fabrication computer language) and printed using a 3D-printer: a heavily modified Ultimaker or hand-made Prusa i3. Solemaker was designed to explore manufacturing and materialization in a UPPS system. Solemaker was also created to prove that mathematical formulas could generate G-code. G-code was to be generated and tested on different FDM 3D printers capable of printing in flexible filaments. The project aimed to allow shoes to be manufactured anywhere. Instead of injection molding, a person could print the sole themselves, or send it to a print service. Key to this process was understanding how to do distributed production. Solemaker gave control over the G-code generation (known as a “slicer”) process to be able to program not only the form but also the behavior of the material. This required an interface, for input.

Solemaker is detailed as a series of smaller projects below, but it is important to note that there were multiple stakeholders involved in every project, who are detailed below.

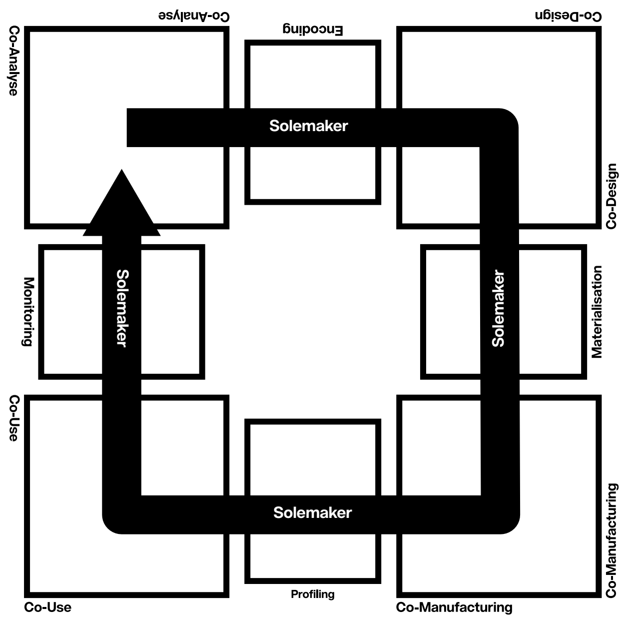
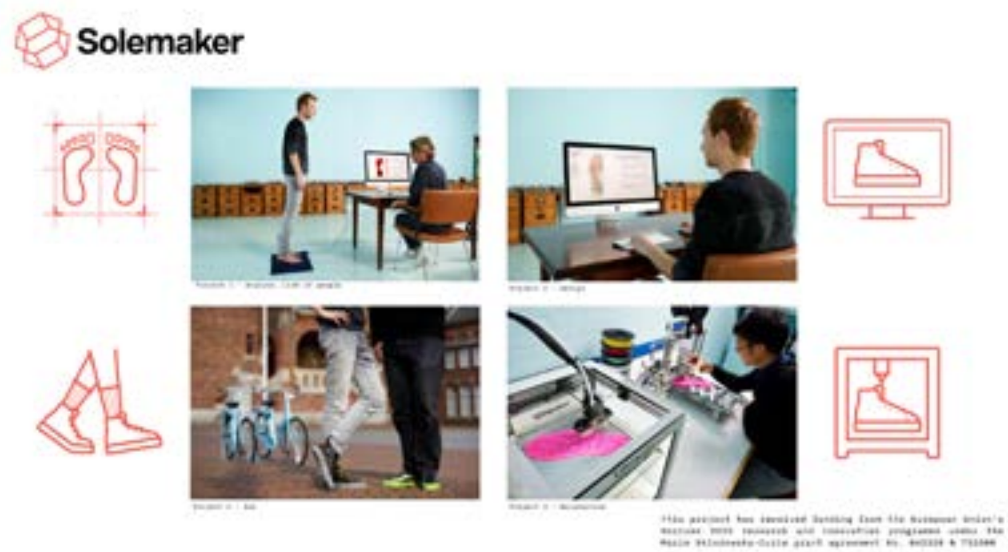


Figure 14. Solemaker in relation to the UPPSS Model. (Opposite) A pair of shoes made with Solemaker and the system as a whole.



3.3.4 Solemaker.pde

Solemaker.pde was the first project to create software and 3D-printed shoe soles, see fig 15.. The project was designed to create a shoe sole using mathematics and algorithms instead of a 3D model. Solemaker.pde as a software creates machine-specific G-code directly from a simple Processing program editor. The G-code is used to print a sole which is sewn to a shoe upper to create a shoe. The Solemaker.pde shoe can be produced in many situations including a private home or industrial manufacturing situation.

Solemaker.pde taught us wearable shoes made with math and algorithms are possible. It is possible to make files for different kinds of the machine allowing for co-production. The G-code for those printers is very different and we learned to write code for that. We learned to use Processing to generate variable density and flexibility in a shoe sole, shown in Figure 16, but to bring this to a larger audience we will need a different interface, perhaps something that is on the web. Through the explorations, we learned that the negotiation of the design characteristics can be achieved but is often difficult. We learned that with that math we can control the flexibility and density of the shoe to ultra-personalize for the wearer, although this will sometimes cause friction between different design characteristics.

There is a need for an intermediary mathematical format, much like an STL model is for a traditional 3D slicer software. We learned that moving the printhead is relatively easy, extrusion is cumulative and challenging. We learned that each flavor printer has a specific startup and end code that needs to be provided for that machine. We also learned that the machine settings for acceleration and jerk (how fast the machine bounces off a corner) are customizable to our materials. G-code gives us direct control of the specific line that is being printed, as shown in Figure 16. This adds a great deal of complexity, especially in the conceptualization of the shoe.

The code and hardware modifications can be found on Github[39].

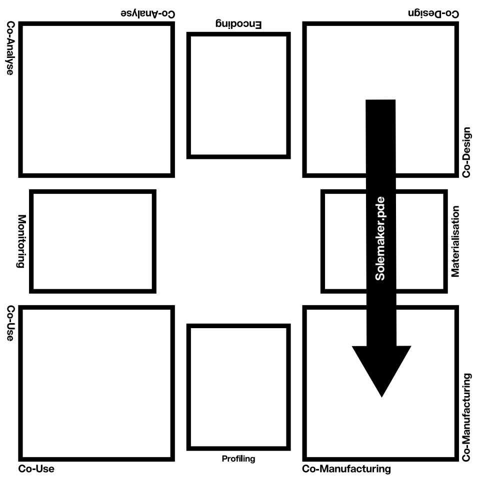


Figure 15. Solemaker.pde in relation to the UPPSS Model

39 https://github.com/troykyo/SoleMakerSavingGcode
40 https://processing.org/

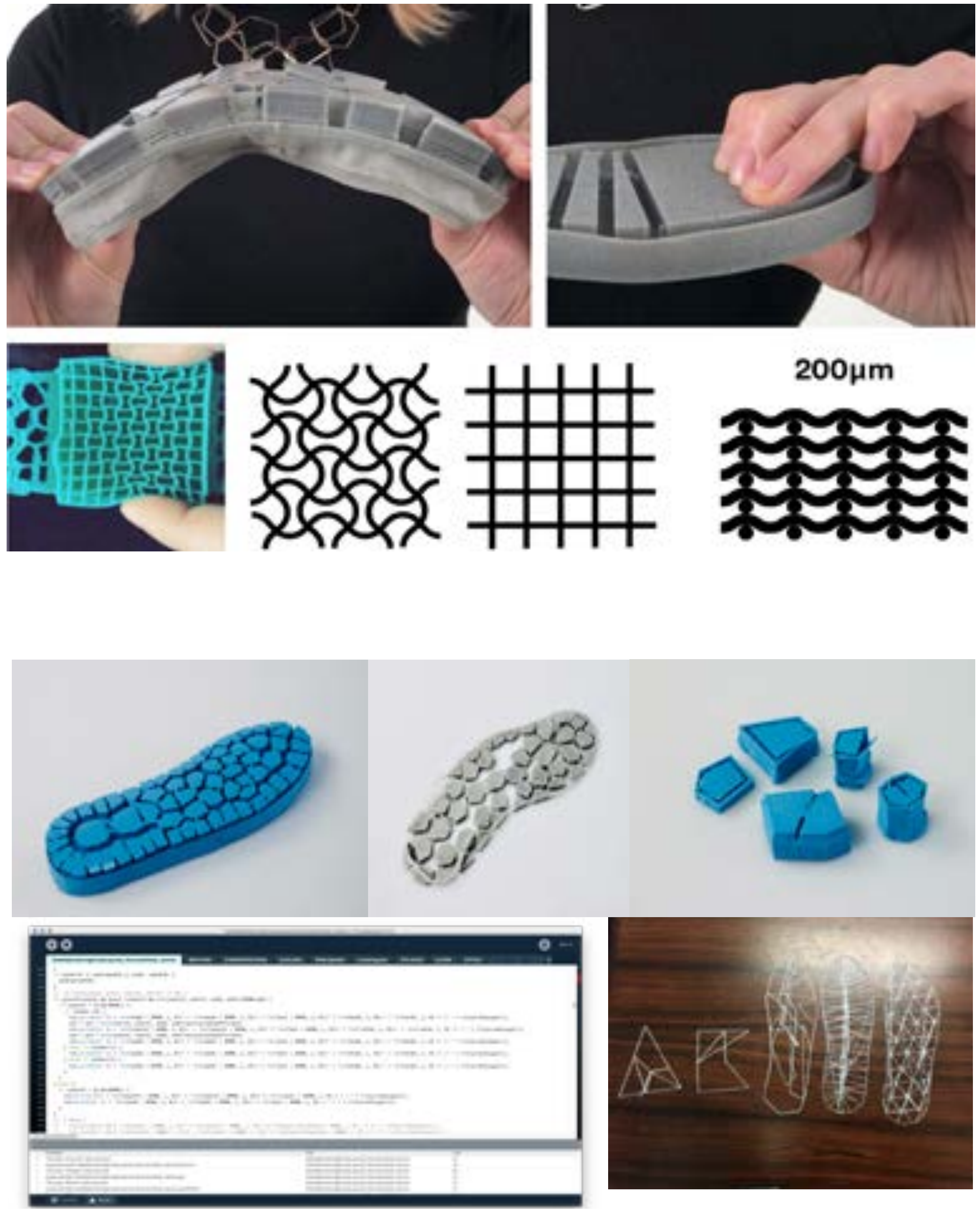


Figure 16. (Top) An example of how the internal structures were programed to behave like stacked textiles resulted in programmable softness and flexibility in the shoe sole. (Bottom) Example of the Processing[40] code and the first samples of prints made from the Solemaker shoe software. Important to note is that 3D files (such as STL) are not used. The shoe is mathematically modeled and printed directly.

3.3.5 SoleScan

SoleScan was a project to create a sensor capable of revealing the shape and pressure of a loaded foot using embroidered digital fabrication technologies, see fig 17 . The project was designed to show the footprint on the screen and pressure image visualizing a 3mm deep 3D image of the foot. The SoleScan software visualized and recorded data of the foot standing on the sensor. SoleScan was originally designed as a shoe insole and later changed to be a pressure pad to be used as part of SoleMaker web platform, but functions as either. Industrial shoe sizes are traditionally measured by a Brannock Device invented in 1925 which tells the length and width of the foot, see fig 18.

In artisanal shoe systems, an outline of the foot may be taken. SoleScan provides a detailed outline of the foot, it also provides a pressure mapping of the loaded (body weight is down) foot. This is measured dynamically over time to provide a more complete data set of the loaded foot. SoleScan takes a crafted sensor and provides data about dynamic pressure of the foot in real time. SoleScan was designed to explore the analysis and encoding of the parametric data in a UPPSS system. Recording foot data is a challenge and compressing it into parametric data is even harder. SoleScan sits as the gateway into shoe personalization.

In this project we created a project that would allow stakeholders to visualize the pressure and presence of a foot. We looked at what resolution was needed to provide us with enough data to parametrically generate shoes. We wanted to provide a system for stakeholders to analyze feet and provide data about the distribution of weight on the foot to provide generative algorithmic parameters for co-design.

SoleScan taught the team members to create data that could be used for personalized shoe design. There are many different kinds of feet, beyond the length and width of the foot we saw many outliers in terms of shape (especially height) and balance from the more than 400 scans at Dutch Design Week 2016. High arches, larger big toes, and small toes confused the system. We adjusted for these on the fly, but we had to also change the scanning process asking users to lean forward and back to capture the full weight shift profile. We thought we knew how complex the feet of all the people , we were surprised that it was more complex than we expected.

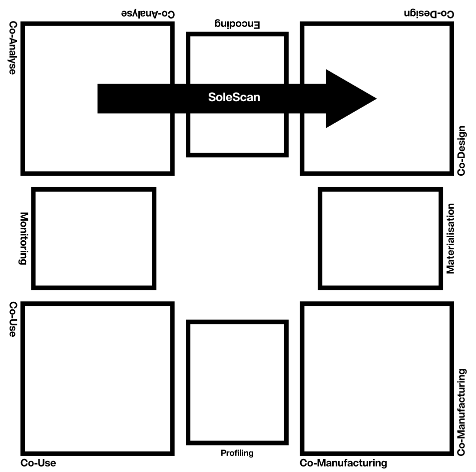


Figure 17. SoleScan in relation to the UPPSS Model

Figure 18. Bart Pruijmboom having his foot scanned. Photo by Bart van Overbeeke

3.3.6 The Edge

The Edge was a project to parametrically change the uppers of a shoe based upon the dimensions of the generated sole made with Bart Pruijmboom, see fig. 19. The Edge was designed to adapt the patterns previously made for ONEDAY shoes into the specific dimensions of a parametric sole, as shown in Figure 20. Once given the dimensions of a sole (often generated in one of the Solemaker programs), The Edge would provide laser-cutting patterns and hole alignment guides so that the leather (or other material) shoe uppers could be attached to the sole, as shown in Figure 21. This was key to the process of generating a complete shoe in Solemaker.io.

Traditional and industrial shoemaking uses a shoe last, a mechanical model of foot, to fit the upper and apply the sole. (There is much debate around shoe lasts in the shoe community. For example, athletic lasts are usually descendants from original last forms made in the 1920s, the material of the time was vegetable tanned leather, which can form around the foot with wear.) The Edge uses a more fashion-oriented "*lastless*" system that lowers the barriers for manufacturing significantly. (Although many shoemakers would claim that this is not a "real shoe.", The Edge scaffolds traditional shoemaking by parametrically generating the pattern for the shoe upper from sole input.

The Edge provides a means to achieving parametric design by generating a personalized upper to fit the dimension parameters provided by solemaker.pde (and later by solemaker.js as part of solemaker.io). The Edge is an example of materializing of design for production. The project takes a designed shoe upper and algorithmically adapts it to external parameters. Project intern Bart Pruijmboom developed the primary code for fitting the upper to the personalized sole.

The Edge taught us that parametric design is complicated as 3D mathmatic models are converted to the topography of 2D. Starting with a pattern designed by a shoe designer, it is possible to parameterize that upper. This enables the generation of the upper alongside the personalized sole. We were able to compare the upper PDF files with the original paper patterns team members made in the ONEDAY project to control that they were close to the correct size for the sole being generated.

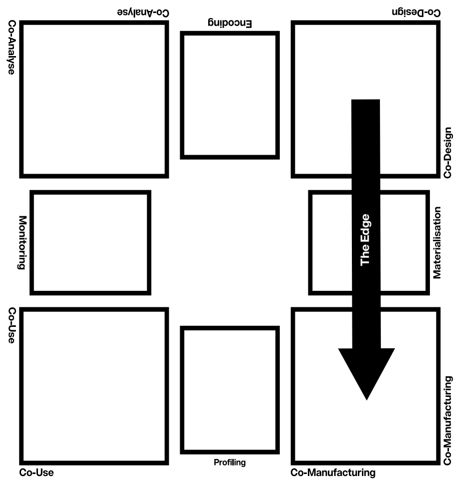


Figure 19. The Edge in relation to the UPPSS Model

41 https://www.sintlucas.nl

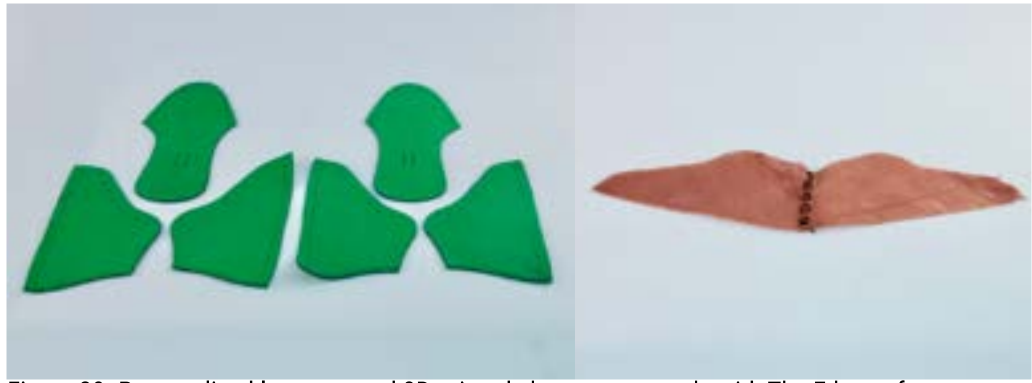


Figure 20. Personalized laser-cut and 3D-printed shoe uppers made with The Edge software.

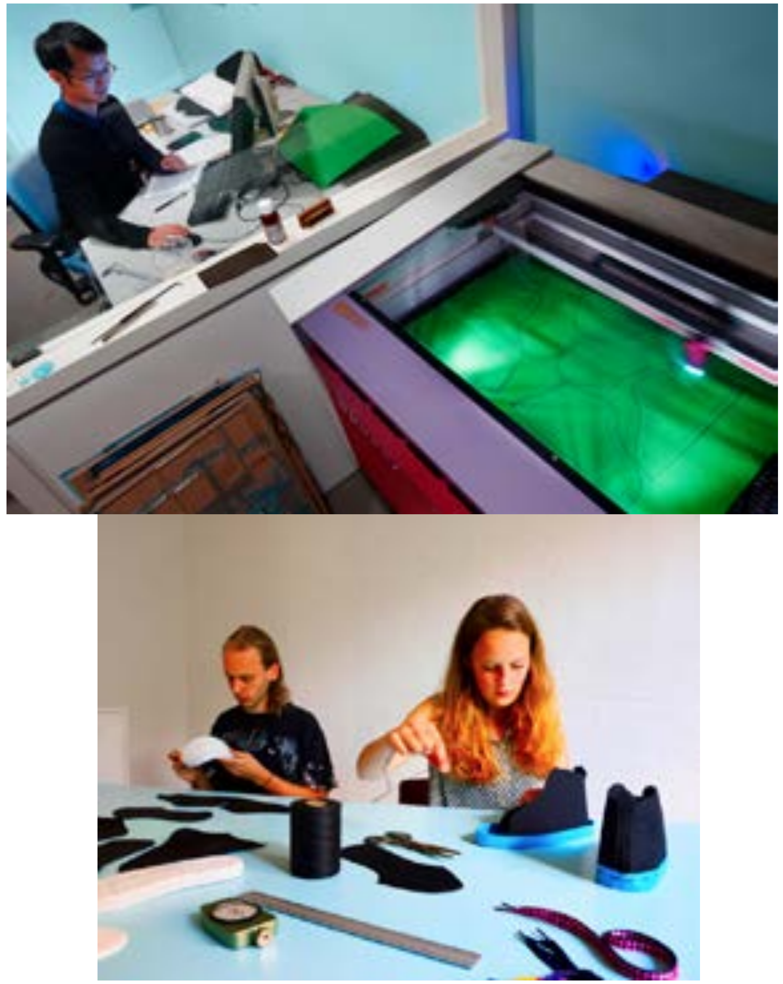


Figure 21. (Top) Henry Lin lasercutting shoe uppers in the TU/e /dSearch Lab. (Bottom)Interns from Sint Lucas[41] college constructing the resulting Solemaker shoes.

3.3.7 Solemaker.io

Solemaker.io, see fig. 21, was a project to combine the scanning and generation of a shoe into a single process, and was coded into a web platform using JavaScript called solemaker.js, as shown in Figure 22. The project was designed to integrate with the scanning aspect of SoleScan, the co-design process of solemsaker.js and the generative uppers of the edge. The project allowed the website user to stand on the SoleScan and have a shoe be dynamically generated via an algorithm for their foot. The user could then modify the scan (seen in Figure 23), visualize the shoe sole in 3D, and complete the process with a G-code file for 3D printing.

At the same time, the edge would generate the uppers needed to laser-cut leather for the shoe. In industrial shoemaking, sketches and designs are usually drafted in a first world country and sent digitally to places like Vietnam for prototyping and eventual manufacturing. Artisan shoemakers have a last library and make modifications to the last before manufacturing a pair of shoes locally (or abroad, depending on the level of detail required).

Solemaker.io put the digital manufacturing files in the hands of the user for distributed manufacturing, as shown in Figure 22. Solemaker.io was designed to explore the data flow different steps of shoe making. As a platform to bring all other parts together, Solemaker.io is an analysis tool as it incorporates the SoleScan into a single screen. Encoding is done as the counter footbed and pressure map is generated. Design is found in the editing interface with different views of the shoe. Materializing is found in the nozzle size and other G-code settings. Manufacture is a result of the shoe's ability to be made anywhere. Profiling is lightly explored with the QR code that users are given to bring them back to how the shoe was made for future iterations.

Solemaker.io provided a larger picture of the UPPSS process. It showed that the entirety of the UPPS process need to be considered when designing an UPPSS. Upon understanding the realities of encoding the data, the project changed.

Solemaker.io demonstrated, see fig. 23, that incorporating analysis data into the design process is difficult. Streaming the data and visualising it in javascript was technically difficult (streaming web hooks that come from very different software sources creates challenges), UX difficult (maintaining a frame rate that the user finds acceptable, above 10 frames per second, is hard in streaming APIs) and UI challenging (the visualization of the SoleScan data is layered below the d3.js data visualization layer). Saving data from a user is complicated under the new data protection laws of Europe known. The software had to run in browser, local to the user, so that the server does not see the users data. Streaming the SoleScan data from the SoleScan server into the local browser created a browser security violation and required a difficult workaround, the streaming web hook from the site instead of a PUT from the SoleScan Server. This also required that the user elect to upload the data at the end of the session. The data had to be anonymised with a software token that would allow a link back to the previous data.

Hardware and software details are available.[42]

42 https://github.com/troykyo/SOLEMAKERCOMPLETE

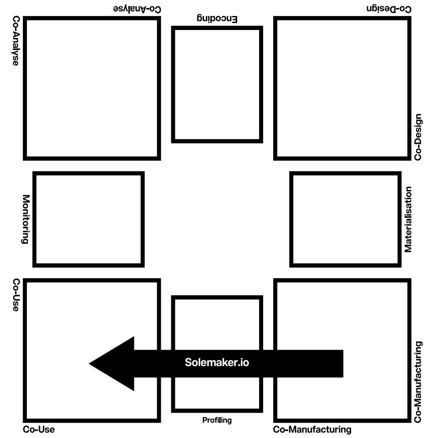


Figure 21. Solemaker.i0 in relation to the UPPSS Model

Figure 22.The www.solemaker.io website interfacing with SoleScan to generate a shoe.

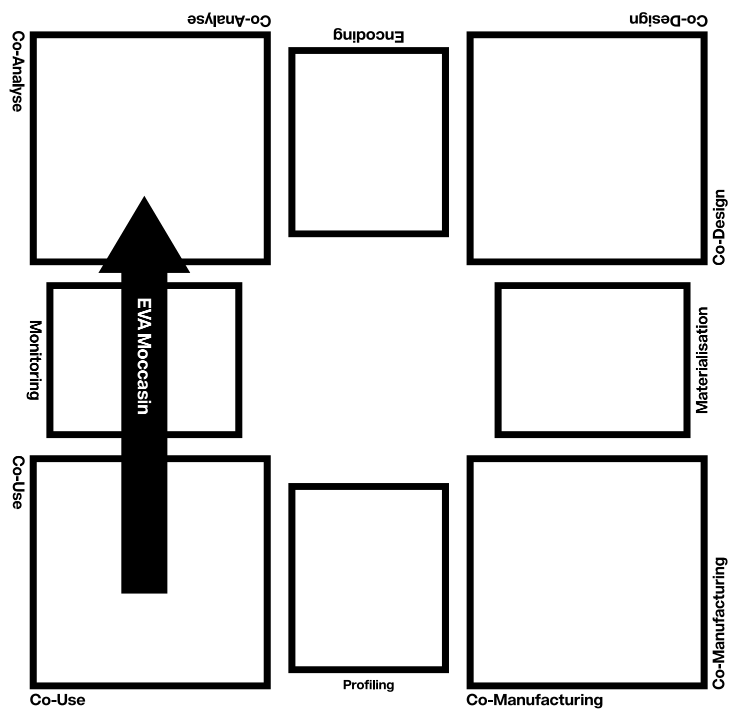
Figure 23 Prof. Loe Feijs demonstrating the Solemaker.io system at Dutch Design Week 2016. Photo by Bart van Overbeeke.

3.3.8 EVA Moccasin

The EVA Moccasin, see fig. 24, was a project to explore sensing and aesthetics in a parametric shoe, made with designer Eva Klabalová. The project was built on top of Solemaker and added 3D printing onto the upper of the shoe, sensing to the sole of the shoe, and created a new aesthetic for the parametric shoe. A new shoe construction was used to explore alternative solutions to the challenges faced in the Solemaker project. It was discovered by SLEM that it is possible to print on the suede side of the leather. The sole was inserted into a moccasin construction to make the sole replaceable and avoid stitching the sole to the upper. Different methods of sensing were explored using electronic and non-electronic sensing, see fig. 25.

The EVA is similar to the others, but allows for greater flexibility in manufacturing and scaffolds the process in a way that proves we can bring more designers to the system. EVA Moccasin was designed to collect data about the foot as it is being worn to make future shoes even more personalized. The project was an exploration into ways of generating data about the use of the shoe. Different methods of gathering data are explored including electronic sensing, color changes in sole abrasion, and micro structures. The EVA Moccasin monitors the wearer's use for future analysis. It explored different methods of decoding data in electronic and material based methods in the "EVA Moccasin: Creating a research archetype to explore shoe use." (Nachtigall 2017).

Software and hardware details are available[43]



43 https://github.com/troykyo/EVA

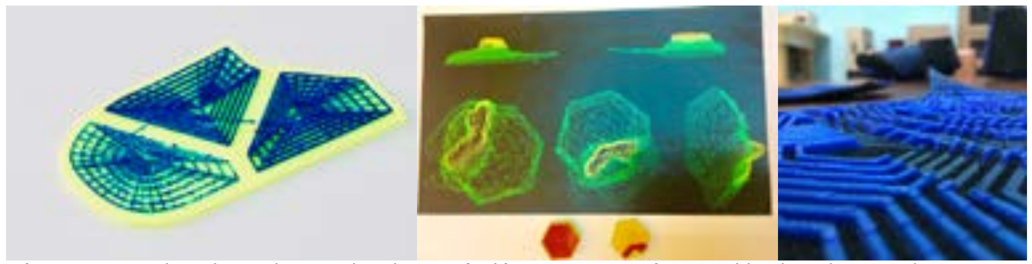


Figure 25. (Top) A demonstrator of diverse sensing methods shown at ISWC 2017. (Bottom) The EVA moccasin with details of the mechanical sensing structure and abrasion sensing.

3.4 The UPPS Game

The UPPSS game, shown in Figure 26, brought together elements of all of the other projects to understand if the knowledge about product–service systems in personalization that had been gained in the other projects was transferable. The game asked if a personal digital crafting experience could be scaled up into a product service system platform for ultra-personalization. The result was normally shoes that had been made and remade to be more personalized, but also the dataflow and customer journey of an iterative personalized shoe system.

The UPPSS game was different than traditional shoe making because it did not assume a production system. It gave the student the possibility of modifying processes thought to be inherent in shoe production, sales, and lifetime. The game asks the player to make a pair of digital fabricated shoes, shown in Figure 26, and grow that experience into a service and system level where they can deal with scaling up and other wicked problems like sustainability. The UPPSS game is a meta view of the UPPSS process as it asked the players to take an overview and think about the services and systemic levels that some would call a design ecosystem (Forlizzi 2008).

The UPPSS game asked the player to confront the data of the shoe in the data flow and the physical materiality in the customer journey. It illustrates that enabling transitions that the data and physical material undertake in the process.

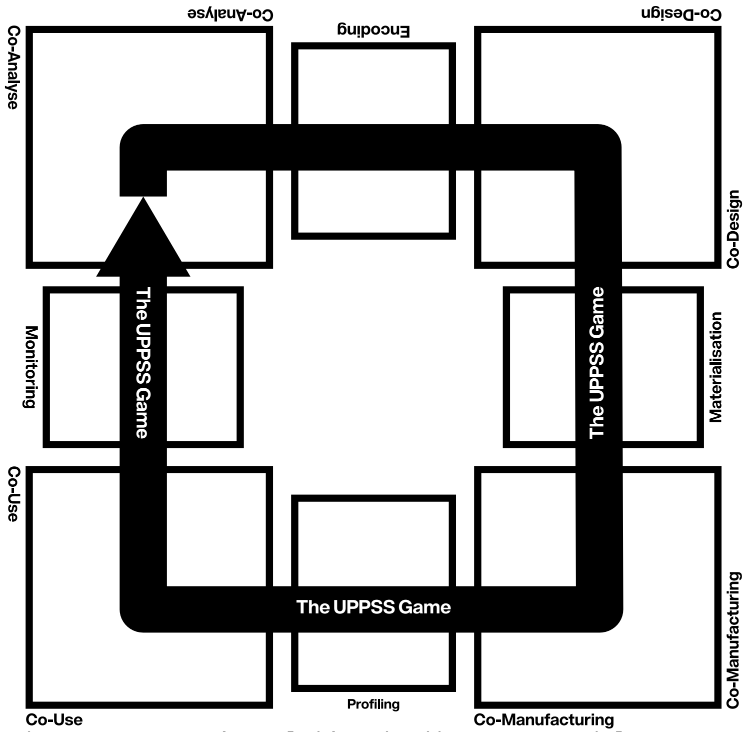
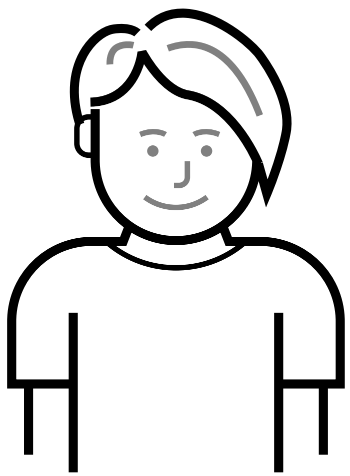
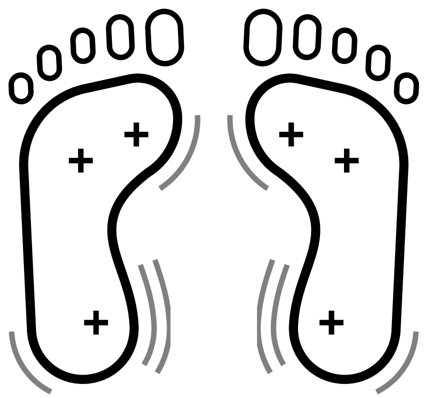
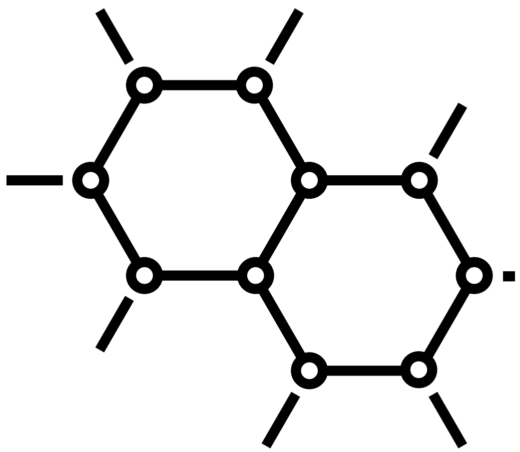


Figure 24. The UPPSS Game in relation to the UPPSS Model, (Opposite) Shoes (top) made as part of the UPPSS Game (bottom).







An Exemplar of Shoe Personalization

Published as "Towards Ultra Personalized 4D Printed Shoes" (Nachtigall et al. 2018) and presented at the ACM CHI Conference on Human Factors in Computing Systems 2018.

The publication considers the process of three designers making four iterations of shoes and five design considerations were identified. The iterations detail negotiating the design considerations to digitally fabricate a personalized shoe. Off-the-shelf software and industry-standard 3D printers were inadequate for what we were trying to accomplish. The final shoe was only achieved by combining generative software technology with tacit shoemaking craftsmanship. Detailed in the chapter, the capabilities of the technology all seemed years away from the craftsmanship needed for the aesthetics, function and behavior of bespoke shoemaking. Truly accomplishing a personalized bespoke shoe would have required programmed internal structures that enable programmed behaviors. That would mean opening the "black box" of technology and writing new software.

4

Project J

4.1 An Exemplar of Shoe Personalization

Role

Project J was instrumental as an exemplar that shoes could be digitally fabricated with a personalized form, interaction, and aesthetic fit using a single material. It encouraged the recruiting of stakeholders as the shoe demonstrated shoe personalization was possible.

Research Question

Can a shoe be personalized using current digital-fabrication technologies?

Research Conclusion

A shoe can be personalized using current digital-fabrication technologies be personalized using current digital-fabrication technologies, but it requires negotiating design considerations, great amounts of effort, and several stakeholders.

Quality of the output

Museum Quality was achieved by concentrating on the material quality.

Favorable outcomes

What worked in the project was that the shoe was aesthetically beautiful. It fit the form and the movement of the wearer as well. This shoe was monomateric. Software was used to change the geometries that would make the material behave in different ways, to adjust the design considerations of the shoe.

Difficulties and Unfavorable Outcomes

The first print was printed lying on its side, which was a complete failure. The generative software Rhinoceros 5 with the grasshopper plug-in made tremendous geometry but was the cutting edge and remains that way for off-the-shelf software. Printing required a completely new drive for the printer to achieve the required print times. While we accomplished personalized form, interaction, and most importantly aesthetic, It was discovered that much more was possible.

Towards Ultra Personalized 4D Printed Shoes

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Abstract

In this case study three designers supported by multiple stakeholders created a pair of fully personalized printed high heel shoes in a period of two months for a single user. The shoes are made with soft and flexible materials for dynamic fit and use. The shoes are not only uniquely formed to the user's feet but the geometry of the material is designed to support and flex with the movement of each foot. These shoes utilize a 4D printing approach in the way they are made to fit the user while they move and change. Designing a shoe to such a degree represents a form of Ultra Personalization. This case study of an ultra personalized approach addresses the negotiation of key design considerations: aesthetics, comfort, robustness, balance and temperature. The findings inform digital fabrication design, software, and tools for designers.

Author Keywords

Ultra Personalization; Footwear Design; 4D Printing; Research through Design, Flexible Material, Design Software

ACM Classification Keywords

B.8.2. Performance Analysis and Design Aids
H.5.2. User Interfaces: User-centered designH.5.1. Information interfaces and presentation

Introduction

What would it be like to have shoes that fit our unique form ways we move? What if shoe designers could take data about our shape, weight and behavior into account when making shoes? Advances in digital fabrication are allowing designers to create shoes in new ways [13], with new materials that fit uniquely to our form and movements [3]. We can use data from scanning the physical human form and talking with people. We can use materials printed in 3D form [9] to be comfortable and look good. We can utilize algorithms to tell the shoe where to be soft, where to flex and where to be sturdy for each foot. In short, this is a shift in shoe design and manufacturing led by digital fabrication [6,18] and inclusion of digital data.

Shoes are often still designed with pen, paper, and lasts (foot forms) (see fig 1 and 2). Our approach in this case study is one of "Ultra Personalization" that includes data in the design process. While this level of personalization is sometimes achieved in bespoke shoemaking, we wanted to make the shoe with a 3D printer. Using soft and flexible materials allowed us to work with a 3-D form with the added dimension of movement (4D Printing). Designing a shoe to be fully 4D printed is very different than traditional shoe making, see fig. 3.

This case study illustrates how a fashion designer, interaction designer, and shoe design/design researcher designed a research product that was worn at a public performance. By research product we mean a fully finished product designed to be lived in, in order to research the process of digitally designed shoes. We address five design considerations including aesthetics, comfort, balance, robustness, and temperature. These considerations are more or less solved in traditional shoes, but digital manufacturing, new materials and individual user data raises these design concerns anew. The design considerations are interrelated creating a complex challenge to be negotiated throughout the design process. While there is research on the possibilities of printing shoes [12], the structures for printing soles [5], and the future of merging data [2], we needed to bring and solve these challenges together in order to create a working research product.

In this design case, scans of the user's feet in multiple positions, fig. 4, along with other personal physical data were paired to interviews about social needs, fig. 5, throughout the process. This data allowed for the creation of digital lasts (virtual and changeable models of the user's feet). Using the lasts, a shoe was modeled through generative scripts. The resulting geometry was post processed, sliced and printed in flexible filament. The first prototype was aesthetically beautiful and novel, but was not robust or usable. The second prototype was robust but was hot, heavy and ugly. The third was still unattractive, but lighter. The final iteration negotiated all five design considerations successfully. We highlight the challenges we faced and reflect upon these in arriving at a successful shoe.

The research contribution of this case is a documented

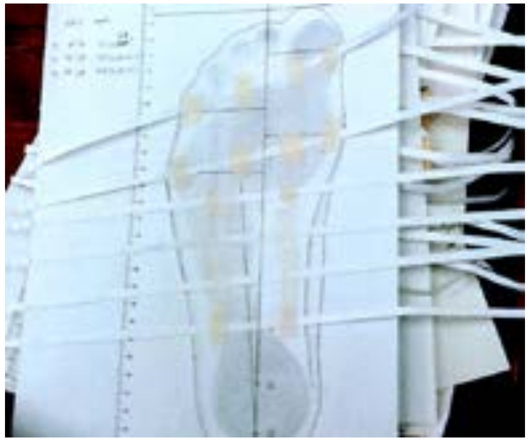
Figure 1 Bespoke Shoe Measuring


Figure 2 Made to Order shoe

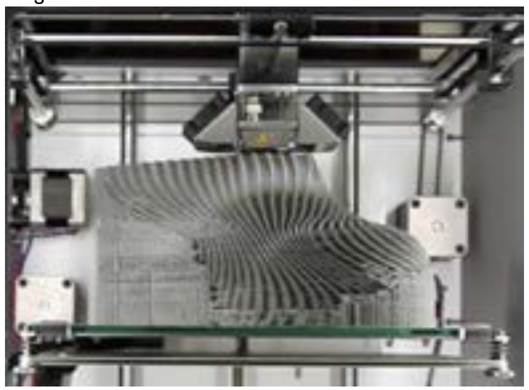
Figure 3 Printing a Shoe

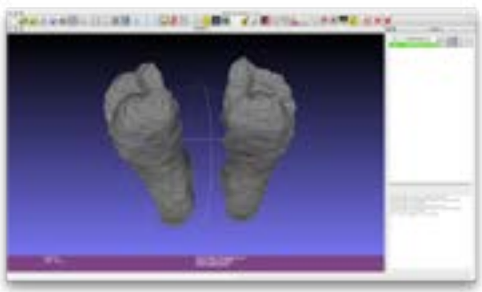
Figure 4 Scan of feet from below


Figure 5 Consulting with the client about her personal needs


Figure 6 Finished shoes worn

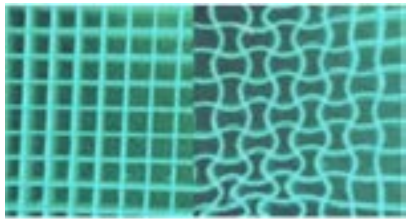
Figure 7 Flexible Material samples


Figure 8 Stitched scan and printed mini last.

account of an exploration of shoe design in the context of Ultra Personalization and 4D printing. We open up our creative process and look at design actions, software tools and the making process. A detailed account of how we addressed the challenges is provided so that other practitioners and design researchers can build on it and share accounts of their experiences. It also serves software engineers and data architects in creating tools for the coming shift in manufacturing and inclusion of digital data.

Background

3D printed shoes are still uncommon, United Nude has made attempts as well as Adidas, Nike, Under Armour and others [18]. Yet these shoes all seem to be born out of a fascination with the technology. The possibilities of adaptive manufacturing can address comfort and style as much as celebrate the new technology. 3D printing allows for unprecedented levels of personalization. Looking to tailoring we find an analogy of where shoes might go. Tailoring can go beyond the classic idea of “tailored” to a level known as “bespoke tailoring”. In this case, tailored garments begin with a base form (known as a “block”) which is modified to the individual, i.e. a tailored jacket. In Bespoke, the “block” is drafted specifically to the individual, then the design begins.

In shoes, we find similar levels of personalization in approaches like Mass Manufactured Ready to wear, Made to Order (fig. 2), and bespoke footwear. However, what happens if we incorporate more data into the design of the shoe? We find that the term Ultra Personalization in textiles resembles bespoke tailoring but utilizes digital data. Ultra-Personalization is described as “embodied services, the service interface can be customized through digital applications and innovative use of data and personalized by means of tailored textiles” [1]. Other examples are found in eLearning[17].

Recent advancements in FDM (Fused Deposition Modeling) printing of flexible materials [11] is changing desktop 3D printing into 4D printing, fig. 7. Printers can now print objects that bend and flex. Computational geometry allows for bend and flex to be specifically defined in an object [9,11]: “4D Printing is a new process that demonstrates a radical shift in additive manufacturing. It entails multi-material prints with the capability to transform over time, or a customized material system that can change from one shape to another” [16]. Examples of 4D printing are developing in Architecture [16], Biomimicry [14] and in toys [7].

Design Methods

Two goals drove the research in this case study.
1) Negotiating the design considerations to create a fully functional shoe. 2) Using research through design to create a research product [10].

Design considerations

The shoes were commissioned by a client who was a public figure needing the shoes for a formal event fig. 6. To meet the challenge of wearing the shoes for a highly public event, our ultra personalized process aimed to meet a series of design considerations. These include:

Aesthetics - The shoes required a specific aesthetic beauty to reflect the social needs of the wearer and express the calculated concept of the design.

Comfort - The shoes needed sink, bounce and flex that charge with the foot movements to maintain comfort over extended wear. The shoes also need to be light enough to raise while walking.

Balance - It was fundamental that the shoe would support her weight and not collapse, bend or buckle under the force of the body, especially at the heel.

Robustness – The shoes need to stand upright, envelop the foot and not fall apart. The side walls need to remain strong yet flexible and intact.

Temperature – Given the shoe is entirely plastic, thermodynamic consideration must be given by adding breathability and preventing sweat condensation.

Research through Design

To arrive at a research product, the shoes are created with a Research through design [8] approach. Research through design is used so that each prototype creates reflections that informs the next iteration. As the final shoe had to be worn it was important that design considerations negotiate with each other over four iterations. We see these shoes as research, not just a series of prototypes. This case is meant as a study of design and how to negotiate design considerations.

Design Process

Developing the Forms of the Foot

3D Scans were made using the Sense 3D topology scanner with the feet in varying positions, fig. 4. The foot was scanned engaged on the ground and in the air. Scans were not only made of the feet, but also the body to inform of any possible differences in leg lengths. Manual measurements confirmed the accuracy of the scans and the weight of the user was recorded. A digital last, fig. 8, from the 3D scans of the user’s feet was created using MeshLab and Cinema 4D.

The Material

The designers chose a styrenic block copolymer thermoplastic elastomer (TPE-s, Shore 95a) known commercially as FilaFlex. This material allowed for the construction of responsive objects with spring, flex, bend, rebound and reflex, fig. 9, thanks to properties such as 800% resiliency. It was chosen because of the need for flexible and strong geometries that support and flex with the foot.

Ultra Personalizing the Geometry

The form geometry was generated using Meshlab, Rhino/Grasshopper, Cinema 4D, and MeshMixer. No commercial software yet exists that allows for the dynamic control of geometry for flexible printing. We used the parametric and generative aspects of Grasshopper combined with the dynamic modeling capabil-

Figure 8 Digital Last Development

Figure 9 Shoe Flex

Figure 10 Enlarged detail of the aesthetic surface effect

Figure 11 Prototype 1 Aesthetic, but not robust

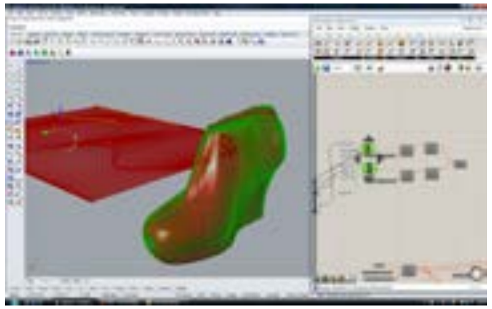

Figure 11 Grasshopper Definition

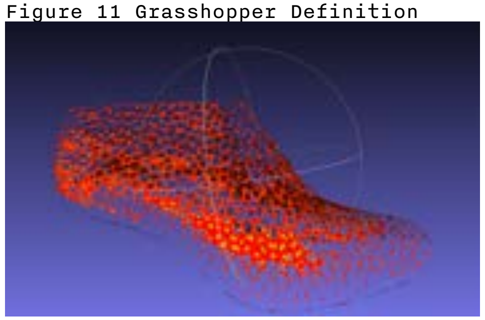

Figure 12 Voronoi Genereated inner wall.

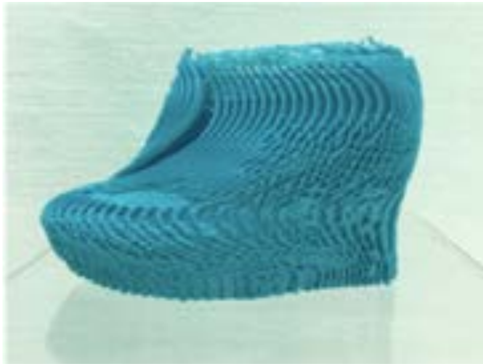

Figure 14. Prototype 2 Hot, Heavy and Ugly

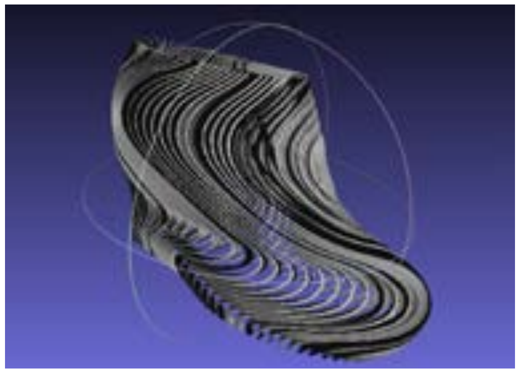

Figure 15 Inverted Normals Geometry Problems

ities of Cinema 4D to make the shoe models.

Aesthetics of the shoe

The shoe was inspired by the idea of force field lines illustrating the movement of the body. This was a result of conversations between the client and designers to develop a sense of style and aesthetics. Surface quality was of great concern and a 0.4 mm nozzle was selected for its level of refinement. Another concern was environmental sustainability. We chose to print the shoe in a single, recyclable material.

Aesthetics	✔	x	x
Comfort	x	x	✔
Robustness	x	✔	✔
Balance	x	✔	✔
Temperature	✔	x	x

Table 1. Design consideration fit per iteration.

Design Iterations

In translating the design considerations into printable geometry, it was found that our design considerations often appeared to be mutually exclusive. Negotiation was needed. We track their success in table 1. A series of iterative prototypes were created using Cinema 4D, Grasshopper/Rhino, MeshLab, MeshMixer, Cura, Slic3r, and Craftware. Managing the design considerations took tens of hours simply passing the geometry back and forth between programs. Prints were made on an Ultimaker 2 and Prusa i3. It should be noted that each of the five shoes required 72 to 108 hours to print.

Iteration 1

Iteration 1 required a lot of set up time, Fig. 10. The designers created a digital last from the foot scans. An algorithmic Grasshopper description generated the external curved lines, see fig. 11, that act as springs in the front and strong support in the heel. The lines remained straight at the back of the heel for stability and support while bending at the talon (the front part of the foot) to help flex and bounce are needed. A generative voronoi algorithm in Meshlab was used to create the internal wall providing airflow and robustness. Areas where stress of the material would happen had more material, fig. 12. Translating the geometry of the shoe into printable gcode was attempted in slic3r and Craftware; both failed. This made the use of variable density infill unavailable. The generative software caused a massive number of flaws in the geometry. Cura was the only software able to slice the geometry, fig. 13. Robustness calculations for Weight support were made based on printing the shoe lying on its inner side. This was done to provide comfort while supporting the weight and dimensional stability.

Iteration 1 Reflections

The aesthetics of the shoe was great; the lines illustrated the intent of the designers, fig 13. The thermodynamics were great as the side walls were mostly open. The shoe failed in terms of weight support and dimensional stability as the whole shoe buckled under the weight of the wearer. The model deformed in unforeseen directions with each step. The shoe was also uncomfortable as the whole shoe deformed. The user remained positive but was nervous.

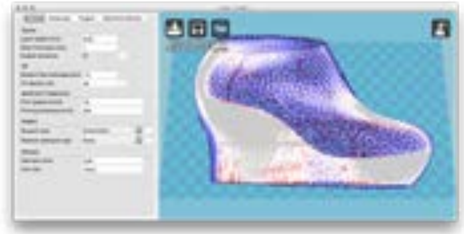

Figure 13 X-Ray view of shoe showing internal structures

Iteration 2

A new approach was taken in the second prototype, fig. 14, to focus on robustness and balance. An additional scan of the feet walking was made. The digital last was adjusted to fit the movement better. The printing axis was turned with the sole being placed on the print bed so that the structure of the infill generated by Cura would be better oriented for weight support. This reorientation required new calculations in grasshopper. The resulting shoe had a thinner heel and the talon became higher. The number of external lines reduced to allow for a more flex and comfort. A new internal wall was generated in Cinema 4D for even more robustness and balance.

Iteration 2 Reflections

The additional robustness and balance caused the shoe to remain solid, but caused it to be far too heavy (nearly 900 grams per shoe). This affected the comfort as there was little flex and bounce remaining making the shoe clunky and uncomfortable. This additional robustness made shoe difficult to put on and take off. The solid internal walls did not allow for enough stretch for comfort. It also made the foot hot as the wall failed to breathe. The new printing axis caused even more errors in the geometry. Inverse normals occur when a face of an object is inside out, fig 15. Non-manifold errors occur when the sides of an object don't close, fig 16. The impact on the aesthetics was severe. The prototype looked like a crude version of the first prototype. The wearer remained positive because although the shoes were ugly, she could walk in them.

Iteration 3

This iteration, fig. 17, looked to negotiate comfort/temperature with robustness and balance. The digital last was once again readjusted to make it easier for the foot to enter and air to flow over the foot. This change required a redefinition and recalculation of the Grasshopper definition. The result was a larger upper heel and even thinner lower heel. Problems in the

Figure 16 Manifold Geometry Problems

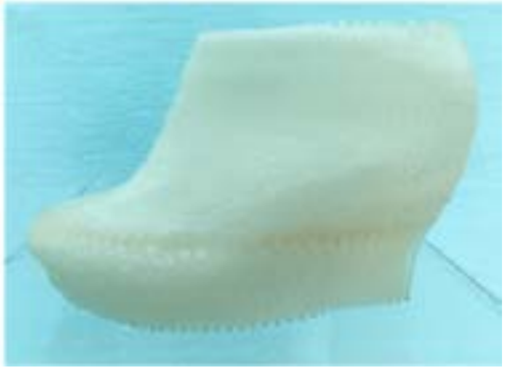

Figure 17 Prototype 3 Aesthetics and temperature problems.

Figure 18 Final Research Product

Figure 19 Grasshopper “Definition” of the shoe

Figure 20 Transparent infill detail

Figure 21 Finished Aesthetic lines

Figure 22 Heel Detail in Prototypes 2 and 3 respectively.

geometry persisted as Rhino/Grasshopper has difficulties generating solid geometries. In slicing, infill was adjusted to rectilinear 20% to be significantly lighter and more comfortable while maintaining robustness and balance. Additionally, the designers manually restricted the 3D printer extrusion in the footbed area to create breathability. This was achieved by manually holding the filament back during printing. The shoe was printed in a transparent version of the material so the infill could be visually inspected, Fig 20.

Iteration 3 Reflections

The weight of the shoe was far more reasonable (494 grams) while it remained strong and supportive with the new infill structures. The footbed underextrusion provided a pneumatic action as air flowed in and out of the sole. Aesthetically, the shoe still had several issues including the pointy aspect of the calculated toe and the surface quality caused by the geometry problems. Being able to see into the bottom of the shoe allowed for a better understanding of what was happening inside the shoe. The user was able to put on and walk in the shoe, but was concerned about the “look”.

Iteration 4 – Research Product

Iteration four, fig. 18, looked to negotiate the aesthetics and temperature now that the shoe supported weight and balance. This iteration started with a rounding of the toe of the digital last. The grasshopper definition, fig. 19, remained the same as we had negotiated balance, robustness and comfort. The infill for balance, robustness and comfort were kept in Iteration 4. Small triangular holes were added at the level of the footbed to bring back some of the airflow from the voronoi algorithm. A triangle was used to minimize impacts on the balance. Difficult to this process was ensuring a fine aesthetic quality.

Iteration 4 Reflections

This iteration illustrated how difficult it is to use available software to create 4D Printed shoes. Inverse normals and non-manifold structures were created by the dimensional stability and comfort calculations of the grasshopper agent. With time restraints and no option for failure, each external line of the geometry was manually repaired, fig. 21. This allowed for insight on how the geometry behaved and interacted when algorithmically generating shoes.

Analysis of the case

There were specific difficulties negotiating design considerations in our Ultra Personalized 4D printed shoes. While the research product required all five design considerations to function together, this analysis focuses on the most challenging negotiations between iterations as seen in table 1.

Aesthetics vs Balance

In iteration 1 to 2, the width had to be increased by nearly 50%, fig 22. The increase ensured proper weight support but was dangerous territory in terms of aesthetics as a thick heel is often referred to as clunky. Adjusting the infill had dramatic effects on the heel dimensions. Software Tool recommendations include the understanding of the forces in play so that the geometries show impacts on the aesthetics. Using Cinema 4D gave the designers a sense of the movement, but not the impact of weight.

Balance vs. Comfort

In iteration 2 to 3 we struggled with software to be able to dynamically create infill based upon the balance, weight and pressure information. While this is supported in Slic3r with variable density infill it was not possible due to the complexity of the generative geometry. We already find the idea of variable infill in the sole of a common sneaker (see Fig. 6) in the heel region versus the talon region. We can see an example of the shoe infill under pressure in Fig 7. This controls the hardness and softness of the final material. Adding control over density of infill in software tools would allow the negotiation of comfort and weight support. Beyond this, the integration of simulation data for dynamic density in infill would help this negotiation.

Robustness vs. Comfort

The side walls need to flex enough to let the foot enter and move of the foot movement. We see this addressed from iteration 2 to 3. Flexibility is desired in specific directions in shoes [3]. Software tool recommendations negotiating comfort and robustness are dynamic infill gradients, intelligent infill generation. Intelligent infill creation will also allow for an even lighter shoe that provides the precise amount of robustness while maintaining comfort. This is also closely related to balance vs comfort.

Temperature vs. Balance

In iterations 2 to 4 the difficulty was keeping the shoe stable while not overheating. A solution is to create walls strong enough to hold the shoe together while allowing airflow in the walls. The designers manually underextruded the material around the footbed to encourage air to move with the bounce in every step. The designers imagined textiles that allow airflow. Tool recommendations are to allow designers to define the printed surface quality of each wall. This effect happens in 3D printing but is commonly considered a defect.

Aesthetics vs Temperture

In iteration 3 and 4 the underextrusion under the footbed to increase thermodynamic behavior had impacts on the external aesthetics, Fig 23. Negotiations between aesthetic quality and temperature results in less thermodynamic performance to keep the aesthetic. Beyond the tool recommendations of the previous category a recommendation of a filament flow sensor that can specifically regulate the amount of material being deposited and communicate it back to the design software is highly recommended.

Discussion

There are many insights to discuss from our case study. Here we briefly discuss the role of data, design tools and craft.

There is a need for programmers and engineers to explore

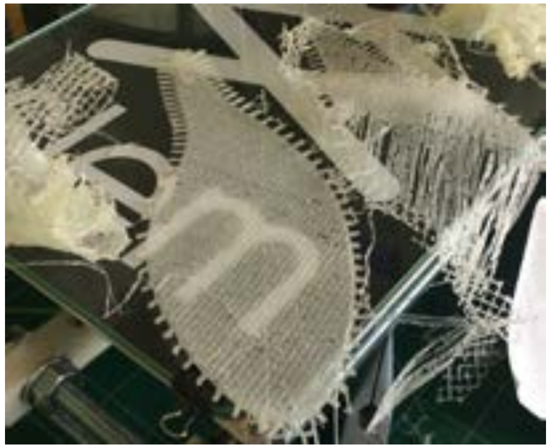

Figure 23 Underextrusion tests

Figure 24 Printing Shoes

Figure 25 All four shoe iterations

and understand how to gather data and create machine code. The complexity of ultra personalization also shows the need for a system to gather information about the user to create better design considerations. Iterative computation might be used to analyze a shoe at the end of its use. The material data from the used shoe could inform the creation of the next shoe. Beyond material, active monitoring would allow the ultra personalization to become even more refined. Future shoe design or any related digital craftsmanship will require team members who are good at data analysis and their parametric translation into systems of personalization.

The complexity of parametric and data design considerations makes us ask if a system of agent [15] based negotiations would be beneficial. While this research and we argue future craftsmanship will require multi-disciplinary team efforts to arrive at ultra personalization, we foresee a future where the software increasingly support designers programs via parametric models that adapts to user data, similar to innovations in architecture and some industrial design.

There is a great opportunity for tools that understand the purpose of the object to be 4D printed, fig 21. Dynamic density infill, surface quality control, fast integration of generative algorithms and basic simulation are only the beginning of what ultra-personalized 4D printed craft may become.

However, we also learned it's important to not lose sight of the human craftsmanship that got us to this point. In tailoring, the best tailors look beyond a single moment of measuring. They look at the movement, posture, and social needs when making a bespoke garment. In this there is a type of craft the tailor practices that is important. Looking at Ultra Personalized shoes from a craft perspective might allow us to inform and better leverage the new design tools.

Conclusion

We see this hybrid craft [4] emerging in the interaction between the multiple designers in our project and the four negotiated material geometry and infill characteristics. When printed, the designers brought forth an Ultra Personalized shoe that the client said "my shoe is very special". This case study reflects on the iterative process supporting these negotiations and hope that it will help the creation of software and understanding of design practice that supports Ultra Personalized 4D shoe making and related digital crafts.

Acknowledgements

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4.2 Critical Reflection

This project took a ridiculous number of hours to complete. This project used digital lasting to develop a personalized shoe using off-the-shelf technologies, while a research product was realized, it took a massive undertaking of effort. The project failed to bring dynamic movement data into the process and the structure of the shoe. This shoe was a very effective exemplar being featured in the media, yet there is no business model that could scale this process up.

Limitations of the work

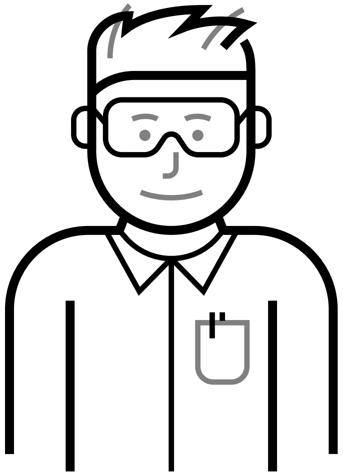
The shoe uses off-the-shelf technology and does not contain variable infill. The complexity of the generated geometries made using many off the shelf slicers impossible The project only used the form of the foot and a general estimation of the weight of the user. Data about the moving foot was difficult to integrate and in the end only two foot positions were considered. The shoe was also only worn for a single day.

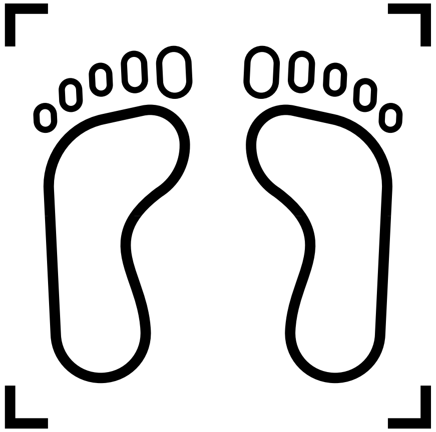
How is this different from a traditional bespoke shoe?

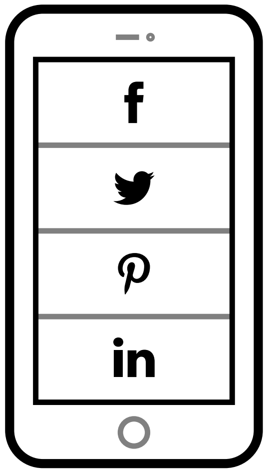
The design considerations of a shoe are typically confronted using materials such as steel, various leathers, and PU in bespoke shoes. This shoe only uses the single material Filaflex. This shoe is more recyclable as it can be reprinted from its own material.

Impact

This project was replicated with a master's student in 2018 using new shape-change material understanding. Results were presented at the Symposium on Computational Fabrication 2019. The paper has been cited as an example of programmed behavior and as a form of digital fabrication.







A Shoemaking Toolkit

Published as "ONEDAY Shoes: A Maker Toolkit to Understand the Role of Co-Manufacturing in Personalization" (Nachtigall et al. 2019) and presented at the ACM Conference on Tangible, Embedded and Embodied Interactions (TEI) 2019.

The ONEDAY shoe kit was designed to be easy to modify into several styles of sneakers, inspired by "Design after design" (Redström 2008). Three versions of the kit were offered, containing differing supplies and tools. While those who supported said they were going to personalize the most, it was actually those who supported the deluxe kit who personalized. The kit demonstrated the potential for bespoke manufacturing. The base form, behavior, and aesthetic of the shoe were defined, yet nearly everyone took the opportunity to personalize the aesthetic or fit of the shoe. Personalizing how the shoe behaved while in movement was more complicated than expected. Many interviewees reported that if they were to make the shoe again, they would concentrate more on physical fit and behavior of the shoe and less on the aesthetics. It is interesting to compare this to mass manufacturing, where any personalization (or deviation from the prescribed design) is considered a defect. The ONEDAY shoe kit enabled a craftsmanship that allowed for personalization, like the gothic church craftsman described in The Sympathy of Things (Spuybroek 2016, 3). **The toolkit allowed users to not only make, but personalize.**

5

ONEDAY

5.1 A Shoemaking Toolkit

Role

ONEDAY was instrumental in showing that users would use a toolkit to personalize shoes by making them themselves. ONEDAY opened the research up to a larger community of designers, makers, and design researchers.

Research Question

Will a wearer personalize their shoe if they make the shoe themselves?

Research Conclusion

People will co-manufacture and personalize while doing as much, depending upon the quality of the tools and materials.

Quality of the output

The quality varied, depending upon the skill, craftsmanship and material choices of the maker.

Favorable outcomes

What worked in this project was many people from all over made and wore their own shoes. Many demonstrated personalization, especially in the fit of the aesthetic qualities.

Difficulties and Unfavorable Outcomes

What didn't work as well as hoped was the degree of digital fabrication. While patterns were provided in a format for laser cutting, many people did not find them and were frustrated by this. It is clear that more examples of digital fabrication were needed on the site and in the material.

ONEDAY Shœs:

A Maker Toolkit to Understand the Role of Co-Manufacturing in Personalization

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Figure 1. The ONEDAY Toolkit being used to make a pair of personalized shoes.

ABSTRACT

Personalization is of increasing importance to designers, researchers, shoemakers and manufacturers as mass customization progresses towards ultra-personalized product service systems. Many attempts have been made to design co-creation platforms that allow end users to personalize their own shoes, concentrating mostly on color preference. This research takes a different approach by designing a toolkit for maker-oriented users to co-manufacture their own shoes. The toolkit was deployed worldwide to different users via crowdsharing. Backers (n=237) were surveyed before deployment and thirty users were interviewed after two years to understand personalization over a full cycle of making and use with the crafted research product. We found that users who have higher quality tools and materials in their toolkits are more likely to personalize their shoes while co-manufacturing. The research provides insights for researchers and designers creating toolkits for designing personalization product service systems/ configurators and engaging in tangible bespoke processes.

CSS Concepts

Human-centered computing - Interaction design theory, concepts and paradigms

Author Keywords

Personalization; Bespoke Shoemaking; Co-Manufacturing; Research Product; Crowdfunding; Toolkit

INTRODUCTION

Co-Manufacturing is becoming increasingly important as Designers, makers, programmers and others develop digital fabrication tools in their local communities [19,45]. This combined with changes in fashion i.e. Instagram takes over the role traditionally played by fashion magazines [40], we see users looking for more personalization At the same time, customization and personalization of shoes is important to large shoe manufacturing and is increasing in importance with 3D printing and other digital fabrication technologies. HCI research is currently interested in shoes as seen in the Smart Soccer Shoes [51], and Shoe the way[38]. HCI is also historically interested in shoes as in the Roulette calculator shoe at MIT described by Steve Mann [26]. Yet these papers focus on the sensitizing and tactile feedback in shoes. We wanted to see how personalization would occur and be perceived over the life of a shoe and designed a toolkit, fig. 1, that could be easily made in a single day.

Technological acceptance in shoes is often limited to materials and sometimes electronics for sports performance. However, the technology used in making shoes is also interesting. To investigate the shoemaking process we turned to bespoke shoemaking as a handmade alternative to the mass-produced /mass-customized systems already offered [9,16]. Our aim was to bring a bespoke shoemaking experience to the user and understand the experience of "design after design". Previous work [8,21,30] shows design practice is interested in the connection between making and personalization. There is also current research into design methods of personalization [22]. Research has shown that user personalization can improve fit [23] but how does the quality of a self-assembled product lead to personalization? Personalization is important to the TEI and HCI community [6,7,11,12,35,41,50] especially in hybrid crafting [15,28] because it creates a better fit aesthetically, physically, and in terms of performance [30]. Hybrid craft is important to shoemakers as we see 3D printers, CNC mills and other digital fabrication technologies entering the studio.

We also see new companies such as JS Shoe, Feetz and Phits already working with digital fabrication to hybrid craft personalized shoes [5,39]. Personalization is challenging, especially for mass production of goods [2,17]. Large shoe companies such as Nike and Adidas struggle with co-creation customization platforms [33], yet are still moving their production into the realm of Ultra Personalized 3D printed (digitally fabricated) shoes [53].

Bespoke and tailored attire is important to technology and society[1]. The bespoke shoemaking process is a material driven, hands-on experience which is commonly held as the highest form of personalization. It is found in shoes in the shape, color, material, material behavior and last (foot forms) [3] as is illustrated in fig. 2. Recent design research [30] has attempted to translate bespoke shoemaking into a 3D printed process and outlines the difficulties negotiating design characteristics of bespoke shoemaking into 3D printing. Materials are important to bespoke processes and so there is great interest in materials and hybrid materials in related TEI and HCI literature [8,13,36].

Our toolkit was designed to help understand the challenges and possibilities of personalization in co-manufacturing as part of our research into Ultra-Personalized product service systems. Toolkits have been shown as an effective method for “enabling replication and creative exploration” [24]. The shoe was designed with a simple, classic style that is easily personalized for aesthetics and comfort. Once the shoe was designed, we designed the toolkit in three levels; Basic, Full and Deluxe. Each level of the toolkit included more tools and better materials to better study how the availability of tools and materials affected personalization in co-manufacturing. We supported the toolkit with online websites and videos to assist in the making and to show the possibilities of personalization. To keep possibilities open, we avoided specific words like “personalize” and “customize” as we looked for their presence to emerge from the co- manufacturing process Moreover, we were transparent about the design process of creating the shoe and the toolkit so others could engage in similar research and practice.

By means of the toolkit, we gathered information about what degree of personalization would emerge in a co- manufacturing process. We surveyed the makers about their intentions for the kit before deploying it, and then interviewed 30 of the backers two years later. Our analysis is based upon the kit level chosen and the extent to which the makers personalized their shoes. Co-creation schema often tend to see co-manufacturing and co-production as valuable with respect to a “tangible consumer input” [34]. We found that those who ordered the deluxe toolkit, and reported no intention to customize their shoes were the most likely to personalize. Whereas, those who intended to personalize their shoes and ordered the basic kit, were less likely to personalize. In the end, personalization was a result of the availability of resources; tools and materials, that could be said to “drive” the maker towards personalized craftsmanship.

Towards Ultra-Personalized Product Service Systems

Co-creation design frameworks such as [17,37] place the personalization in the domain of co-design. Co- manufacturing is seen as “tangible consumer input” [34]. Bespoke shoe personalization brings the user into a craftsman role where personalization is highly possible. As an alternative to Co-creation, we use a theoretical Ultra Personalized Product Service (UPPS) system [43] approach that iteratively creates through the stages of Co-analysis, Co- design, Co-manufacturing and Co-use. In each phase, stakeholders play different roles which can serve the personalization of the Product, Service or System. Co- Manufacturing includes the distributed assembly by several different people, where mass production demands uniformity in the final product, co-production leaves the final product up to the user. Thus, co-manufacturing can be seen as a sort of bespoke practice which can result in personalization. Co- manufacturing is not new and has its roots in assembly practices that are widely applied in the maker community.

Makers

This research targeted makers, but specific toolkit design decisions were made to ensure that the toolkit appealed to a range of users to see if and how they personalize. The maker community has a history of personal fabrication that is relevant to the type of personalization manufacturing we are interested in [4,10,27,31,42,44,48]. Makers have experience in assembling, co-manufacturing and personalization [6]. Makers have a large number of digital and manual fabrication tools / skills available that allow for personalization[19]. Moreover, there is a maker vision of the future, Fab City [49]; a city that makes everything it needs; food, transportation and manufactured goods such as shoes. Idealy, only data enters and exits. Our shoe toolkit was created inside this ethos.

Research Products

Maker-oriented users expected a kit that would produce a full shoe. The aim of the toolkit was to produce a shoe Research Product. Research Products hold four interdependent qualities; inquiry-driven, finish, fit, and independence [32]. As part of the research we wanted the user to live with the shoe. This required that the shoe toolkit and the resulting shoe must fit the foot and the style of the user in order to integrate into their everyday life. Shoes are also an artifact that is situated deeply in a user’s everyday life [46] providing a vehicle for researching “conceptually rich artifacts” [18]. Shoe use is typically not a fast user experience, but rather a form of daily slow interaction [20]. It was important to the research that the toolkit created a final product that would help the user participate with the object, reflect upon their decisions, consider personalization, and give them agency over it. As we see in other recent research with Research Products [14,47], it was important to give the user time to make and wear the shoe.

DESIGNING THE ONEDAY SHOE

We started with a series of design goals for the shoe:

1. The toolkit must create a shoe research product that the user could wear as a normal shoe over the expected lifetime of a shoe (18 months).

2. The toolkit needed to allow and encourage personalization while not making it mandatory.

3. The toolkit needed to engage the user in co-production rapidly (we adopted an eight-hour time limit).

4. The toolkit needed to be affordable for makers.

The resulting ONEDAY sneaker was designed to be simple,

Figure 2. Bespoke shoemaker Mario Bemer personalizing form, style, materials, color and material behavior at this workshop in Florence, Italy.

modifiable and manufacturable in a single day. Bespoke shoes are a labor-intensive process and are sewn by hand [3]. The process can easily require sixty hours of labor to manufacture. With the limitation of eight hours to assemble the kit and keeping the kit economical, a few compromises had to be made. We chose sneakers because they do not require complex industrial machinery to realize and while full bespoke shoes would require great amounts of time and skill, sneakers are easily made and commonly worn worldwide across ages and styles. Moreover, The part of the shoe that requires the most time and cost is the sole. A commercial sole was needed to reduce the time/costs of the last and sole processes. As a result, more attention was not only put into the selection of the materials; the leather, insoles and waxed yarn, but also to the tools. We detailed the design of the kit as it was cut, sewn, punched and crafted by hand.. A shoe designer helped us create the shoe. The shoe designer remained a partner in the project and eventually took over the project entirely, creating more toolkits.

The Soles

In early 2015, the sneaker was finding a high place in fashion. Designers like Hugo Boss were creating high fashion sneakers like those found in the Futmid collection. We picked a cup sole that looked identical to the sole used by Hugo Boss from sole manufacturer *Procalcado*. The soles were injection molded in a coated SBR rubber 85A shore made to last for 18 months. The soles have a minimal internal cup structure that supports the foot and allows for the addition of insoles. The soles are made to be sewn by a sewing machine but we developed a hand hole punch as a Bespoke process calls for hand sewing,. The soles were made available in black or white.

The Base Styles

Given the design constraint of working with a cup sole, we started with a classic sneaker shape. We designed a simple sneaker reminiscent of the original sneakers of the 1900’s, which many people today would recognize as a Converse sneaker. We generated four different base styles that while similar in construction, have their own signature style as depicted in figure 3. The styles range from an Ultra High Top over the ankle model to an Ultra-Low Top summer style. We designed a style template that can be seen in frame one of fig.1.

The Cutting Patterns

Developing the cutting patterns was the most difficult process. It was vital that the cutting patterns fit perfectly as the shoes would be manufactured without a last. The last is too bulky to ship and would have made the kits prohibitively expensive. Several prototype patterns were made using common paper tape on a last chosen to fit the cup sole. Five iterations were required to create a cutting pattern that would look good in the four different base styles pictured in figure 3. The holes that attach the uppers to the cup sole are difficult as two-dimensional pieces are shaped into a curved three- dimensional sole. Also, note that the holes in the nose of the toe tend to move to center as they progress to the right, fig 3. This is done to shape the nose of the shoe for the toe box. The patterns were provided in many formats including illustrator and PDF file for digital fabrication.

Pilot workshops

Ensuring that the cutting pattern worked with a range of different kinds of users was difficult. Three workshops at the SLEM shoe innovation academy with users ranging from accountants to professional shoemakers, allowed the tuning of the shoe kit.. Many problems were discovered, especially in the hole alignment between the upper and the sole. The patterns were revised three times. The included video still shows the original hole guide measuring system. In our final workshop, students made the shoe twice to see how far they could personalize with the kit to check for problems.

Figure 3. Multiple shoe styles from the same cutting pattern.

Figure 4. Using the base shoe patterns to realize a personalized style of shoes.

Additional Styles

During the pilot workshops, we worked with students to create several different styles of shoe using only the base patterns shown in figure 3. We modified the Adobe Illustrator and .svg files so that the user could easily modify. Figure 4 is an example of how the base patterns can be used to create a completely different style of shoe that one of the students made in a pilot workshop. It was critical to the cutting pattern we had designed that the holes on the sole remained the same, eliminating risk of confusion by the maker when making their own shoe.

From Shoe to Toolkit

Creating a shoe as a kit available from our website may seem difficult, but dealing with the complexity of the research was even harder. We report on our process here to help others looking to make similar toolkits. The toolkit was converted into three levels to explore levels of personalization by varying the materials, material qualities and tools. In this section we describe crowdfunding the kit, designing separate versions of the kit, creating the instructions, and logistics. We offered the toolkit in options ranging from 30€ to 100€. These prices were close to the cost of the quantity and quality of materials included. The kit was named ONEDAY to encourage users that they could finish the project in a day and the tag line "Make your own sneakers" was added to stress the co-manufacturing and attract makers.

The kits

In order to understand how much personalization resulted from bespoke materials, tools and material quality, the three levels of the toolkit with increasing tools and qualities were offered to be made with the user in the co-manufacturing process.

1. The Basic kit contained shoe soles, wax thread, special bespoke needle and instructions. The user has a selection of black or white soles. Backers were instructed to find a soft material 2-3mm thick and provide their own hole punch.

2. The Full kit added leather, a hole punch, shoe laces EVA insoles. (Fig 5) and a selection of black or white soles and Black, Chocolate, Nude or off- white leather.

3. The Deluxe kit included cork foot beds and Vegetable Tanned Leather for uppers and shoelaces. A selection of black or white soles and Sienna or Nude color vegetable tanned leather

In our pilot workshops we saw that some users needed only the bare minimum of tools and materials to start while others needed everything placed in the kit. Instructions were made available online, as a print out in the kit and made available through a series of online videos. The instructions were created to make the process seem simple, yet show the makers where to pay special attention. For example, the places where the leather overlaps near the toes and needs to be shaved (scythed) down to prevent a bump that rubs against the foot causing discomfort.

Licensing

The toolkit was previewed at Maker Faire Rome. Many makers, especially those who are more entrepreneurial, were worried about the licensing, i.e. who owned the design of the shoes. We knew from the pilot workshops that the shoe maker feels special ownership over their personalization of the shoe. After reflecting on this fact, we elected to use a creative commons 4.0 open culture license allowing anyone to take the design and make a commercial product with the shoe design and patterns. This ensured maximum creativity and encouraged personalization.

Figure 5. Photos including tools, materials and inspiring end results.

Logistics and Shipping

After a successful Kickstarter campaign, we shipped kits to 237 backers on 6 continents. The kit was designed to fit in an A4 book box that could be easily delivered. Two colors of soles in eleven sizes with three kit options including six, four (Full) and two (Deluxe) leather offerings created complexity. The project had 132 separate configurations for the 237 kits. It would seem that shoes and complexity are made for each other. We wrote a script to generate shipping labels with codes for all the options allowing us to easily package and shipped the vast majority of the kits on December 17th 2015.

Delivery of the Patterns

Patterns were delivered via a Github repository. Just before shipping a significant issue emerged with the patterns. A workshop participant made a second pair and told us that the patterns were too small. After a few stressful weeks of trying to discover what was wrong with the patterns we realized that it was the printer. Many home/offices printers print at 96% scale to avoid cutting off content in the margins. We added square boxes in specific sizes to the paper, instructing makers to measure these boxes, but this remains one of the biggest difficulties as not all makers read and measure.

How the kits allow for personalization

The ONEDAY kit was designed to allow for personalization by allowing several opportunities to modify the shoes form, material, fit and aesthetic. It targeted makers and asked the user to reflect upon the object in use. Examples can be seen in Fig 6,7, & 8. Sole sizes ranging from a 35eu to a 47eu were offered.. The designed instructions included 4 versions of the sneaker, the ultra-high top, the High Top, the low Top and the ultra-low top, illustrated in figure 3. Particular attention was paid to the development of the pattern to create patterns that could be easily modified into many different kinds of sneakers, i.e. fig 3. Many materials such as vinyl and denim were also tested. The patterns were modified to allow the user to find their own soft material 2-3mm in thickness for the Basic kit. We encouraged the upcycling of older fashion products. The Full and Deluxe kit included leather in four colors and two qualities.

Inspiring images were added to Kickstarter and the Oneday website [29] with illustrations showing how to modify the pattern, such as fig 5, along with laser cut files examples of laser etched leather. Also the terms personalization and customization were specifically avoided throughout the project. The expectation was that the makers would make and wear the shoes for 18 months with most personalizing the shoe in some way.

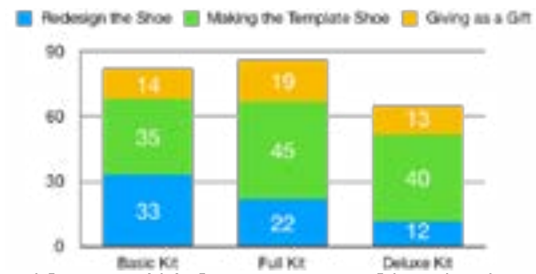

Table 1 Initial survey results about intended use of the kit based upon which kit was selected.

FINDINGS

Beyond the description of how the kit was designed, we surveyed Kickstarter backers on how they intended to use the kit as part of the backer survey. Two years from the December 2015 ship date backers were sent a request for interview. 30 backers were interviewed about their kit use and if/how they personalized their shoe. Backers who gave the kit as a gift were excluded.

Initial Survey and analysis

After the completion of the Kickstarter, a survey was sent to the backers. We asked about the sole / leather color and how the user intended to use the kit. Kickstarter has strict rules about marketing/demographic questions which severely limited our inquires. In the survey we asked whether the kit was intended to "make the template shoe", "redesign the shoe" or "give the shoe as a gift", see table 1. 35% of the makers chose the Basic kit, 37% chose the Full kit and 28% chose the Deluxe kit. Roughly 20% wanted to give the kit as a gift; less in the Basic kit 17% and more in the Full kit 22%. More interesting was the choice between making the template shoe and redesigning the shoe. 40% of the Basic kit chose to redesign the shoe. This is far less in the Full kit, 26% and even less in the Deluxe kit 18%. Making the template shoe is the opposite with 42% of Basic, 52% of Full and 62% of Deluxe. The backers first name and shipping country was fed into a GDPR compliant gender api [52]. 99 Backers were identified as Male (49%) and 70 as Female (35%) with a minimum of 80% accuracy, 16% were indeterminable.

The different kit levels roughly spread evenly over the backers providing adequate groups of all the types of kits. The survey indicated that people who backed the Basic kit intended to personalize the shoe by redesign much more than the Full or Deluxe kit backers. The kits appeared spread reasonably over males and females 15% more identified as male, although 16% are not identified as a binary gender.

Interviews and analysis

Thirty of the backers who did not give the kit as a gift responded to our request for interview, all 237 backers were asked to interview multiple times. 17 respondents were male, 13 were female. 14 backed the Basic (B) kit, 8 the Full (F) kit and 8 the Deluxe (D) kit. The interview questions centered on why the maker wanted to make the shoes, if the maker had made the shoes, how the experience went, how they personalized the shoes, and how they would do it again. The interview questions were developed to evidence the state of the shoes and express if/how the user personalized. In the following sections quotes that exemplified the respondents in the Basic, Full and Deluxe kit groups are presented along with interesting exceptions. Respondents are classified by number and kit i.e. B1 is

Figure 6 Photos of the Basic kit shoes by mrlaurenss, swkang94, and 1womaninspace on Instagram

the first person in the Basic kit interviewees. A series of images from Instagram by the users of the kit reflect the responses to the survey as seen in Basic in fig. 6, Full in fig. 7, and Deluxe in fig. 8. A reflection on what each question means is added to summarize the analysis from the data.

Why did you support the ONEDAY kit?

All three groups had similar answers to this question, providing clear motivations behind the purchase. B7 said "I work in wearable tech and have done a couple of shoemaking classes. Hacking shoes is hard. I thought this would give me a neat way to incorporate some electronics into sneakers.". F2 said "I wanted to learn how a shoe is made and possibly make some shoes of my own. This was the easiest way in, although admittedly not the most representative way on how artisanal (or handmade) shoes are made.". This was also summarized well by D5 "I was interested in the process of shoe making.".

Interest in shoemaking, gaining new knowledge and integrating with their professional practice drove makers to engage with the toolkit. This shows that we reached our target audience and many different kinds of makers.

Where are your ONEDAY's now?

We wanted to understand if and how each of the makers made the shoes. Half (7) of the Basic kit makers admitted to not having made the kit; such as B11 "still incomplete in a box, but I want to do it!" or B8 "In the drawer, waiting for me to make them, I'm feeling ashamed...". The other half did make and wear the shoe exemplified by B1 "My Oneday's are with my other shoes". The Full kit respondents seem to be represented by F3 who said "My Oneday's are in active use!" Although F6 admitted that "My ONEDAY's are in the trash. I loved creating them but they never really fit my foot and were uncomfortable to wear after a while." The Deluxe kit makers seemed to have the best experience, this was expressed well by D4 "My ONEDAY's are in my closet for me, (I can wear them to work) and my daughters' are on her feet right now.".

The summary analysis is the Basic group still has a strong desire to make and, as shown in the following questions, personalize their toolkit, but many had yet to start. Most Full kit makers succeeded in making and were still using the shoe, although one respondent expressed the need for more fit personalization (which they apparently did not do). The Nearly all the deluxe kit users made their shoes and had them still in active use. Also, the materials were holding up better than expected in the shoe kit design.

How did you personalize your ONEDAY's?

With this question we wanted to see how users engaged with personalization. The Full kit users were divided as shown by F3 saying "I inserted some padding inside to make them more comfortable." and others like F2 saying "I was happy with the kit as is -no personalization.". The Deluxe kit engaged with personalization in terms of material and color exemplified by D5 who said "I added worn, black leather from army surplus gaiters to the brown that I had selected from you.". Half of the Basic group had not yet made the kit but had ideas B12 "I will personalize them by using a vegan material and a fitting color", the half who did mostly made the shoe outside a few who engaged in some personalization such as B3 "I made my own design, only used the outline of the included design.".

Personalization of color, material, form and style is seen in all three groups with the Deluxe group showing the most personalization as a group , the Full group being around half and a small number personalizing in the Basic group. The basic group spoke of how they would personalize on a conceptual level, but after two years had not engaged in the process. This shows that in co-creation platforms and UPPS, personalization can be found in co-manufacturing, and more important, designers can encourage personalization in co- manufacturing by designing space for it to happen. Additionally, personalization occurs more often when the user is presented with high quality tools and materials.

Would you make it again?

We asked if they would make the kit again in order to learn about the overall experience. Many Basic kit makers expressed disappointment yet hopeful resignation, B6 "I kind of want to but I feel a little bitter about the last one lol. The kit needs to have a bare minimum of more stuff." This frustration of not being able to complete the kit was seen often in the makers of the Basic kit. One of the ones who did complete it said B1"I would, but not now as they are still in good shape". Many of the Full kit makers expressed a desire for better materials "I would like to have thinner

Figure 7 Photos of the Full kit shoes by discopenut, judithsterkenberg and jonnyjwhite on Instagram

more durable soles. Mine are broken from wear already" F4. The sentiment was shared by the Deluxe group. D2 "I might get another pair if the sole is black and the thread is black. Both of those components got dirty easily." Others seemed to have mastered the kit saying D3 "I would rather learn how to make a leather shoe probably using a last (assuming it is possible without using specialized machinery). Perhaps starting from something simple like a "Clark" and building up to a proper looking smart shoe." This is supported by D7 who said "Yes. Now that I know how to make them, I would go and start to do something more personalized."

This question shows personalization is more prevalent when there are fine materials and tools involved. An interesting outlier in the results is user F1, who was the only Full kit user who didn't make the kit, said F1"I didn't make them, but use the tools a lot!". It also shows makers of all kinds respond well to co-manufacturing, but personalize more when presented with higher quality materials. The quality of the toolkit affects the choice to personalize a shoe despite what the user intends to do with the kit. The level of skill and craftsmanship of the user affects the likelihood of the user to personalize in co-manufacturing. Finally, in order to engage a user in personalization of the fit of the shoe, multiple iterations are required.

What kit would you recommend to someone else?

In order to know about the ideal kit, we asked the users what kit they would recommend to someone else with a series of choices:

1. Just the Soles.

2. Soles, Leather, Insoles, Shoelaces

3. Soles, Leather, Insoles, Shoelaces and tools

4. Soles, Leather, Insoles, Shoelaces and tools with precut leather

5. Fully constructed ONEDAY's

The largest response for Basic, Full and Deluxe interviewees was category 3. Soles, Leather, Insoles, Shoelaces and tools. The Basic kit users had results in all five categories. The Full kit had a one person who responded "just the soles" or "A Fully constructed ONEDAY". The Deluxe kit had one user category 1 and other who wanted category 4 . When asked for comments, the Basic kit is represented by B5 "I just like the idea, the plan: I still think it's really great and good for the environment because of little material displacement.". B7 said "More digital files that could easily be sent to laser cutters would be really rad for this project." The Deluxe group, at the other end of a spectrum, are represented by half who wanted more style patterns D3 "Create additional styles! That would be fun!" and the other half who wanted a complete accessory set D5 "I would like a similar set for leather bags and a leather belt". The Full kit level is summarized well by F4 "For someone who wants to have special shoes yet lack of the creativity, it would be nice to show more creative examples for people to follow step by step and give instructions about shoe maintenance."

The responses strongly indicate that the involved makers want a kit that has all the tools and materials, but that they want to do the bespoke processes of cutting, punching and sewing. Almost everyone who made the shoes wanted more personalization and options for themselves and others. A few users expressed the desire to engage in hybrid craftsmanship with digital files for the laser cutter. While we did offer these, it is obvious that they were not prevalent enough in the project (this sentiment was share by three of the interviewed makers) and shows an interest in hybrid craft.

CONCLUSIONS

There is a difference in personalizing while designing (co-design), or personalizing when making (co-manufacturing). Personalization is important to the social and psychological needs of users, as seen in the interviews and Instagram photos. HCI and TEI have long investigated the integration of technology as part of a product (prototype, demonstrator, artifact...). In Oneday, the technology is in the system and service needed to create a shoe. What results is a hybrid craft experience that opens up large opportunities for the user to personalize. We show that the public is willing to engage in a co-manufacturing of a project designed with technology.

There is an opportunity for designers, researchers, shoemakers, engineers, programmers computer scientists and others to explore the technology of designing and making a thing. The "computation" of HCI can occur in the process or service instead of in the artifact. We see

Figure 8 Photos of the Deluxe kit shoe by dreisbuyck, david.filar. and e_mcavoy on Instagram

opportunities for that computing to occur over the lifetime of an artifact in the form of use (wear & tear) and user experience in the Oneday systemic and service aspects

Co-manufacturing can result in more personalization than co-design. In the explored Oneday case, the expectation was users who co-design the project with their own materials, tools and ideas would result in greater personalization. This was confirmed in the initial survey. The users who backed the basic kit reported intent to redesign the shoe. Then on a scale up to the Deluxe kit, backers reported they intended to make the template shoe. The Basic toolkit was more open and required co-design. The openness and endless possibilities of the basic kit results in many concepts but inhibits users from developing past the concept into a making phase. The Premium toolkit was a more closed system that required only co-manufacturing. Users respond well to co-manufacturing, but also personalized more when provided higher quality materials and tools at a higher cost. The cost of the kit may have motivated the users to complete making the kit. This was counter to our expectation and survey result that a lower cost and openness of the basic kit would result in more people personalizing with the shoe kit.

Users are more likely to personalize and use a research product when engaging in a hybrid crafting process for co-manufacturing when fine materials and tools are provided.

Designing a toolkit to fulfill the specific needs of co- manufacturing to understand personalization is challenging. Designing for co-manufacturing requires a common archetype that can be personalized not only to the individual but to a city, neighborhood and/or time period. Personalization via co-manufacturing works well with simple and classic design. Additionally, the two year process and research product approach were key to this research. Only by waiting did it become apparent that the initial intention to personalize is often not always completed with action. Research Products changed our idea of the user into a co-use situation, the traditional user is using the shoe, the design researcher is using the data from the shoe and the social/psychological experience with the shoe in design, making and use. It was important to recognize this co-use.

LIMITATIONS AND FUTURE WORK

This work only looks at sneakers as the time limitation of eight hours made other shoe styles difficult. There is an opportunity to explore other shoe styles such as high heels, dress, and sport shoes with longer time limits. The limitations on Kickstarter surveys were heavier than expected and more investigation into the skills of the users and motivations in action might revel even deeper motivations. Also, backers previous experiences with Kickstarter might have influence on their decision process which we could not look at. Many users expressed that they would personalize more a second time using the kit.

We see the kit being used in other interesting ways. For example, shoe designer Rueben Lekkerkerker launched a sustainable shoe collection Ruit [25] with the kit and a homeless shelter continues to use the kit to develop self worth. The toolkit appears to have social impact in ways we had not considered. We invite other researcher to use the toolkit and help explore personalization.

ACKNOWLEDGMENTS

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5.2 Critical Reflection

The research to capture the skill levels of the participants and would most certainly capture that next time. I would try to engage more people in the two years after interviews. This research was performed before the GDPR regulations were created. I would be much clearer about what I was researching next time. This project only looked at a single kind of shoes, the sneaker, in a format that was very popular at that time.

Limitations of the work

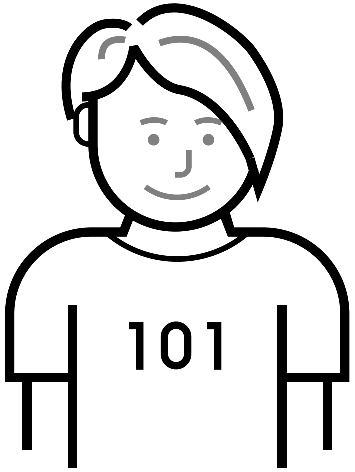
This project represents only sneakers which still use a standard shoe size. Examples of platforms and boots were seen in the project, they were rare and not the intent. Using the mass-manufactured sole limited the fit of the form and behavior of the sole. Many users expressed that they would like more control over the fabrication of the sole.

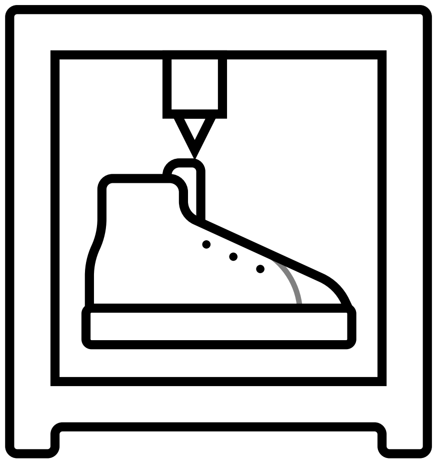
How is this different from a traditional bespoke shoe?

In bespoke shoemaking, the sole is constructed to the foot of the user. Typically, materials with greater durability and beauty are used to make the sole.

Impact

Multiple shoe kits have used the open-source nature of the kit to make their own toolkits. Two brands have been launched using day and a homeless shelters has been using the toolkit as a way to build personal self value. Additionally, the toolkit has cited and used in a paper at ISWC 2019 Conference.





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A Multi Stakeholder Design Project for Product Service Systems

Published as "Encoding Materials and Data for Iterative Personalization" (Nachtigall et al. 2019) and presented at the ACM CHI Conference on Human Factors in Computing Systems 2019.

Closing the loop of the dataflow into a system that brought usage data back to be analyzed meant that a personalized shoe could generate data for future shoes. Mathematical structures in the physical material were used instead of the electronic sensing commonly found in wearable computers. A relationship between the data and material that went beyond the engineering standard of digital twinning and instead created a relationship between the data as a material (Dourish 2017) and physical material as data. The shoe was both physical material, but at the same time was data. The use of data in the craftsmanship, what in the paper we call "**hybrid craftsmanship**," is transdisciplinary. Craftsmanship and technology were both needed to understand the process. Wearing the shoe as a designer provided information about th physical material and data material simultaneously. Understanding the data material this way created a greater understanding than the sum of the parts. The paper presented twelve challenges and learnings gained while facing the challenges of designing the UPPSS Solemaker.

Solemaker

6.1 A Multi Stakeholder Design Project for Product Service Systems

Role

Solemaker was instrumental to the research in that it showed data a multistakeholder design project could use data as if it was a design material. Through a series of iterations a system of Design, Manufacturing, Use, and was crafted. The paper argues for systems of personalization that lead to iterative personalization over lifetimes of the research product.

Research Question

Can shoes be ultra-personalized with the wearer's data?

Research Conclusion

Data can be used to digitally craft a personalized shoe. The same 3D-printed structures can make data for more shoes.

Quality of the output

The resulting shoes started as quite basic pieces, then simple yet wearable., As the project developed the quality became a more stylized and bespoke.

Favorable outcomes

What worked in this project was that the design considerations developed in Project J were successfully negotiated using code to digitally fabricate personalized shoes. The fit of the form, interactive behavior and aesthetics were well addressed with code.

Difficulties and Unfavorable Outcomes

What didn't work in the Solemaker project was tracking the data. The data of each printed object was difficult to keep attached to the artifact. Timestamps and photos were taken, but the massive number of times where nothing was printed made connecting the two difficult

Encoding Materials and Data for Iterative Personalization

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Figure 1: Overview of four shoe design projects that together created a loop of iterative personalization. These shoes were digitally fabricated with parametric data and worn as everyday shoes. From left to right we see an example of each project. The shoes started as a generic sizes and progressed to personalized shoes that created data for subsequent shoes while in use.

ABSTRACT

Data is changing how we design consumer products. Shoe production is a prime example of this; foot size, footstep pressure and personal preferences can be used to design personalized shoes. Research done around metamaterials, programming materials and computational composites illustrate the possibilities of creating complex data & material relationships. These new relationships allow us to look at future products almost like software apps, becoming a kind of product service systems, where the focus is on its iterative personalized improvement over time. Can we create systems of such data driven objects that in turn allow us to design new objects that are informed by the data trail? In this paper we report on four RtD project iterations that explore this challenge and provide a set of insights on how to close this new iterative loop.

CCS CONCEPTS

• Human computer interaction (HCI);

KEYWORDS

Shoe Design; Personalization; Data & Material Relationship; Iterative Design; Programmable Materials

1 INTRODUCTION

The relationship of data and materials has long fascinated interaction design and HCI as seen in tangible bits [28]. More than a decade ago, computational composites [54] addressed making things with data. More recent research about the materiality of data by Dourish et al. [14] , personalization using data by Benford et. al. [6], and iterative design by researchers at Autodesk [40] opens up new design spaces. Additionally, Vallgårda et al [55] have shown the importance of time in design. Thinking about time and access to complex data allows to design the behavior of things thanks to advances in metamaterials [26], material programming [53], and data science.

Many makers, designers and design researchers have adopted these materials in a form of hybrid craft that enables new kinds of personalized objects. This can be seen in the work of Benford et al, [5] Devendorf and Ryokai [12], Efrat et al. [15] and Magrisso et al. [36]. At the same time, we have seen our understanding of design change in the form of research products [42], design with time [41] and data-enabled design [9]. We need to only look around to find objects creating data about our everyday life. Moreover, digital fabrication allows new opportunities for encoding data into materials. When placed in the context of iterative personalization, things rarely dreamed of outside bespoke tailoring or science fiction become possible. In order to deeply understand these new data and material relationships we chose shoes as our context of application and research through design as our research method.

There are three reasons why shoes are a good artifact to research iterative personalization: 1) human movement is rich with data [47], 2) there is a long history of bespoke shoe personalization [1, 21], and 3) most people go through many shoes in a year [56]. Additionally,many companies including Nike, Adidas, Feetz, Ecco, Under Armor, and United Nude are exploring data driven, digitally fabricated, personalized shoes. Their (and our) current challenge is to create a system where the shoes themselves create a data trail for the next pair of shoes. To tackle this challenge, we used a research through design method. We created our

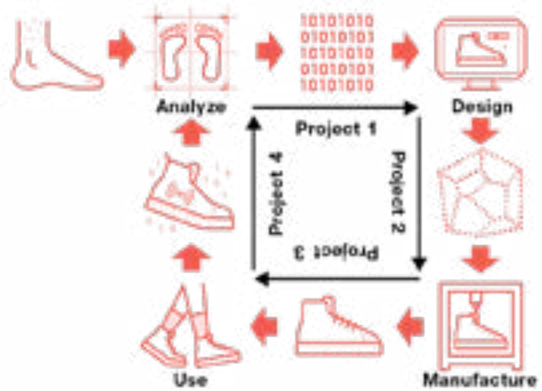

Figure 2: Adaptation of the Ultra Personalized Products and Services (UPPS) system model describing the loop of iterative personalization used for our shoe design projects.

own bespoke shoes by developing tools and techniques that explore data & material relationships in personalized shoe design. We used a theoretical model of Ultra Personalized Products and Services (UPPS) [49] to build on our understanding of iterative personalization. Four projects based on the phases of UPPS model, fig. 2, allowed us to complete a loop where shoes are not only personalized by parameters, but also generate data for the next pair of shoes (fig 1D). Focus was given to encoding materials (creating shoes for the form, movements and behavior of the foot) and encoding data (recording form and pressure over time) to generate increasingly personalized shoe iterations.

We clearly did not have the resources to invest in an entire shoemaking factory. Instead, we digitally fabricated a series of shoes using 3D printing, laser cutting, digital embroidery and hand construction. This hybrid craft [12] process was inspired by bespoke shoemaking (bespoke is considered one step above tailored, comparable to 'engineered to order'). Being fitted for a pair of bespoke shoes goes beyond the length and width of a foot. The artisan shoemaker looks at current shoes for traces of use. They observe how a person walks for signs of behavior. They feel the foot to understand the bones, ligaments and soft tissue of the foot. They converse about pain and lack of sensation. Detailed notes and past experience lead to tiny adjustments of the last (base form of the foot to create a personalized shoe) that adjusts the shoe to the movement and behavior of the wearer. Only then an artisan shoemaker crafts a shoe using a signature style.

This research unpacks the first-hand challenges and learnings we experienced in making the first full shoes. This research also shows the potential of ultra-personalized research products, and invites design researchers to join us in encoding materials and data for iterative personalization.

2 BACKGROUND & RELATED WORK

More than a decade has passed since Vallgårda and Redström [54] showed the possibility of computational composites, expanding on the work on "Computational Things" by Hallnäs and Redström [23]. Examples in the past decade such as hand knitting [45], hybrid craft [58], wearing screens [11], personal fabrication [3], and metamaterials [27] help to demonstrate the potential of crafting using hybrid data and material in design.

There is a significant interest in materials that can be digitally fabricated with specific behavior. The arrival of flexible materials in desktop 3D printing (such as TPE & TPU) has changed how we look at the infill (inside) structures of 3D printing as described in

"The Design Space of 3D Printable Interactivity" [2] or "Design and fabrication of materials with desired deformation behavior" [7]. Moreover, Ion et al. have shown the aesthetic properties of these materials in "Metamaterial Textures" [26], the possibility of behavior in "Metamaterial Mechanisms" [24] and computation in "Digital Mechanical Metamaterials" [27]. These materials geometries have even been used to make shape changing shoe treads [25].

Around the same time Dourish has shown data to be a material [14]. Researchers at Autodesk used data from EKG scans of a car driver to generate several iterations of a car chassis [40]. This form of iterative design created several objects from a single analysis session. This is not the only case, we see other examples of data being used as a material for design in data enabled baby bottles [8], personalized greeting cards [6] and facial makeup [30]. Engineering has approached data as a twinning process where the physical object and it's digital twin are mirrored [50]. In HCI many shoe projects have also shown ways to generate data from shoes:

"Energy scavenging with shoe-mounted piezoelectrics" [48] creates not only electricity but data about when it was created. "Shoe me the way" [46] show the shoe as a computer and output device. "The development of methods and procedures to determine the dynamic and functional properties of sports shoes" [56] describes how to record data from feet inside of shoes.

Our research built upon the possibilities of materials and data but is situated in the following work: "Being the Machine" [12]. Devendorf and Ryokai have shown the value of hybrid craft, and through their examples present a form of bespoke personalization between the maker and the machine. We used the idea of hybrid craft to join computational materials with data, resulting in the programming of an object's form, aesthetic and/or behavior like "Towards Ultra-Personalized 4D Printed shoes" [39]. "Research Prototypes to Research Products" [42] highlights the everyday experience of an object and how it can record data when constructed to have the qualities of an object in use. We created fully functional shoes that create data through actual use as a research product. Finally, an ultra-personalized products and services [51] point of view, helped us to open how HCI looks at the object, and also consider the services and systems associated with that object over a lifetime.

Figure 3: Timeline of the four projects and team members needed to complete a loop of iterative personalization.

3 RESEARCH METHODOLOGY

We engaged in this research from a Research through Design (RtD) perspective as a way of creating "conceptually rich artifacts" [20]. We emphasized the material and data relationships of our designs, especially how to encode data and materials. To share our understanding of 'encoding' we use a methodology inspired by "Tangible Products" [13] to describe the design process. The method illustrates the evolution between projects by describing each project's challenges and developed learnings that connect with the next project. First Person descriptions are important because they unravel the complexity of a design project and unlock the perceptions and understanding of the designer. Recent design research including "Living In A Prototype" [10], "Productive Frictions" [57], and "Can I Wear This?" [35] use autoethnographic techniques that include first person descriptions and observations of the context and the design itself, as described in "Designing for, with or within" [52]. Moreover, we see this as a form of annotated portfolio like "The Tuning of Materials" [31], "Attention to detail" [29] and "Annotated portfolios" [19].

Our methodology was informed by research products [42]. Research products are high quality artifacts used as research tools that can be deployed in a natural setting. Research products hold four interdependent qualities; inquiry-driven, finish, fit, and independent [42]. Our research products took the form of everyday shoes. It is like a product that is often personalized and can be created in a small digital fabrication setting such as a fab lab. Testing a full system of encoding data/materials for iterative ultra-personalized shoes could easily require an industrial process and assembly line. Yet hybrid craft and a research product methodology allowed us to synthetically engage with a system much like a bespoke shoemaker, instead of a large corporate producer.

Several personalization models could have been used for engaging in this research. "Digital Footprint" [4] describes data enabled personalization based upon the Design, Manufacture and Use of an object. Models like "Plantar Foot pressure to estimate foot behavior" [22] concentrate on the analysis of the footstep. It was important for the loop of iterative personalization that the use and making phases were equally represented to account for a research product.

We needed more space for analysis alongside design, manufacture, and use leading us to the theoretical model of Ultra Personalized Products and Services [49]. UPPS gave equal balance to the four phases and we adapted it to shoes in a system of personalization as seen in fig 2.

Over two years, four projects were cumulatively undertaken at the Wearable Senses Lab of the Eindhoven University of Eindhoven in order to close the loop of iterative personalization. Many tools, techniques, and materials in the process were created as part of the bespoke shoemaking experience including: making/modifying 3D printers, creating pressure scanners, hacking filament sensors and creating a web architecture. We even tried to make our own filament but failed as flexible materials require large scale infrastructure. Each project required bringing together experts to help develop new machines, new software and integrate it together as shown in fig 3.

We hope that the challenges uncovered and learnings developed during these 4 projects will help to spark a deeper understanding in how iterative ultra-personalization could become an everyday reality. Do we need to return to a reality of bespoke shoemaking, or could technology, scaffold together with craft, produce a new system of designing and producing shoes?

4 ANALYZING THE FOUR PROJECTS ENCODING DATA AND MATERIALS

From the four projects carried out we formed an understanding of the complex system of encoding data and encoding materials that were needed to close the loop of iterative personalization. Each project was built on the previous one to result in a full loop of iterative personalization. (The projects were actually iterations building upon each other, but we refer to them as 'projects' to avoid confusion with "iterative personalizaion".) Project 1 developed a 4D foot scanner to encode a footstep into parameters related to size and flexibility. Project 2 took the footstep parameters and negotiated them with the design considerations from bespoke shoemaking in code using no 3d models other than gCode simulation. Project 3 moved all of the software to the web to encode the data obtained over time, thus allowing the creation of data trails for one or multiple shoes. Nonetheless, it required significant software

	Challenge 1	Learning 1	Challenge 2	Learning 2	Challenge 3	Learning 3
Project 1: Encoding a Footsetp	Reading the body	A general purpose sensor is not personalized	Understanding the behaviour (footstep)	Temporal composites	Comparing data	Designers need data
Project 2: Encoding a Material Shoe	Adapting generative algorithms	Negotiation of design considerations	Standardising programmed material behaviour	Ranges of quality and precision	Manufacturing misinterpretation	Limits of the current technology
Project 3 Encoding a Data Structure	Saving and storing the data trail	Ideal vs actual	Quantity and scaling up	Profile the thing (shoe), not (only) the person	Profiling predicted use	Potential for self - directed machine learning
Project 4: Encoding Shoe Use	Adding sensing (to the shoe)	Multi-purpose hybrid material geometries	Mechanical Sensing Material Structures	Active vs passive monitoring	Storing and decoding use	Understanding temporal composites as material

Table 1: A summary of the challenges and learnings developed over four RtD projects encoding data and materials for iterative personalization.

rewrites. Project 4 redesigned the shoe to encode use data for future shoes. What follows is a detailed description of how the challenges and learnings developed in each project. In order to make the knowledge gathered understandable and transferable, the main highlights are summarized as challenges and learnings in table 1.

Project 1: Encoding a Footstep as Data

The aim of project 1 was to encode a footstep as analysis data. We considered using commercially scanners like those of RS Scan which dynamically analyze footstep data [18] Instead, we fabricated our own as a hybrid craft project. Making our own allowed us to see the idiosyncrasies of each footstep and experience the encoding of data from scanning first hand. Commercial solutions abstract the raw data from the sensors and it was important that we experience that raw data and make our own visualization. Consulting with a podiatrist, the team used a digital embroidery machine to create an 8 x 16 matrix of capacitive sensors using a Cypress CY8CKIT-050 5LP to read the data at 20hz per second. The software was written in Octave in order to allow calibration and visualization in real time. Beyond the difficulties of a reliable calibration of capacitive sensing, a number of important challenges and learnings arose as we deployed the sensor at a public design exhibition and scanned over 400 feet (see figure 3). We wanted to analyze many foot sizes, from children to adults. We included children because of the public exhibition setting but they were not part of our target group because their rapid growth is a particularly difficult case.

4.1.1 Challenge 1: Reading the body.

Determining the precision of the scanner to be suitable for general use was difficult. People have very different kinds of feet. Multiple outliers such as high arches, long toes and very thin feet were misinterpreted by our scanning software. Many of them needed special attention in the software to encode the footstep into a digital representation. Some of them, the ones that could not be solved by software, needed sensors with different pressure ranges in specific areas of the foot. However, adjusting for one foot would make another less precise. After testing a series of samples, we decided on a spacing of 14 cm over 8 vertical capacitive TX lines and 1.8 cm over 16 horizontal capacitive RX lines. This was a negotiation between size and accuracy.

We faced the same precision issues in relation to weight as we expected users weighing from 20kg to 130kg. The way the capacitive sensor worked was by measuring how far the foot sank into the sensor pad. We tested industrial spacer fabrics and ended up laser cutting holes in a grid pattern for better compression under different weights. This was important as the four smaller toes of the foot apply relatively little pressure and they need to be measured. The outcome was an image of the foot's pressure where we could even see 4mm 3D of the curve of the foot.

4.1.2 Learning 1: A general purpose sensor is not personalized.

The level of imprecision often seen in current scanning systems seems to be dictated by the need to make the scanner work for the general public. Personalized sensors would allow for the encoding of data to be more precise for each user. A system of iterative personalization must accept that the first iteration can only achieve a level of personalization dictated by the general purpose sensor. Fixing a problem in the sensor could only be taken to a certain precision before it would cause problems to other users. We learned to accept that the level of precision available from the general sensor could work as a starting point but more precise sensing means would be needed after each personalized iteration of the shoe. The solution would be to personalize the sensor too.

4.1.3 Challenge 2 Understanding the behavior footstep.

Mass customization in shoes looked for ways to offer users control over color, shape and size [44]. Programming materials with digital fabrication allowed us to create something far more nuanced in terms of behavior. Different areas of the foot apply pressure differently over multiple footsteps. For example, the heel, talon and big toe at times support the whole weight of the body. The smaller toes and arch rarely support significant weight. The second challenge was dealing with a footstep over time. We needed to shift the weight from the heel to the toe to understand the pressure of the foot over the footstep multiple times. Commercial systems often use a pad that can record three footsteps and a technician selects the "best" step. We had to adapt our software to record the size and pressure over that footstep. Dealing with static shape was already difficult, but movement was far more complex. Designing for human locomotion is

Figure 4: The SoleScan pressure pad and software recorded footstep size and pressure. Photo by Bart van Overbeeke

complicated as many researchers have noted [7, 33, 34].

4.1.4 Learning 2 Temporal composite.

We learned that it was important to deal with time and design based on movement, not just a single static moment. Instead having the data of someone standing on the sensor, the data needed was a "temporal composite" [32] of the footstep. Constructing this temporal composite was prone to errors as many people walk differently. The encoded data would serve as the parameters to generate the size, shape, flexibility and density of the shoe, making each shoe personal to the footstep. To do this we looked at the areas of the foot that generated each tread cell on the bottom of the shoe. The maximum impact value was translated to a density parameter for the tread and comfort in the insole. The change in pressure was used to create a flexibility parameter.

4.1.5 Challenge 3 Comparing data.

While looking at the over 400 encoded foot scans, commonalities and specific differences emerged which are key to iterative personalization. When we scanned our own feet, we could see a difference between a morning scan and an evening scan. We consulted a podiatrist who explained us that the foot expands during the day with the pressure of the body. We found other commonalities such as the curvature of the side of the foot was softer in older than in younger people. Older people lose soft tissue with use and the feet become squarer. If we could slow the scan down (not as easy as it may seem) we would see the soft material of the foot spreading during the impact and raising of the foot.

4.1.6 Learning 3 Designers need data.

We learned that designers need to look at data from multiple scans, shoe iterations and users. Designing a shoe that is generated to each user means understanding the user population intimately. Being present and scanning the feet at the exhibition taught us to look at how people walk and how that data appeared within the software. It was important for the next project (encoding a material shoe) that we understood intimately how the data was entering the system through the scanner. Our first-hand experience with the data allowed us to gain a common understanding for redesigning the algorithms that generated the shoes. It was part of our developed hybrid craft to understand the data, the extremes seen in collecting it, and how that encoded data related to the real footstep. In order to differentiate and error from an outlier, and a small problem from a critical issue.

4.2 Project 2: Encoding a Material Shoe

To generate a shoe from parametric data, we started with our previous work on algorithmic methods for generating 3D printed shoe soles [17] and added parameters for some of the design considerations identified in "Towards 4D Printed Ultra Personalized Shoes" [39]. Significant advances were made to our software [16] to make the algorithms generate the shoe soles with encoded parametric data and adapt the comfort, balance (flexibility), and robustness to the user. Two digital fabrication specialists worked with a computer scientist to allow changing the density of each tread and the space between those treads of the sole independently. A tread is a single area of a sole, much like a tire tread. No off the shelf software or 3D modeling was used. Instead we made our own software to generate 3D printer gCode, laser cutting .svg's and computerized embroidery DST files. Our previous first hand hybrid craft experience drove us to create code [17] that controlled the digital fabrication technologies used whenever possible. For example, we built and modified several Prusa i3 3D printers to achieve full shoe size while using commercially available 3D printers to understand the subtleties of printing flexible materials and make structures that behaved in specific ways (see fig 4). More than 270 samples were created to achieve wearable shoes like those seen in figure 1B,C,D.

4.2.1 Challenge 1 Adapting generative algorithms.

We rewrote our previous software [16] to integrate contour and pressure data from project 1 to generate the shoe. Previously, the shape of the shoe was created from the contour of the foot. Programming this into software was no easy task. We found areas where two design considerations were implementing different geometry in the same physical space. These negotiated design characteristics required crafting hybrid geometries that could combine, give precedence to or move one of the considerations. Additionally, advice from an expert French last maker taught us to slightly rub the big toe (bring the toe of the shoe in 5mm) to give a point of reference to the feet. Finding ways to make the software understand these techniques was difficult and time consuming. The new software transformed the temporal composite and footbed outline parameters from the project 1 in a .json wrapper. A new function was added to generate laser cutting files for the shoe uppers from the parameters. Beyond the tread, the sidewall was challenging. The side walls needed to be robust yet flexible enough to support hundreds of thousands of foot flexures, especially at the talon of the foot . Keeping the sole flexible and sturdy at the same time was challenging. All shoes suffer this problem (look at any old pair of sneakers), but approaching the challenge from an algorithmic perspective changed how we understood at the shoe.

4.2.2 Learning 1 Negotiation of design considerations.

As one can imagine, a deep understanding of both material and data was needed to create the required geometries. Negotiating behavior geometries went beyond the multidisciplinary mindset of the team stakeholders and resulted in transdisciplinary understanding. We found at least five areas that needed special negotiation in the algorithm. One was a sole tread needed to be soft for comfort and hard for balance. This required shifting the soft area to footbed and away from the tread. Another, as mentioned before, was the sidewalls, which was required to be flexible and sturdy. We had to negotiate these two design considerations so that the shoe was comfortable yet robust enough. The sidewall required a tiny zigzag of two 3D printed lines to make the wall soft and flexible while adding strength. The amount of zigzag needed to be driven by the footstep scan data.

4.2.3 Challenge 2 Standardizing programmed material behavior .

Beyond the basic issues of printing with a flexible material and using 3D printer specific gCode flavors, we ran into several challenges that were specific to encoding a material structure. There is a complexity to the materials, machines and techniques used. Prior research shows how the shoe deforms under the weight of the body, directly affecting the balance and gait of the body's movement [18]. We originally intended to use selective buckling structures, but negotiating design considerations required new techniques. We developed a layered structure that easily could be adapted in density like the textile structures described in [39]. We created an algorithm that assigned the seed points to the existing Voronoi tread algorithm based upon the pressure centers of the moving foot. The flexibility of the shoe was determined by the distance between the treads. Determining the densities required testing and trials. We made our own pair and wore them for a week. After wearing the shoes (in fig. 1, image 2), maximum and minimum densities were added based upon the area of tread. We also set a minimum distance between seed points and a maximum number of seed points to ensure the support of the food during movement.

4.2.4 Learning 2 Ranges of quality and precision.

We learned the importance of standardizing programmed material behavior. Some areas needed selective buckling [43], such as inside the footbed. Other areas needed rectilinear textile like structures where we could adjust the spacing between rows and columns to create sponge like result, as in the treads of fig. 6. Some regions were very complex and important to the behavior. We found the 3D printer had difficulties with certain structures in certain colors on certain days. We experienced under extrusion leaving areas soft and flimsy, and over extrusion making areas hard and rigid. Having no solution at that moment for imprecisions in printing, we had to accept to work within ranges of quality in the materials structures. Although, we would later find part of the cause (as described in the next section), this issue also showed us that a hybrid craft requires working with the qualities of the materials available.

4.2.5 Challenge 3 Manufacturing misinterpretation.

Figure 5: 4D pritnting personailzed shoe soles using direct gCode in the SoleMaker software and data from project 1. Photo by Bart van Overbeeke

Once we developed control over the quality and behavior of the tread, footbed, and sidewalls we had another challenge. As explained in learning 2, our standardized programmed material behavior fluctuated over days, and by the filament's color. While negotiating design considerations like the balance and temperature of the shoe, we encountered a problem with the back pressure in the nozzle of the 3D printer. Pressure built up in the nozzle and shifted the programmed extrusion by as much as 8mm when the material exited from the nozzle. Moreover, with certain geometries, not enough material was sometimes deposited creating stringy and sometimes broken filament extrusions.

Several tricks were invented and taught to us by the 3D printer maker Ultimaker to alleviate these problems, but the final product was not exactly what we programmed. We ran a series material tests using an experimental filament flow sensor. These tests allowed us to see exactly how much material was travelling into the print head and helped us to create a better understanding of how gCode was translated by the machine. We found that certain geometries deposited as little as 72% of the material the code requested. Software changes helped alleviate some of the problems found in certain geometries. Slowing the speed or combing (retracing) the printed line on important areas allowed the back pressure in the nozzle to refill areas. This was applied after sharp direction changes, especially on curves.

4.2.6 Learning 3 Limits of the current technology.

There are limits to the technologies and materials we are working with. To design material behavior these limits must be accepted or improved upon. Dourish has shown how "some data is more important than others" and used an example of a post script compiler [14]. 3D printing technology is far from WYSIWYG (what you see is what you get). The quality of the material structures had a level of precision that was similar to the early days of graphic design. We found that certain geometries were far more critical and required more delicacy (slower speeds and more detail in gCode). To design we not only had to understand the quality and precision, we had to understand where the important areas were and take measures such to increase precision. Iterative personalization required us to adapt our tools and techniques alongside the software in a dynamic way.

4.3 Project 3: Encoding a Data Structure

With our understanding of the need for machine learning and with the complexity of the system growing we needed a place to save and store foot scans, temporal composite .json files, design files and digital fabrication files. Iterative personalization required a data trail structure to store that data between iterations. Project

3 was a web platform that created a web interface and a database to profile the shoe analysis, design, manufacture and use. The web platform was built with Docker modules that supported all the other code: the pressure pad scanning software, the sole tread software, and the uppers generator software alongside social log-ins, a QR code generator and database system (see figure 5).

4.3.1 Challenge 1 Saving and storing the data trail.

While attaching the pressure pad scanning module data to shoe design software we realized how complex the data gathered to the generate the shoes could be for a single user. Developing the web platform in project 3 taught us how to encode data and store it for multiple iterations and multiple users. The web platform provided a place to save and store the information together enabling the profiling and comparison of data. This data included: 1) The pressure pad scanning temporal composite as a .json file. 2) The raw stream of data with as much as 100mb per scan. 3) The data from the sole software and the shoe upper generator stored as a .json containing the contour array, and tread Voronoi seed point array. 4) The machine code as a .gCode file, .svg and instruction manual. 5) A field in the database for the filament flow sensor (for future documenting ranges of quality in material structure). This was connected to a social login module was added to allow users to integrate Facebook, Twitter, LinkedIn, GitHub, QR code or email.

4.3.2 Learning 1 Ideal vs actual. Applying the idea of digital twining is difficult in an everyday context. Digital/physical twins may be born identical, but they grow into unique individuals. As we started to look at profiling and use data, we learned that there was an opportunity to track the differences between the ideal and actual shoe. Storing all this data allowed a quality check from the material production cycle and could be used instead of rigorous physical testing of the manufactured shoe. If we consider that 3D printing implies a distributed co-manufacturing [38] system of many people with printers in many locations, this type of data becomes vital. The comparison between ideal and actual seemed to be true across multiple iteration of shoes as well. The past data could be used to not only to control and generate the next pair of shoes, but a whole closet of shoes for different users' needs and desires. It was also important to understand the distinction between the ideal designed version and the actual manufactured version of the shoe. The actual version of the shoes is not identical to the ideal version.

4.3.3 Challenge 2 Quantity and Scaling up.

The web platform gave us a way to store hundreds and thousands of feet into the system due to its modular construction and scalable architecture. The majority of our modules ran in a browser, saving any risk of the server being overtaxed. This helped us to address concerns around security as well. All data about the foot and generated shoe was stored in the user's browser until it was uploaded to the web platform at the end of the process. Users could log in with their social networks or by email as mentioned in the last section. We also gave them the possibility of generating a QR code that would link to an anonymous account.

4.3.4 Learning 2 Profiling the thing (shoe), not (only) the person.

There is an opportunity for integrating more data sources resulting in better personalized results. An important learning in project 3 was that we could profile the shoe and not necessarily the person. This allowed a deeper understanding of the material of the shoe. We realized the iterative personalized process was a shoe to shoe process. Conversely, we realized that sociometric and psychometric data on top of our physiometric data could help us make lifestyle predictions for the fashion of the shoe. This made us more acutely aware of how we could use machine learning (as explained in project 1).

4.3.5 Challenge 3 Profiling for predicted use. Simple calculations of the user's weight and the physics of the material lifespan allowed a general prediction of how long the shoe should last. We combined this with a supposition of our shoe designer on to how long the styles we developed would remain in fashion. With this information, we could estimate how long the shoes would last in terms of steps. However, we also realized that we did not have information on how much we expected the person to wear the shoe (just how long we expected the aesthetics to remain fashionable). These simple simulations hold much potential for just in time manufacturing, sustainability and material lifetime coordination.

4.3.6 Learning 3 Potential for self-directed machine learning.

With more than 400 scans in the system, we had enough virtually generated shoes to begin comparing the resulting files. We learned that we could predict use and compare it to the actual use across user populations. While we did not apply it in this research, it is clear from our understanding of the database that machine learning techniques could be applied. These techniques have the potential to enhance the experience of the worn shoe not only in an iterative way, but across entire populations. Moreover, key to iterative personalization was comparing users to themselves over time and seeing how others who are slightly older may also relate. It is clear that machine learning has the potential of becoming a vital tool in this encoding process.

4.4 Project 4: Encoding Materials that Encode Data

Project 3 showed us that we could manage data across the shoe iterations and users, but as seen in project 1, personalization only improves if the sensing of the individual becomes more precise. Our final project looked at encoding data from the shoe while it was in use. We did that by integrating electronics and encoding material structures to store data about the size, pressure and behavior based overview the process followed). Previous work by Autodesk into iterative generation of car chassis [40] helped guide our process of generating data in project 4. We worked with a shoe designer to change the style of the shoe to a moccasin construction to solve the problem of sewing the sole to the upper. This change, provided a space for electronics and made it possible to swap the sole. In short, making the project more sustainable and a better research product.

Figure 6: Screenshot of the web interface of the online version of project 3. Data from project 1 is imposed under the design software from project 2

4.4.1 Challenge 1 Adding electronic sensing to the shoe.

Adding sensing capabilities to a shoe was not easy. We first 3D Printed textile like structures using conductive PI-ETPU 95 filament to create sensors in the sole. Electrodes were manually added to the 3D Printing using small gauge wire in the footbed of the shoe. We created a row/column scanning matrix with a 4 x 10 resolution crossing in points specifically designed to register pressure in the key areas identified in project 1. These were connected to an Arduino Teensy and data was logged at 20hz. The textile structures, previously mentioned, were varied so structures previously designed for comfort, robustness and flexibility would also act as pressure sensors. These sensors were printed for specific force ranges identified from the first scans. For example, the heel sensor was made for a much higher impact force than the four smaller toe sensors.

Changing the filament to conductive ETPU had large impacts on the comfort and flexibility of the shoe. ETPU was far less flexible. We had to renegotiate the design considerations of the footbed to provide comfort to the foot and insulate the electronics. We developed a new triangular textile weave pattern (warp, weft, & werf) that created a softer material behavior to counter the stiffness of the sensor. It also added more flexibility.

4.4.2 Learning 1 Multi-purpose hybrid material geometries.

Creating multi-purpose hybrid geometries that could perform electronic sensing alongside its material properties was a great discovery. However, combining its properties with the design considerations previously encoded in the material was challenging. The new geometries needed to be significantly different because of the specific material properties of the conductive filaments. Being aware of how to negotiate design considerations (leaning 1 in project 2) made the team ready, and more importantly willing, to deal with the additional complexity required to create the multi-purpose hybrid geometries. Engaging in the hybrid crafting process enabled even greater possibilities as the challenge of adding sensing capabilities became a new design consideration.

4.4.3 Challenge 2 Mechanical Sensing Material Structures.

As an additional technique to store the use, we looked at making structures that would break over time, much like winter tire treads. We learned in project 1 that generating a shoe with foot data required making a temporal composite of the footstep. In this project, we explored if we could encode material structures that changed with use to create a mechanical temporal composite. We saw an opportunity to use the material property of breakage with selective buckling [43] in the shoe tread. This required maintaining the density control from project 2 and adding small single lines of filament into the buckling structure every four layers. These layers would stretch and eventually break. A small sensing system was developed that would measure if each single line was broken after being used.

4.4.4 Learning 2 Active vs passive monitoring.

There are times to use active sensing, and times to use passive sensing. During the testing, we realized it was complicated to read the single line sensors with

Figure 7: A selection of the several samples developed to create electronic and mechanical sensing inside the structure of the shoe soles.

a 3D printer-based system as there was a deformation of the overall material with wear and tear. While it was possible by hand, it required a lot of time. What we did notice is that in areas of heavy pressure, the shape of the overall geometry of the tread had changed due to the breaking of the internal pieces. First seen as a problem, we rapidly found out inspiration for a way of combining wear and tear, with an evolving form of the shoe sole.

4.4.5 Challenge 3 Storing and decoding use.

Beyond electronic and material geometry-breaking, we used color change to indicate abrasion. We were inspired by wearing a pair of shoes seen in fig 1. (the third image starting from the left) for many months and noticing abrasion in the material in the talon and heel. For the first twelve layers of material (2.4 mm in height) we added material color changes every four layers. Pictures were taken of the soles in use and using the method of photogammatry described in [37] we were able to see how much material had worn off due to abrasion. As this often indicates when someone walked incorrectly, we were able to see where a stronger material would be needed.

4.4.6 Learning 3 Understanding temporal composites as material.

We learned that the material itself could store data about use to be decoded later if designed to do so. Each of the three methods told the story of use differently by creating different data trails. Combining all three, they painted a larger picture, but turning the iterative corner required a deep material/data relationship. Based on past experiences 3D printing shoes. We had a preconception that using textile like geometries was superior to selective buckling and metamaterials. We ended up using all three techniques in project 4 to create the encoded material with negotiated design characteristics and sensing/storing capabilities.

5 REFLECTION

With project 4, we were able to close the iterative personalization loop. The data used in project 4 was more precise than the original data from project 1. In the previous section, we presented our challenges and learnings (see table 1). In this section, we try to summarize them in an effort to make our work transferable to other researchers interested in ultra-personalization. More specifically we discuss encoding material, encoding data and the data/material relationships that developed during the 4 projects.

5.1 Encoding Materials

Encoding materials with form, behavior and sensing required creating multi-purpose geometries often with multiple materials. We learned to create these by negotiating design considerations while programming to make 3D printer gCode. This started simply as density vs. flexibility. It allowed us to approach sensing as if it were just another design consideration of the shoe. This was achieved by many people working together to adapt the generative algorithms while having a deep understanding of the material (ie. flexible filament), tools (ie.3D Printer), techniques (ie. gCode commanding the printer) and data(.json pressure files). It was complex and required people from several disciplines willing to engage in hybrid craft. Creating the encoded material required not only new tools and techniques but also an open attitude and varied skill set.

3D printing flexible materials geometries requires designers to work in ranges of quality and precision when programming the materials structures. We worked through the challenge of standardizing the programmed material behavior accepting that there are ranges of quality that are defined by the Technology (3D Printer), material (the filament, not only the type, but also color) and, as we learned in the process, the direction of travel in creating the geometry itself. Part of the discipline of hybrid crafting is a deep understanding of how digital tools works and how to program them.

Starting off trying to build an electronic sensor shoe would have taken us down a very different journey. We arrived at iterative personalization thanks to the fact that we chose to hybrid craft a bespoke shoe in a full wearable research product. Wearing the shoes while making the shoes inspired us to go deeper. Others have previously integrated off the shelf electronic sensors for iterative improvement, but our work at a base material level allowed us to personalize the sensor itself. It may seem obvious that personalized sensors would create more personalized data, but only by 3D printing electronic sensors we did realize from first-hand experience that we had several opportunities to gather better data. This exploration opened the door to mechanical sensing.

Mechanical (non-electronic) wear and tear sensing from encoded structures could be used in many places, not only in shoes, but in many other places where wear and tear is important. We were surprised during our research to discover that some snow tires already use material indicators in the tread. Most interesting from our research was the idea that mechanical sensing could be programmed to already provide a temporal composite for iterative personalization instead of computing one from the electronic sensors.

Designers, makers and researchers often think of 3D printers to be like paper printers. Our experience was the 3D Printer more

closely resembles a knitting machine. A knitting machine works with ranges of tensions and yarns. There is a precision to the size of the stitches in a sweater that lends itself to certain kinds of patterns and motifs. There are fundamental rules about how far a single color of yarn can jump before the thread comes loose or how many stitches can be jumped. There is a quality a knitting machine can achieve that we see in material structures essential in both knitting and 3D printing. Our experience in this process was that new insights informing digital fabrication came from people who work with textile machinery. There are limits to the technologies, but experience with tools from other disciplines helps understand those limits in new ways.

5.2 Encoding Data

Encoding data for iterative personalization needs compressing time into a temporal composite to provide parameters to the generative algorithms that encode the material. This temporal composite is in a way an impressionist painting like Picasso's 1938 'Seated Woman' where the painter combines many moments from many painting sessions. We condensed the behavior of users footstep in a computational way of understanding movement over time. This idea of a paining asks more questions such as how do we capture different activities that the wearer is engaged in? Can we encode data that captures enough of a specific behavior that we can understand as designers it is happening? Do we need to understand or is this a question of precision and interpretation?

Personalizing the sensor to the individual results in better data, but it is not exactly the same format of data. In encoding data for design, the process used to generate the temporal composite needs to be rewritten. The designers need data to understand how to create temporal composites in a way that creates a better shoe. Unlike current objects that are designed once and mass manufactured, iterative personalization requires the designer to stay involved in the product service system to interpret this data and create new styles. We expect that designers of such system will share our experience that the temporal composite becomes a design material. This is especially true as we consider the difference between the active electronic sensing versus the passive mechanical sensing.

We see many kinds of quality and precision, not only in the encoded material but also in the encoded data. This includes the data available, the materialization processes, the system training, the negotiated algorithmic generation, and challenges with incorporating new shoes designs into the system. As discussed in encoding materials, the precision of the encoded material is different than the encoded data, we see this as a relationship between the ideal, predicted and actual use. In iterative personalization, we need to be able to compare each iteration so that the level of personalization can grow. The data trail of an object is the narrative story that informs generations to come.

Iterative personalization requires that the system is trained to be better over each version, just like user statistics improve software in each version. This is an evolutionary system that requires software and algorithms to be trained regularly. The iterative personalization loop is also a feedback loop where we can tell from the data if our data profile of the shoe is correct. Not only can we compare shoes, the encoded data from analysis and profiling is ripe for machine learning. Not only can we compare each shoe version to the previous one. We can compare similar size and pressure patterns over time, and the ideal vs actual shoe that was made to name to name a few. As the database grows with multiple users and multiple shoe versions, it is clear that self-directed machine learning will become a key tool in dealing with the complexity of the data.

5.3 The Data/Material Relationship

In working over two years to encode materials and data for iterative personalization we noted the data & material relationships changed. In the beginning, the materials we were designing with were the physical filament fed into the 3D Printer. As we came to be familiar with the idiosyncrasies of the material (every color of filament is different, the data from the footscan is a temporal composite), tools (3D printers are susceptible to ambient temperature, humidity, time of day, electric line tension...), and techniques something magic happened. The algorithms used to encode the design characteristics and sensing became really important. The project members began to speak of the algorithms as if they were the material. Not using 3D files, but rather generating gCode and seeing it for the first time on the printer prevented abstraction by a screen. We found ourselves voraciously adding code libraries to control the data just slightly differently. We found our team at the white board rearranging the pressure calculations to make the pressure sensing slightly more sensitive to high impact pressure for someone who is running. Several of these instances changed the design language of the lab we worked in. Hybrid crafting resulted in a new discipline of designing data and material relationships over time.

The sense of time that iterative personalization changed our role as designer. Depending upon the moment of the lifetime of the shoe we found our activities and perceptions changing. Time is a key element in what we made. The temporal form of the shoe depended upon where we were at in the UPPS cycle. Sometimes the 'shoe' was pure data, some times it was material. Developing the skills to see the shoe as both unlocked the possibilities of iterative personalization. Data allowed us to move through the temporal form of the shoe and capture moments of that lifetime.

6 DISCUSSION, CONCLUSIONS AND FUTURE WORK

In this paper, we reported on four iterative projects that form a system of iterative personalization. We contribute with lessons learned and techniques for traversing the encoding of data and materials. Our exploratory work aims to enrich the possibilities for makers, designers, engineers and researchers who are developing data-material relationships, especially as a hybrid craft. We extend the capabilities of prior work into material programming [53] and contribute to the understanding of encoding materials designed with generative algorithms from encoded data. Along the journey, we show new tools and techniques for computational design emerging and a trans-disciplinary understanding of data and materials developing in design.

Iterative personalization is a making something more personalized by using a data trail created by previous from generations. Iterative personalization might be seen as combining the iterative improvement for design synthesis by Autodesk Research [40] with Vallgårda et al's ideas of temporal design [55] as iterations over a lifetime. This opens up a door to not only our sneakers being increasingly personalized every time they become worn out, but that these sneakers encode data for all of our shoes including dress shoes, running shoes, high heels and other sneakers. We look forward to one day encoding the data and materials for such a closet.

Iterative Personalization shows the potential of Ultra Personalization. This research demonstrates that the Ultra-Personalized Product Service (UPPS) system is beneficial to the design of systems of iterative personalization. This is achieved by encoding data and encoding materials in ways that remember how the thing was made and used. We show how a product service system can support iterative personalization by subdividing the complexity of the lifetime. Moreover, the collection of data across the lifetime of the shoe opens up possibilities for post-human concerns such as sustainability, not only over the lifetime of a shoe, but in multiple shoe over multiple lifetimes. The ability to use data as a designer provides new frontiers for hybrid craft, allowing designers to consider the why of the object, not just the how.

Iterative personalization also builds on the idea of the research product[42]. Not only does each shoe become a research product for successive shoes, there is a potential that thousands of shoes becomes a research product informing all the other shoes that follow, and perhaps more than show. Our everyday things may combine data across large numbers of artifacts informing each other. New potential for hybrid craft emerge as new outliers and expressions emerge from the data, creating new material geometries. The role of the designer becomes more active in the process as the behavior of individuals changes over time. The cycle in some ways resembles software development working with more software developers in hybrid craft may open more possibilities.

Understanding and designing the data and material relationship over the lifetime of an object tells us new things about materials, use, and people in their natural setting. The insights gained during this research are only a first step into encoded material and data for iterative personalization. We hope to create several more iterations of the shoes for individual wearers and understand the limits of iterative personalization in shoes. We also hope others will join us to explore the data & material relationship to iteratively personalize of all kinds everyday things.

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6.2 Critical Reflection

The project would have reached even greater depth had a sub-versioning system been used to track the code development along with automatic photography in the manufacture phase. Doing it manually was attempted, but given the great complexity of dealing with the algorithms, the tracking and design development need an automated system to allow the craftsperson to concentrate on the data–material relationship.

Limitations of the work

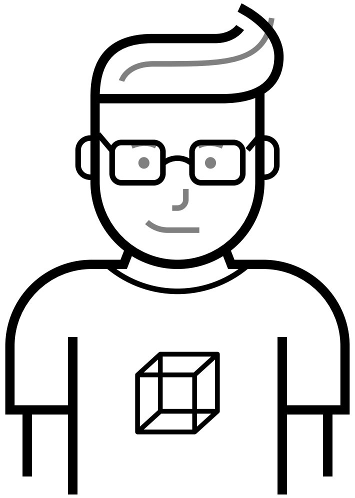
The resulting shoes were wearable. A pair was worn regularly for at least 8000 steps per day on the streets of Berlin. It was found that the material used (TPE-S) does become hard at sub-zero temperatures, limiting the use in cold winter months. The paper also fails to present the resulting theoretical model in a way that is accessible to others.

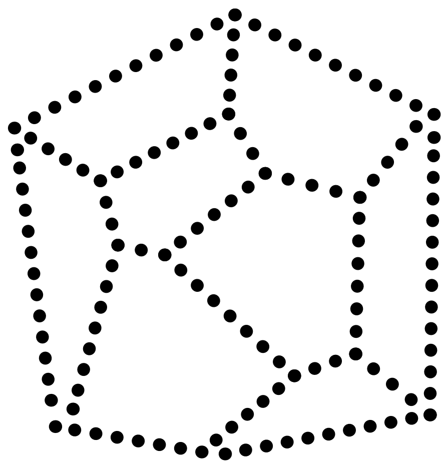
How is this different from a traditional bespoke shoe?

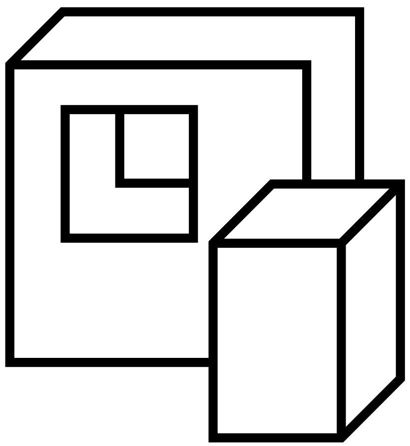
Solemaker is different than the classic bespoke shoe because it uses data to make the materials in the sole and uppers. The shoes realized are far more modern in style than the bespoke shoe. More research is needed to make a direct comparison of the bespoke shoe and the Solemaker shoe.

Impact

Many student projects have used the methodology employed in the Solemaker project. The project has been cited by other research.







7 Unpacking Solemaker

An annotated portfolio to inform theory

Published as "Unpacking Solemaker into a Model for UPPSS" (Nachtigall et al. 2019) and presented at Conference on Research Through Design (RtD) 2019.

The paper argues for a systems approach to UPPS based upon the findings of iterative personalization presented in Chapter 6. Solemaker increasingly used the UPPS model (Ahsmann 2016) as the project developed. At the end of the Solemaker project I reflected on what my practice meant for the UPPS. This includes looking at the stakeholder relationships and embracing the collaborative nature of the system. This includes **enabling transitions** in UPPS where the **phases** are tied together. The work of designing the system of UPPS is important in those enabling transitions where a significant amount of time is invested.

7.1 An annotated portfolio to inform theory

Role

Research Question

Can reflecting on the conceptually rich artifacts improve theory?

Research Conclusion

Yes, artifacts in the hand of the craftsperson can be annotated and used to inform theory.

Quality of the output

276 artifacts ranging from terrible failures to museum quality shoes.

Favorable outcomes

What worked in this project was sorting the physical artifacts into the boxes that represented theory. This allowed reflection that theory can never represent the richness of practice, but practice can inform theory.

Difficulties and Unfavorable Outcomes

What didn't work was the connection of image to code. The names of each G-code file indicate the date and time of the file generation, which was correlated to a designer who made photo. What this did not correlate to was the state of the code generation of the file at that point. An attempt was made to use versioning on Google Drive, but it was insufficient. The system would greatly benefit from automated version control and systemic lifetime tracking to inform circular development. Don't expect the craft person to do it as they are busy crafting.

Unpacking Solemaker into a model for UPPSS

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EVA Moccasin Data Generating Shoe. [Nachtigall and Klabalova]

Keywords

Personalisation; Shoemaking; Digital Fabrication;
3D Printing; Design Practice and Theory; Ultra-Personalized Product Service Systems

Abstract:

Solemaker research is a collection of four RtD projects related to personalized shoemaking. Across these projects, we created 272 material samples that explore how to make shoes that are digitally fabricated for the individual.. This shoe personalization system utilised soft materials, 3D printing, digital embroidery, laser cutting and our own digital tools. Achieving Solemaker meant hundreds of material samples for only a few research products; all were algorithmically generated. Our work exemplifies a change in making and craft practices through digital fabrication. In design theory, this is encapsulated in a model of digital personalization known as Ultra Personalized Product Service (UPPS). To investigate these links in the context of our material and making approach, we compared our hybrid craft practise to the model of UPPS using a system of physical boxes. We unpacked our work into boxes representing the model. This afforded ways to map projects together by means of a common language. This resulted in previously unseen connections, new understandings of the theoretical model, and new enabling transitions between model pillars. We present our unpacking "material sample boxing" process, a refined definition of the model, and the "physicalized" enabling transitions between the UPPS model stages.

Introduction

Figure 1. Spike Shoe Photo: Troy Nachtigall An example of our previous work in 3D printed shoes that inspired us to write software to make shoes without 3D models.

Design practice and theoretical models almost always differ. Theoretical models cannot express the subtlety and nuance of practice (especially when the practice is creating personalized objects, such as shoes). Many design practitioners and researchers are dubious of theoretical models. This is summarized well in the words of Watkins about theoretical models being like toothbrushes (Watkins 1990). Yet, case studies can inform a theoretical model (Binder and Redström 2006). To this end, we describe our practice of personalized digitally fabricated shoemaking. We then unpacked all our physical samples into boxes and analyzed our finding using the theoretical model of Ultra Personalized Products and Services (UPPS). This included intermediary knowledge created during the process.

Our research into ultra-personalisation, fig 1, started by observing how a bespoke shoemaker investigates a client's current shoes before making a new pair, fig. 2. This inspired us to design a system where the shoes themselves create a data trail for the next pair of shoes. There was no road-map for making shoes this way. Digitally personalized shoemaking provided a new rich area of practice. Bespoke shoemaking inspired this research practice as the shoes are highly personalized to the foot, movement and style of the wearer. The artisan shoemaker has a deep, often implicit, understanding which inspires a great deal of trust in the skill and taste of the artisan.

Data seemingly cares little for the material that makes it or the person that is manipulating it. Programmers usually create tools for large numbers of people with little concern for the individual or the materiality of the data. We joined bespoke shoemaking with computer programming creating a system of personalized shoemaking with a data driven back end.

Figure 2. Visiting bespoke shoemaker Mario Bemer Photo: Troy Nachtigall. Mario Bemer demonstrating how he builds a bespoke shoe in his Florence, Italy studio.

Designing a system that scaffolds bespoke craft with data driven technology was no easy task. The materials, tools and techniques were invented by us and/or highly experimental when we started in 2015. Over two years and four projects, 272 samples, 3 demonstrators, and 4 research products we digitally manufactured data driven bespoke shoe.

Making each sample required a great amount of effort and many stakeholders. At the end of the project we "unpacked" (Storni 2012) the entire process into boxes. This allowed us to look at the theoretical model of Ultra-Personalized Products and Services from our practitioner's eyes. While the UPPS model had peripherally informed our process, our first hand, practiced based research allowed us to fill the gaps between practice and theory. We literally compared our practice to the theoretical UPPS model by placing every sample we could find in our studio into physical boxes representing the different steps of the UPPS model. We found gaps that helped us to refine and redefine the UPPS model including adding enabling transitions.

Theoretical Background & Related Work

Shoemaking is a complex practice. It can be executed by a single artisan in a small studio or by large companies with thousands of workers in far off factories. The side of shoemaking that relates to our work is personalization, a topic of interest to shoemakers of all sizes. This interest in personalization is historical seen in "Boots and shoes: Bespoke Bootmaking." (Bell 1937) or "Metal fittings on the Vindolanda shoes" (Greene 2018). Our research and practice was inspired by visits to shoemakers, shoe museums and archaeological sites to understand shoemaking practice. We also studied personalization in large scale shoemaking. Adidas, Nike, Under Armour, Reebok, Ecco, United Nude, Desma, HP and many others are making attempts at personalized shoes. We can see these in papers such as or "Getting to the bottom of footwear customization" (Weerasinghe & Goonetilleke 2011) or "Mass Customization at Adidas" (Piller 2012)

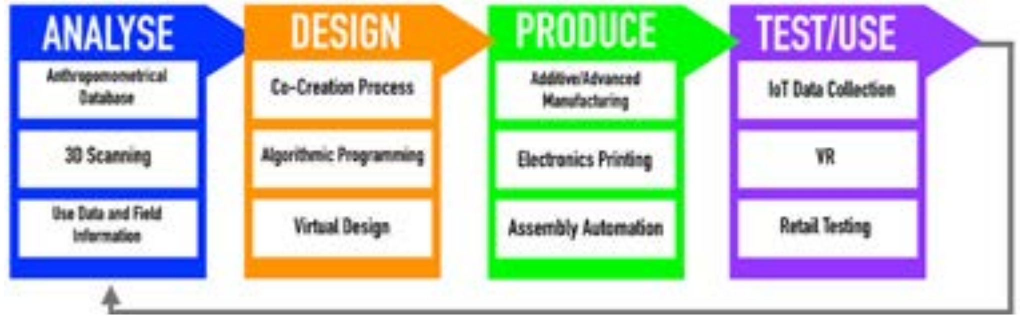

Figure 3. Original UPPS Model extracted from a presentation by Click NL, proposed by the UPPS Field Labs projects supported by the 3TU Technical Universities of The Netherlands.

Unpacking (Storni 2012) inspired us as a way to deeply look into an object and its making. Storni looks deeply into a designed object that have constituents and aspects. Unpacking for Stroni is a way to "provide a perspective on design practices that allows us to focus on the movements and the transformations that lie behind products" (Storni 2012). We build upon Storni by making unpacking a process of boxing. Grouping the samples by movements and transformations of the material & data in each sample to create a new kind of annotated portfolio (Bowers 2012).

Research Products unlike research prototypes, are inquiry-driven, finished, fit, and independent (Odom et al. 2016). These objects are typically created as single pieces or small batches to actively be used in everyday life. Research products often resemble artisan products but are inquiry-driven. We worked in a style resembling bespoke shoemaking with digital tools to make shoe research products which were worn as part of the research process.

Encoded Materials use new kinds of flexible materials, making the digital fabrication of personalized shoes increasingly possible as seen in our previous work "Towards Ultra Personalized 4D Printed Shoes" (Nachtigall et al. 2017). Material Science and HCI shown data defining how internal structures bend and flex (or don't) in recent research such as "selective buckling" (Paulose et al.2015), "metamaterials" (Ion et al. 2016), "programmable materials" (Vallgårda 2017), "personal fabrication" (Baudish and Muller, 2017), "using algorithms" (Feijs et al. 2016) and "dynamic behaviours" (Ballagas et al. 2018).

Ultra Personalization Digital tools and techniques for making personalized products have reached a level of precision that allows the personalization of the form, material, and behaviour of a shoe (Nachtigall et al. 2018). Adding systems of foot scanning, cloud services, and use sensing enables a new form of mass-personalization. This mass-personalization takes place inside of a data-rich environment that concentrates on the needs of the user. We find researchers and practitioners calling this "Ultra-Personalization". We find examples in "Designing ultra-personalized embodied smart textile services for wellbeing"' (Bhomer et al. 2016), eLearning (Hutchison & Mitchell 2010) and the medical domain (Trifiletti Showalter 2015). There are examples that suggest ultra-personalization is an important next step; "Styling evolution for tight-fitting garments" (Kwok et al. 2018), and "Optimal design for additive manufacturing: opportunities and challenges" (Doubrovski et al. 2011).

Ultra-Personalized Products and Services (UPPS) was a theoretical model for personalization that we encountered during our practice based research. The UPPS theoretical model proposed by the 3TU Dutch Technical Universities. UPPS explains personalized products and services as a system of Analyze, Design, Produce, Test/Use (Ahsmann 2015), fig. 3. We see UPPS being used in a series of field labs around the Netherlands, where it is defined as "(1) Products in which personal data is obtained before use - such as 3D scans - and (2) products in which the data is obtained during use" (Stolwijk & Punter, 2018). The goal of UPPS is stated as "The development of radical new product propositions for the manufacturing industry through the innovative use of data and by making products fully customized." (Stolwijk & Punter, 2018).

A Flexible Design Practice

While we had the theoretical UPPS model roughly in mind during our design practice, there was always the feeling that our practice was more complicated than what the UPPS model expresses. This wasn't surprising as theory cannot fully understand the richness of practices or contexts. Nonetheless, we kept exploring how to use data to analyze, design, make, and profile shoes; all while encoding data for more shoes. In a series of four iterative design projects we created 272 samples, fig. 5. This included four pairs of fully wearable shoes, one foot scanning pressure pad, a material demonstrator and 266 other material samples/failures. These samples were made over two years. We scanned feet, programmed software, created printers (and other digital fabrication machines) and wore the generated product to understand the how and why of digitally fabricating personalized shoes.

Figure 4. Early work: printed samples showing development of our own software to make gCode for flexible filament FDM 3D printers.

This practice included the algorithmic programming of each of the samples detailed in our previous work (Feijs et al. 2015). No off the shelf 3D modelling software was used, rather we programmed the material to achieve detailed control over internal flexible structures by hacking the gCode language (Kramer 1994). Our earliest samples are seen in figure 4. GCode is little more than X,Y, Z coordinates with a move command G1, a speed variable F (usually in millimetres per minute) and an E extrusion variable. A line of gCode typically looks like “G1 X10 Y20 F300 E4.57. This roughly means move to the point AT 10mm by 20mm at 300mm/minute (slowly) and extrude 4.57mm of filament along the way. The most basic algorithm of the software is calculating the distance between two points to define how much material to extrude (§which took many hours and people to perfect). We arrived at the software through a combination of theoretical calculations and practical samples. In our practice the 3D printer stopped looking like a “printer” and started to seem like a computer-controlled hot glue gun. In time, the 3D printer more resembled a TNT (non-woven) textile loom. We increasingly found our hands inside the printer making changes while printing. TPE and TPU flexible filaments created complex structures that bent and flexed (or didn’t) in specific ways. Thin wall geometries being very soft and flexible. Geometries that fill a space with 45% or more seeming solid and strong. Combining hard and soft properties mathematically in code allowed us make shoes that are fit to the individual in terms of comfort, support, flexibility, and aesthetics. We described developing these design considerations in our previous work (Nachtigall et al. 2018). In the next section we present how we created a system of foot scanning, shoe design, shoe manufacturing and use monitoring that resulted in a wearable shoe that collected data to make more shoes. While other research into encoded materials was informing our work, we chose a first hand hybrid craft experience. We developed our own algorithms and material structures and explored the relationship between data & material. What resulted was a research product (shoe) that provided data and a rich context about the RtD research process.

Figure 5. Making Samples. A selection of the 272 samples created during the four projects.

Four Design Practice Projects

From Analysis to Design - SoleScan, fig. 6, was a project to create a sensor capable of revealing the shape and pressure of a loaded foot. It was made using digital embroidery technologies. SoleScan was designed to show footprint as 2D foot dimension outline and pressure as a 3 mm 3D image. The software visualized and recorded data of the footstep on the sensor. This project taught us that there are many different kinds of feet, beyond the length and width of the foot. We saw many outliers in terms of shape (especially height) and pressure balance from the 400+ scans at a public exhibition. High arches, large big toes, and small toes confused the system. We adjusted for these on the fly, but we had to also change the scanning process to capture the full weight shift in a footstep. Even if we thought we knew how complex the feet of all the people, we ended up realizing the footstep was far more complex than expected when turned into data.

From Design to Manufacturing - Solemaker, fig.7, was a project to create software for 3D printed shoe soles and laser cutting shoe uppers. Solemaker was designed to allow a user to co-design the size (footbed), the aesthetic (tread), support and comfort (density) of a shoe sole. In Solemaker we learned to negotiate design considerations with geometry and algorithms. We wrote code directly into machine gCode instead of using slicer software (slicer software take a 3D model and transforms it into the .gCode that a 3D printer needs, like Microsoft Word generating a postscript file but for a specific printer). This required different kinds of .gCode for different 3D printers. We faced challenges as materials or colours (of the same material) had different flexibility and density. This required creating a unique relationship between the specific material and data controlling it.

From Manufacturing to Use - Solemaker.io, fig. 8, was a project to gather the data from the analysis, design and manufacture of the personalised shoe. The project allowed website users to stand on the SoleScan and have a shoe dynamically generated via an algorithm for their foot. The shoe sole could then be modified in a design interface and complete the process with a gCode file for 3D printing. At the same time, it would generate the uppers needed to laser cut leather (or similar material) for the shoe. Solemaker.io brought together the various modules needed to make a fully functional demonstrator. Solemaker.io served as the database for all the data and shed light on the idea that machine learning can be used to understand shoes over large populations.

From Use to Analysis - EVA Moccasin, fig. 9, was a project to explore sensing and aesthetics in a parametric shoe. The project was built on top of Solemaker and added sensing to the sole of the shoe. A new shoe construction was used to explore alternative solutions and add 3D printing on the leather shoe upper. The printed sole was inserted into a moccasin construction to make the sole replaceable and avoid stitching the sole to the upper. Different methods of sensing were explored using electronic and mechanical sensing. Sensors were internally printed inside the sole structure to collect personalized data about the wearer. EVA Moccasin showed multiple ways of sensing inside shoes to make the next shoe more personalized.

Figure 6 Analysing the Foot. The SoleScan foot scanner revealing the pressure of the users foot.
Figure 7 Designing the shoe. Photo: An early version of the Solemaker.io software being used to design the tread of shoe sole
Figure 8. Manufacturing Shoes Printing shoe soles on modified commercial and self made 3D printers Photos: © Bart van Overbeeke.
Figure 9 EVA Moccasin. A Shoe that is generated from footstep data. The shoe records data during its lifetime of use for future shoes.

Research Methodology: Material Sample Boxing

Theoretical research models can often be like maps drawn by people listening to stories from others who went somewhere (or didn't). In our research, we went there, described it in detail, and updated the "map". This meant programming shoes with code, data, digital fabrication and soft materials. This was a new way of making shoes when we set out. Designers, artisans and other practitioners know that understanding a craft requires making numerous swatches and samples. This is especially true when engaging in a process creating a new form of craftsmanship. Making this process explicit is often very challenging for practitioners. Only once we had accomplished making a full shoe (that also recorded data) were we were able to utilize the embodied complexity of all the created samples to explore our practice and the UPPS model in a profound way. Our aim was to provide a complex picture of our practice and what it meant to the UPPS model.

Previous to the research we visited bespoke shoemakers, fig 2. and started to make shoes using digital fabrication as seen in our prior work "Towards Ultra Personalized 4D Printed Shoes" (Nachtigall et al. 2017) or the 'Spike Shoes' in figure 1. This attracted us to the model of UPPS in figure 3 (step 1 in fig. 10). The UPPS model informed our design practice as we created the four projects described in the previous section resulting in the 272 samples in figure 5 (step 2 of figure 10). Working with a graphic designer we created the icons in figure 11 to help describe our practice while making the samples in the projects (step 3 of figure 10). As we completed our practice of shoemaking we realized that the small line connecting Test/Use to Analyze in figure 3 was more significant than previously thought. In figure 10 step 4, we used the icons to describe how the shoes from the Eva Moccasin (fig. 9) made data to make more shoes in a circular system. It was at this time that we changed the labels of the UPPS system as well. We added "Co-" to the stages making them Co-Analyze, Co-Design, Co-Manufacture and Co-Use. We made this change because of the number of stakeholders involved in every project. Using a person's data made them a specific stakeholder. Programmers, designers, digital fabrication specialists,podiatrists and others were all involved in the system. We were all users of the data. Thus, the person we were making the shoes for came to be called the wearer. Throughout findings we use the "co-" terms to communicate the aspect of multi-stakeholder collaboration required in this hybrid craft.

Unpacking into boxes

In order to better understand the model and our practice, we created a series boxes labeled with the UPPS model phases: co-analyze, co-design, co-manufacture and co-use (figure 12a). The practiced based design researcher scouted the studio and collected 272 samples (swatches, failures, demonstrators, research products) and considered the material, code, behaviour, manufacturing process, stakeholders and that each embodied. He placed the samples in the box that represented them best (figure 12). Sorting many of the artefacts was a frustrating process even though he had direct experience with the code and creation of every sample, artefact, and research product.

Many of the samples (more than half) fit into two boxes. After much consideration the samples were forced into a single box (figure 12b). The contents of the boxes are shown in figure 12c. Storni in "Unpacking Design Practices" (Storni 2012) only unpacks a single item. We had hundreds that came from all over our system. Our process was more like reverse engineering, an archaeological excavation and a dumpster dive. All at the same time happening in our own studio. We took inspiration from annotated portfolios, which Bowers describes as "a means for capturing the family resemblances that exist in a collection of artefacts, simultaneously respecting the particularity of specific designs and engaging with broader concerns." (Bowers 2012). We realised that there were transitions between the boxes (step 6 figure 10). The in-between samples enabled transitions between them. We developed icons and names for the transitions (step 7 figure 10). In the following section we present our findings and example samples from each stage. We detail our process of unpacking in greater detail, and describe the enabling transitions we discovered via a series of examples.

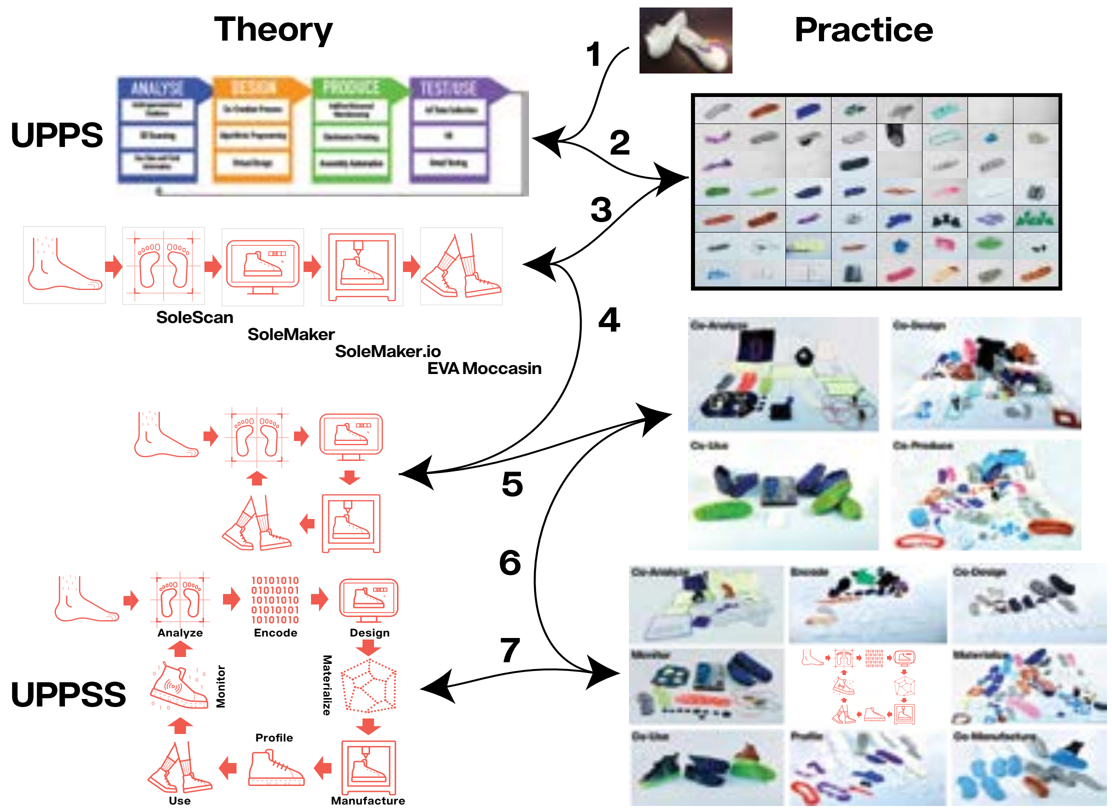

Figure 10. Mapping Practice to Method. A map of the relationship between our shoemaking practice and the UPPSS theory

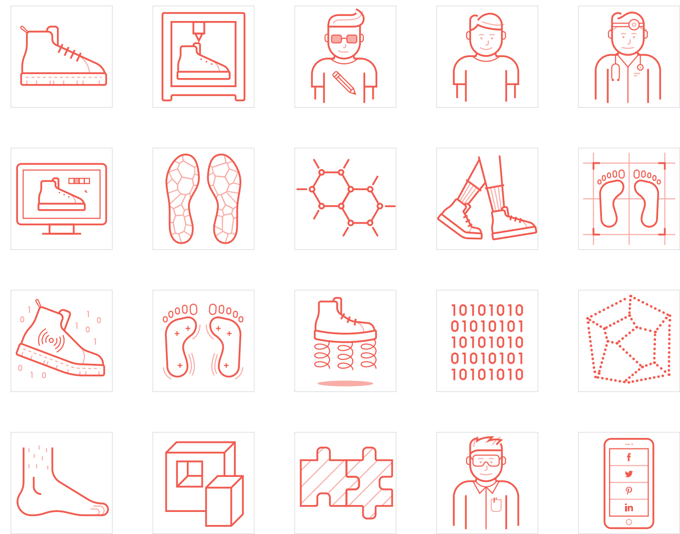

Figure 11. Illustration: Max Pirsky A series of icons created to describe the shoemaking practice.

Findings

From the 272 digitally fabricated samples we created, we selected a sample from each box that exemplifies that stage of the UPPS model. The following findings show the intermediate design knowledge (Höök and Löwgren 2012) between the practice and model. As described above, we started with boxes for each of the UPPS model stages and sorted all of the samples into the boxes, fig 12. Following is an example of each box.

Figure 12 Unpacking the samples into the Analyze, Design, Produce and Use boxes. a. Boxes were made b. All the samples were meticulously unpacked along with their source code. C.Final Groupings of the first unpacking.

An Example of Co-Analysis #263 Foot Pressure Pad, fig. 13, was made in the SoleScan project to parametrize the footstep and size of the user. It is a prime example of the co-analyze stage. The capacitive sensor revealed the foot size and footstep pressure of feet up to a men's size 47 EU. It was exhibited at a public exhibition where more than 400 feet were scanned. The sensor worked well with feet and shoes. This example is made on digital embroidery technology. Making the sensor required an electronic engineer capable of programming, a podiatrist, two digital fabrication specialists and the practice based design researcher.

Figure 13. Foot Pressure Pad. This sample is made from 100% polyester fabric, conductive ripstop nylon, rivets/snaps, polyester embroidery threads, 4mm cork sheeting and industrial spacer fabric, Eletrosola 4x0 071, a Cypress CY8CKIT-050 5LP,and Standard Electronic Headers. It was created on a Brother PR655 digital embroidery machine using soft textile techniques. Software was written in Processing and Matlab. The sensor samples at 20 Hz over a 16 x 8 matrix resolution revealing 4mm of 3D form.

Discussion In using the foot pressure pad to scan hundreds of feet we realized there is an extreme complexity in the analysis process. Many outliers were found in the process and the software required many updates. A very close stakeholder relationship was needed. Moreover, revealing the foot pressure using capacitive distance sensing was very accurate. There was a serious challenge in converting the entire footstep data (an image over time) into single parameters for the generative Solemaker design software. This sample worked great as co-analyze, but presented problems as we transferred the data to the design software.

An Example of Co-Design: # 236 Variable Density Sole, fig 14, was the first wearable pair of shoes made in the Solemaker project with variable density sole treads and flexibility. The software was heavily edited to add an interface that allowed each cell to be selected and the density set manually. The parametric data from SoleScan was not yet added. This sample represents the co-design phase because it shows how the software could be used to personalize the tread by a user. The practised based design researcher and digital fabrication expert did the vast majority of the programming with the computer scientist advising. This sample marked a point where many of the involved stakeholders began showing initiative.

Figure 14. Variable Density Sole. This sample was made from FilaFlex Silver TPE-s Filament on a handmade Prusa i3 with a 0.4mm nozzle fabricated specifically for shoe manufacturing. The shoe upper is made from 100% Technical polyester with a waterproof performance finishing. The dynamic density soles were written in Processing.

Discussion It is clear that we would have designed the system differently if had we known how SoleScan would parametrize the footstep. Adding tread tools increased the software complexity as many arrays managing the math were needed. Changing the internal geometric structures added a significant amount of rendering time and .gCode file size (megabytes instead of kilobytes). Because of its complexity, we had to re-tune our algorithm to negotiate the behaviours we were programming. This sample worked well, but lead to a vast number of problems in the co-manufacturing phase.

An Example of Co-Manufacture: # 113 Bend and Flex Sole, fig 15, shows how we made the shoe soft or hard, floppy and stiff in specific places (treads, footbeds, sidewalls) using specific mathematical geometries. This project required the practice based design researcher and two digital fabrication specialists work countless hours to perfect the software & hardware relationship. The relationship had to be established per machine, filament, and filament colour. This required adding parameters and code to account for these differences. Additionally, changes in ambient temperature, humidity and other contextual variables could change the co-manufacturing reality.

Discussion As with many manufacturing processes, there is a large difference between the ideal computer model and the actual output. When 3D printing for dynamic behaviour the differences can change the amount of bend and flex (and other design considerations) dramatically. For example, we created parameters for colour differences per printer as more transparent filaments create a softer behaviour ver-

Figure 15. Bend and Flex Sole. This sample is made from FilaFlex Silver TPE-s Filament on a handmade Prusa i3 Slem Silver with a 0.4mm nozzle fabricated specifically for shoe manufacturing. The sole was created using the Solemaker software. A new technique for negotiating support and flexibility was created.

sus the opaque filaments. Dealing with this complexity showed us that a system can become large and complicated unless we give a local digital manufacturing specialist the tools to be able to adjust the software to a specific printer in a specific colour on a specific day.

An Example of Co-Use: #188 Brown Knit Shoes, fig 16, were digitally fabricated and worn for a four month period on the streets of Berlin. These shoes exemplify co-use as they were a fully functioned as a pair of shoes worn as a research product. The code was written by a computer scientist working with the practice based design researcher and a digital fabrication specialist. The style and behaviour of the shoes were designed by a shoe designer and the practiced based design researcher. The experience of making and wearing these shoes inspired the making of the EVA Moccasin.

Discussion Wearing the personalized shoes for an extended period of time taught us how the shoes behaved during a long day. The shoe had personalized flexibility,comfort and support but there was too much flexibility and not enough comfort. The shoes performed well in the fall season but, as the temperatures became sub zero Celsius, the material became stiffer and harder. In wearing these shoes the soles began shaping to the foot and discolouring where the foot applied pressure to the ground.

There is something between the boxes

Unpacking the samples into the boxes was a long and challenging process. Reflecting on our sorting revealed a struggle with over half of the samples which fit into at least two boxes. In discussing the difficulty with fellow authors we realised that a majority of the design happened in connecting the data from one box to the next. Apparent in the data & material relationships was that many samples illustrated how we connected the phases of UPPS together. Many sample connected one phase of UPPS to another phase. These in-between phases seemed to represent a large amount of the involved stakeholders' time and effort. Icons, then descriptors about what we saw happening were assigned to these spaces. These descriptors are as follows:

Figure 16. Brown Knit Shoes. This sample is made from FilaFlex TPE-s Filament on a handmade Prusa i3 3D Printer with a 0.4mm nozzle fabricated specifically for shoe manufacturing. The leather is 3mm thick vegetable tanned leather. It was laser cut and etched on a Trotec Speedy 300 laser cutter The sole and uppers were created using the Solemaker software.

Materialization enabled the array data of co-design to become the .gCode of co-manufacturing. As we see in sample #113 Bend and Flex Sole, fig 15, the code behind the object enabled the 3D printer to create the object. Encoding enabled the footstep data SoleScan to be used as a parameter to algorithmically generate the sole treat densities previously seen sample #236 Variable Density Sole, fig.14.. In the data, this was a transition from a Matlab file to a compressed .json file. Monitoring enabled the data of co-use to become co-analysis. The Eva Moccasin was able to make data for co-analyze as seen in sample #188, fig.16, which gave us new insights in how this could be done. Once the entire process was completed, the importance of the space between co-manufacturing and co-use became apparent. Profiling enabled co-manufacturing to become co-use. We needed to store the data about the foot pressure from the co-analysis, how the user changed the shoe design, and the details including errors about co-manufacturing. This would allow a detailed system to track the shoe use data against the profiling data as we see in #113 Bend and Flex Sole, fig 15.

We named these physical spaces between the boxes enabling transitions as we discussed how the samples could fill the spaces. We unpacked each sample a second time and placed it in the box or space between the boxes, as seen in fig. 17. We report specific examples of artefact samples that exemplify the spaces, fig. 18, and discuss why each is in that space.

Figure 18 New family of groupings added in the second Unpacking resulting in enabling transitions

Figure 17. Unpacking the samples into the boxes and spaces between the boxes realizing the enabling transitions that connect the boxes.

An Example of the Enabling Transition of Encoding: # 38 The Heel imprint in a shoe heel, fig 19, was made to increase the comfort of the shoe. The outline and footstep pressure data was used to create a softer geometry, allowing the foot to sink in and be supported. This required encoding the footstep into parameters that the co-design software could use to generate the sole. This example shows the moment when we effectively integrated the outline of the foot, but the pressure data failed as we attempted a soft gradient of material.

Discussion This sample is one of fifty-two where we needed to perfect the code and data transitioning from co-analysis data to the co-design software. This transitioning required numerous hours achieve. During the public demonstration of the system we found many problems caused by outliers such as very high arches, over fitting caused by over personalizing to a single person, and a miss calibration of the upper and lower boundary parameters. Some might compare this phase to debugging software, but something more fundamental was happening in the function of the overall system. An understanding was being created between two complex systems. We had to learn to deal with outliers that caused unexpected behaviour in the negotiation of design considerations of the sole.

Figure 19. Heel imprint. Made from FilaFlex Clear 75a soft TPE-s Filament on a modified Ultimaker 2 with a 0.8mm nozzle. The heel footprint seen is a composite pressure image created by the SoleScan software, written in Matlab. Solemaker software then generated the heel of a shoe with a softer density in the heel area to make the footbed more comfortable. Difficulties connecting the two software parameters resulted. An encoded composite was added to correct the problem.

Figure 20. Open Footbed: This sample is made from FilaFlex Clear 75a soft TPE-s Filament on a Prusa i3 Slem Silver with a 0.4mm nozzle that was fabricated specifically for shoe manufacturing. It is discoloured from the printer nozzle running too hot. This sole is a prime example of selective buckling support mixed with open cell breath-ability to keep the shoe from overheating.

An Example of the Enabling Transition of Materialization: # 58 Open Footbed, fig 20 shows one of the many errors between code and manufacturing. The gCode geometry needed to be printed on the 3D printer. In this example we were negotiating the comfort of the sole against the robustness of the shoe. Changing a single parameter for comfort in the co-design software resulted in the opening of the entire footbed. It was not what we were looking for, but inspired many other geometries.

Discussion Materialization was the single most represented enabling transition with more than 100 sample failures. These represent the difficulty of programming 3D printing geometries that are negotiating design considerations for form, behaviour and aesthetics. One of the most notable peculiarities from these samples is that a 3D printer modified for flexible filaments behave more like a knitting machine. The tension is a game of pushing flexible filament at the exact right speed, too little and nothing comes out, too much and things get blocked up thus nothing comes out.

An Example of the Enabling Transition of Profiling: # 113 Into the Spaghetti, fig 21, is a dramatic result of what happens when the 3D printer under-extrudes (fails to deposit enough material). We worked with many different printers in the materialization process: commercial and hand-made. Each kind of 3D printer has slightly different initialization code, bed size, and nozzle size. Occasionally, the wrong printer, material, or colour profile was used. Each printer has its own way of behaving, even if two are the same brand and model. Moreover, the direction of travel of the print head and sequence of print features in specific gCode geometries caused over and under extrusion of material. This changed the behaviour of what we had programmed.

Figure 21. Into the Spaghetti This sample is made from Ninjatek Cheetah TPU Conductive ETPU Filament on a modified Ultimaker 2 with a 0.8mm nozzle. It was generated using the Solemaker. A profiling error resulted in the under-extrusion.

Discussion Creating data for new shoes meant that the precise details of the co-manufacturing exist in a profile. The flaws in co-manufacturing often did not render the shoes unwearable, they needed to be recorded as a baseline for co-use. Profiling remembers the multitude of variables so that each shoe can be understood individually. It was important to track this small internal flaws for co-use sensing as it could affect the behaviour of the shoe over time. This would become very important as we added mechanical sensing for co-use.

Figure 22. Wear and Tear Demonstrator. This sample is made from FilaFlex 85a TPE-s and Ninjatek Cheetah TPU Conductive ETPU Filament on a modified Ultimaker 2 with a 0.8mm nozzle. A teensy 3.2 and neopixel ring provide user pressure feedback from the ETPU sensor. Mechanical sensing is shown in abrasive colour change and linkage breaking available for the public to handle.

An Example of the Enabling Transition of Monitoring: # 265 Wear and Tear Demonstrator, fig 22,was made in the Eva Moccasin project where we learned that monitoring data over the co-use of the shoe was vital. A demonstrator was created to show how both electronic and mechanical sensing could be added to the shoe as describe in "EVA Moccasin: creating a research archetype to explore shoe use" (Nachtigall 2016). The enabling transition of monitoring collects and carries data from the use of the shoe back into co-analyze .

Discussion Monitoring during co-use allows for a complex picture of the varying activities that were undertaken while wearing the shoes. While this data generally reflects day to day walking, special activities such as dancing and tennis can create very specific data. The data gathering in the monitoring phase is not just beneficial in co-analysis to make the next shoe, it can indicate needs in a full closet of shoes.

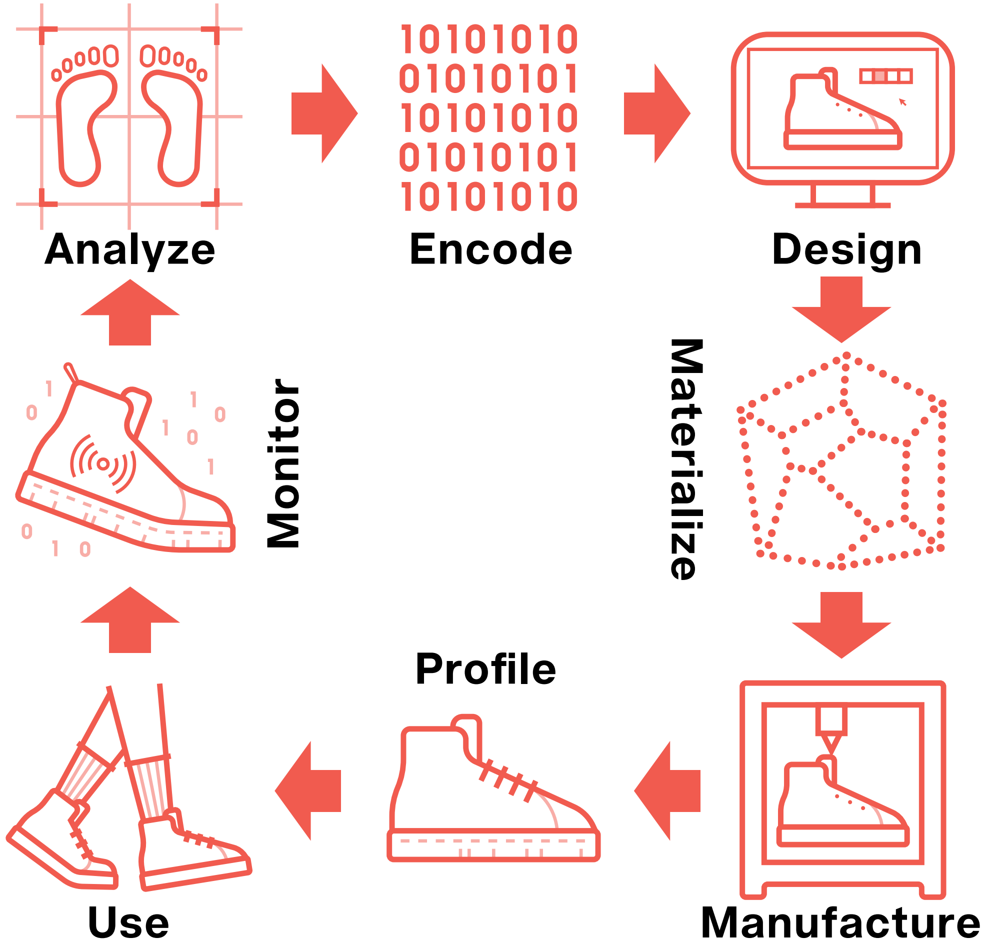

Figure 23. A Model for UPPSS : Based upon our practice of personalized shoe making, we arrive at a model of UPPSS that is a system that includes enabling transitions.

Discussion and Conclusions

The four Solemaker projects came together as a complex system for making personalized shoes that make the data trail to make more shoes. By unpacking into boxes we came to the following conclusions.

The UPPS model contains enabling transitions that connect the stages of UPPS proposed in (Ahsmann 2015). The four enabling transitions presented show that the model lacked a level of description relating to the data back-end of the system. The new model is a circular process of co-analysis, encode, co-design, materialize, co-manufacture, profile, co-use and monitor. The enabling transitions were equally important as the rest of the stages. In designing the system, the enabling transitions required more time than the existing stages. As stakeholder practice was embodied in the samples, these newly defined stages could be integrated in the model with a high level of detail. Encoding makes explicit the way a physical thing and/or its behaviour becomes parametric data for co-design. Materializing makes the negotiation of data needed to transition from a digital construct to one that can be digitally fabricated into a thing. Profiling remembers the data about the thing and strategically proposes a use for the object based on its strengths and limitations. Monitoring shows the importance of carefully planning and setting up the collection of data that will loop back into analysis.

The UPPS model is a cooperative process. Many stakeholders, including the wearers whose data were used, were involved in every sample that sorted into the UPPS model. It is important that the definitions of UPPS reflect that importance. We conclude that the stages of UPPS could be re-coined to reflect this stakeholder relationship: Co-Analyze, Co-Design, Co-Manufacture, and Co-Use. We use Co-Manufacture instead to Produce (from the original model Ahsmann 2015) as Co-Production carries a strong definition that includes the entire production process (sourcing, manufacture, etc.) seen in marketing research (Jiménez et al. 2013).

A better naming of the practice and process of UPPS is Ultra-Personalized Product Service System (UPPSS). In the four projects we quickly observed that designing an UPPS is the creation of a system with: a complex interplay of data and materials, a series of services that the stakeholders interact with, and enabling transitions that interface the stages of UPPS together. The change from UPPS to UPPSS creates a model that depicts the practice of designing a system that creates the products and services. In line with the research done in Product Service Systems (PSS), the UPPSS model thus considers all stakeholders, infrastructure, resulting products and services at the same level (Tuckker 2004). This also reflects a move from a vertical production to a horizontal collaborative setting like that shown in "Designing Smart Textile Services through value networks, team mental models and shared ownership" (Bhomer et al. 2012). Figure 23 summarizes the new UPPSS model.

The way in which we unpacked the complexity of our samples into boxes is also a methodological contribution to RtD and unpacking (Storni 2012). Unpacking a large number of samples builds upon the idea annotated portfolios, capturing groupings of artefacts under specific labels and reflections (Bowers 2012). Unpacking and boxing our understanding of the data and materials behind each and every sample helped us to acknowledge and revise the UPPS model. We made the model more descriptive based on our personalized digital shoemaking practice. Thus, supporting the validity of that model. At the same time, the model provided inspiration to create intermediary knowledge of designing a system that creates shoes using a data & material relationship.

Finally, this paper provides a complex picture of practice in digital craftsmanship. The enabling transitions shown here are a description of encoding data and materials to behave in specific ways. The encoding is based upon a scaffolding of a bespoke craft with digital technology. The practice often required crafting the behaviour the sole in data and material simultaneously. Even if Solemaker never made a second pair of shoes for the same person, the data could make other shoes better which is important for design.

Future Work

More than 100 pieces of .gCode did not print. The meaning of the materialized data that didn't print could also be important. Perhaps creating a system that tracks the designers practice in a form of sub-version control (eg. git or mercurial) could assist in understanding data that does not materialize. We observed a deep relationship between the data and material in the system. It is important to investigate how data & material form a new relationship and answer why it is important. It's seems highly possible that a new discipline is emerging with a new material understanding

Developing the circularity of the model in a deeper way would also bring more understanding to the how and why of personalization. The model needs to be generalized for design researchers and practitioners in personalization. We intend to use the developed model as a departure point for design, perhaps in the form of a game. The UPPS Field lab (www.UPPS.nl) has proposed their own change to the UPPS model by adding a stage of collect to the theoretical model. We see this more as a enabling transition which may be a better term for what we interpreted as monitor. Also, as the model is a system, product service system research and cybernetics research may be able to provide more insights.

Finally, the practice of digitally crafting personalized shoes and other objects has many facets to be explored. We invite other practitioners to use join us in personalizing objects form, behaviour and aesthetic to create an individual everyday design.

Acknowledgments

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7.2 Critical Reflection

The results were based upon the experiences of the design researcher and required the researcher's direct reflections on each artifact. These reflections could have been richer if a subversion system such as Git[44] or Mercurial[45] was used. This would need to include a camera attached to the printer. This was attempted in experiments with Ultimaker. It was discovered that the motherboard of the 3D printers was not capable and that a daughter board such as Octoprint[46] would be required. This was not implemented but should be. Additionally, this would allow the consideration of the the code that resulted in nothing being printed. Reflections on this were presented at the workshop "Doing things with RTD" (Andersen et al. 2019) at CHI 2019.

Limitations of the work

The results are based upon a theoretical approximation of a digital-fabrication shoemaking system. While it makes shoes and is based upon years of industry experience, it is only an approximation of what a future system may be. It is based upon emerging technology of 2015 which has already been replaced with newer emerging technology. Also, the paper fails to present the resulting theoretical model in a way that is accessible to others.

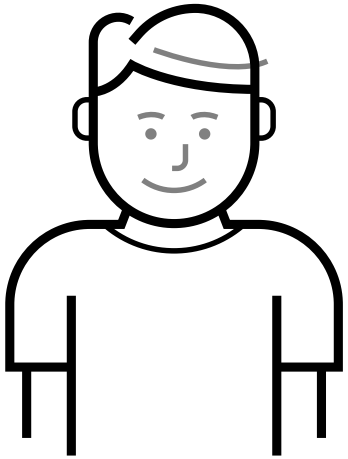
How is this different from a traditional bespoke shoe?

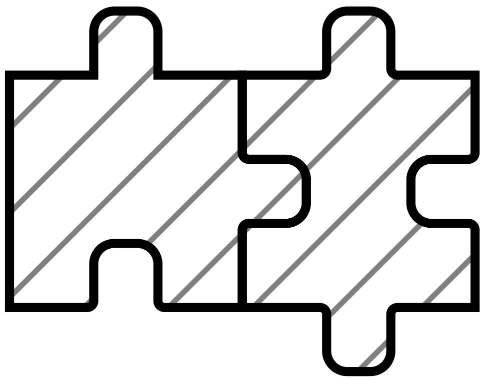
Bespoke shoemakers often keep samples to remind them of technique, skills, and knowledge. This project could have been done as an ethnography with bespoke shoemakers studios but this would likely fall to the social sciences.

Impact

The theory from this project was implemented into a design game and transmitted to design students which resulted in the paper in chapter 8.

44 https://git-scm.com/
45 https://www.mercurial-scm.org/
46 https://octoprint.org/





8 Digital Craftsmanship and the UPPSS game

A Design Game to Support the Crafting of Product Service Systems

Published as "From Personal to Ultra-Personalized" (Nachtigall et al. 2019) and presented at the International Conference of the DRS Special Interest Group on Experiential Knowledge - EKSIG 2019.

The findings of the research are operationalized into a UPPSS game that was taught in a course called **Digital Craftsmanship**. The game found that data (and data as a material) is difficult for designers. The design game helped overcome this difficulty. The game includes an embodied shoemaking is experience that the UPPSS design game helps abstract that knowledge to scale it up into a product service system. Students created dataflows and customer journeys that allowed them to create their own web based UPPSS. This showed that the knowledge of UPPSS is transferable.

8.1 A Design Game to Support the Crafting of Product Service Systems

Role

The UPPSS game was instrumental in showing that the theory could be implemented by means of a design game. The UPPSS game showed that a physical making experience could inform a complete Product Service System.

Research Question

Can the knowledge generated previously be transferred to others using a design game?

Research Conclusion

Yes, but the knowledge is transferable to varying degrees.

Quality of the output

The resulting shoes were wearables and personalized. One of the teams demonstrated that the system was possible by implementing the system on a website.

Favorable outcomes

What worked in this project is that students were able to create an UPPSS complete with data flow and customer journey.

Difficulties and Unfavorable Outcomes

It was difficult for the students to devise methods to create data using physical materials.

From Personal to Ultra-Personalized

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FThe UPPSS design game is used to change an individual shoe making experience into a detailed product service system with customer journey and data flow

Abstract

We envision a near future where shoe design is more than sketching shoes. Shoe design becomes the crafting of parametrically generated, data-driven, iterative forms along with multi-stakeholder Product Service Systems (PSS). Accomplishing shoes that embody this requires new forms of digital craftsmanship that build upon ever emerging hybrid crafts. New forms of digital craftsmanship are scaffolds of data and digital fabrication into Ultra-Personalized Product Service Systems (UPPSS). In the complex process of UPPSS designers are confronted with challenges; product challenges in negotiating design considerations, with service challenges in customer journeys and systemic challenges in of data flows. Design games are rarely used to design shoes but offer a lot of opportunities. In this article, we describe and deploy a design game for UPPSS shoemaking. The game was designed to help designers to confront these challenges. This included using code to program the digital fabrication of a pair of shoes. The UPPSS game was deployed with 16 industrial design students over nine weeks. Each wrote a reflection on what they learned. The reflections were analyzed to see how the design game resulted in facing the challenges of an UPPSS that is summarized in an interpretive framework. Conclusions were drawn from the challenges and opportunities confronted in the game, and what this meant to the emerging practices of digital craftsmanship and UPPSS.

Keywords

Design Game, Ultra-Personalized Product Service System, Shoe-making, Research through Design, Digital Craftsmanship

Introduction

Previous research on computational composites (Vallgårda and Redström 2007), Meta-Materials (Ion et al. 2018), and data-driven design (Bogers et al. 2016), has shown how data and materials can be crafted together to form things. The idea of digital craftsmanship, previously seen as a workshop (Jacobs et al. 2016) is emerging in the form of bespoke craft. Examples include research done in academia (Wensveen et al. 2016) or in the maker movement (Papavlasopoulou et al. 2017).

At the same time, emerging technologies are enabling new possibilities in personalization (Benford et al. 2018, Zoran 2015, Magrisso et al. 2018). Personalization means that the product and service are made to fit the style, form and behaviour of the user. While this can be done in bespoke shoemaking, the challenges of scaling up into data-driven (user data drives parametric digital fabrication) iterative (generations of objects inform their predecessors) product service systems remains in the roadmap into a future of Ultra-Personalization. Ultra-Personalized Products and Services are defined as "(1) Products in which personal data is obtained before use - such as 3D scans - and (2) products in which the data is obtained during use" (Stolwijk & Punter, 2018). In previous work we connected the two systematically (Nachtigall et al. 2019b) Shoe-making has been shown as a domain with the potential to illustrate Ultra-Personalized Product Service Systems (UPPSS) and bespoke personalization (Nachtigall et al. 2019b). Moreover, shoes have a very long history of personalization (Ball 1937, Greene 2019).

Industry and academia are very interested in shoe mass-customization (Piller 2012, Weerasinghe & Goonetilleke 2011), and we find examples of bespoke personalization in small companies such as Solemaker or Feets, and in large companies like Adidas (Piller 2012), Nike, Under Armour, Reebok, Ecco, United Nude, Desma, HP and many others. Shoes are also a good place for data, the first wearable computer was embodied in Shannons and Thorp's shoe (Mann 1997) with many examples of continued interest in computation in shoes as computers (Schirmer 2015) or as the result of a computational process (Feijs et al. 2016).

Yet, training industrial designers to design an UPPSS remains a challenge, and data-driven iterative shoe personalization systems is no exception. Industrial designers have difficulties scaling up shoe design into services and systems while maintaining a high level of craftsmanship. In order to understand how to address the challenges of designing UPPSS we created a design game for scaling up bespoke shoe personalization. This was connected to helping students recognize and develop connections between the math, data and computing courses they had before (calculus, data analytics, programming) and the demands of contemporary systems design.

In this paper, we explore the value and possibilities of the UPPSS design game by analyzing the reflections from industrial design students after working with it. The game was needed to make objects like shoes that are crafted to the individual. Using an interpretive framework developed by (Nachtigall et al. 2018), we evaluate their understanding of UPPSS design. From the findings, we draw conclusions about how the game supported the creation of an UPPSS system, suggestions are made to the interpretative framework, and we reflect upon the emerging design practice of Digital Craftsmanship for Ultra-Personalization.

Related Work

"The Stuff of Bits" by Paul Dourish (Dourish 2015) showed data to be a material that can be used to design with. Although the actual application of data as a design material to support the next level of personalization is a challenging and complex process, research on computational composites (Vallgårda and Redström 2007), Meta-Materials (Ion et al. 2018), data-driven design (Bogers et al. 2016), and the development of frameworks that suggest how to act on data (Forlizzi 2012) in general, are at the forefront of design and HCI research. Based upon earlier explorations into product ecologies (Forlizzi 2012) and on research done on PSS (Tukker 2004), Ultra-Personalization grows out of the research done into embodied smart textile services (Bhömer et al. 2016). Ultra-Personalized Product Service Systems (UPPSS) are data-driven iterative personalization PSS with multiple stakeholders and enabling transitions (Nachtigall et al. 2019b). Closing the iterative personalization loop in UPPSS requires dealing with product, service, and system challenges. The following sections describe these challenges in the emerging field of UPPSS applied to shoe design. For a summary see table 1.

Product Challenges / Learnings		Service Challenges / Learnings		System Challenges / Learnings	
Adapting Algorithms (AA)	Negotiation of design considerations	Reading the Body (RB)	A general purpose sensor is not personalized	Saving and Storing the Data Trail (SD)	Ideal vs actual
Manufacturing Misinterpretation (MM)	Limits of the current technology	Profiling Predicted Use (PU)	Potential for self - directed machine learning	Quantity and Scaling Up (QS)	Profile the thing, not the person
Standardizing Material Behavior (SB)	Ideal vs actual	Understanding Behaviour (UB)	Temporal composites	Comparing Data (CD)	Designers need data
Mechanical Sensing Material Structures (MS)	Active vs passive monitoring	Adding Sensing (AS)	Multi-purpose hybrid material geometries	Storing and Decoding Use (SD)	Understanding temporal composites as material

Table 1. An interpretive framework of the challenges and learnings faced when making a shoe based UPPSS, These are used to form the classification schema to evaluate the UPPSS game.

Product Challenges and Opportunities

Parametrically generating shoes for a specific foot requried **adapting algorithms for the negotiation of design considerations (AA)**. Researchers are applying specific geometries such as selective buckling (Paulose et al. 2015) in programmable materials (Vallgårda 2017) using algorithms to make flexible shoe soles (Feijs et al. 2016) and create dynamic behaviours (Ballagas et al. 2018). Algorithms translate these materials into dynamic forms (Frens 2006) using of computational co-design (Malakuczi 2017).

However, the results are not always what was expected. **Manufacturing misinterpretations (MM)** are unintended results that can appear when the limits of the technology are reached. To overcome these situations a designerly understanding is needed; i.e. human-material interactions (Giacardi and Karana, 2015) or how materials evoke a material conversation (Karana et al. 2016). Another way to look at it is as a process-led material based research that leads to design innovation (Marr and Hoyes 2016).

The next step is **standardizing programmed behaviour (SB)** when using data as a material. We see these opportunities already being addressed in the form of research products (Odom 2016) where specific quality requirements (inquiry-driven, finish, fit, and independent) allow the research to be deployed for long periods over the product lifetime. Additionally, challenges include creating a consistent and uniform result having digital fabrication technologies a different precision than industrial manufacturing. Real-time feedback and feedforward can already be seen in concrete 3D Printing (Wolfs et al. 2018) which illuminates new opportunities for UPPSS digital fabrication.

Finally, UPPSS requires data to be created by the resulting products. While traditionally been done with electronics, i.e, (Hertenberger et al. 2013), **material structures for sensing (MS)** allow also mechanical (Zheng et al. 2019) biological (Steiner et al. 2018), and chemical (Kao et al. 2017) sensing to produce data.

Service Challenges

The service challenges of UPPSS revolve around the customer journey. In shoe design, it shifts towards an intimate relationship with the wearer that requires management and trust.

To start the process of UPPSS (and continue iterations) a **reading of the body (RB)** is needed. An analysis of the (physical) characteristics of the wearer provides a design DNA of the wearer. There are many methods to gather data about the body such as footscans to lasts (Zhang 2010). Challenges include variability of body shapes and sizes (Griffin et al. 2016). Yet, new opportunities include using images to create body sizes creates (Mok and Zhu 2018) and convert that into digital fabrication (Hong et al. 2018).

Closely related is capturing of a movement or action (or a series thereof) of the foot as **Understanding Behaviour(UB)**. This could also be the social dimensions of where a shoe is worn. In shoes, this is can be a footstep; how the user strikes the heel to the ground and progresses to the talon and big toe. Human locomotion is complex as humans evolved to be bipedal (Hagman 2005). This complexity and how it translates to materials is described in "The development of methods and procedures to determine the dynamic and functional properties of sports shoes" [Vertomenn et al. 2011].

UPPSS requires the storing of data across times at many points of the process and comparing it to how it was expected to be used. There is opportunity for **profiling predicted use (PU)** to compare that against the actual use. This can be found in predicting the needs for the shoe with i.e. machine learning (Nácher et al. 2010), or using the data to predict life events of the wearer such as puberty (Busscher et al. 2011). This becomes more complex if we adopt a model of distributed manufacturing.

In building a system with data as a material, there is a challenge to make the right kinds of data described as **adding sensing (AS).** Sensing in shoes is commonly performed electronically (Shenck and Paradiso 2001) or from other places on the body (Skach et al. 2018). There is an opportunity to achieve this with materials that change as part of a computational system as seen in DuoSkin (Kao et al. 2016), Grow Kit (Steiner et al. 2018), and the EVA Mocassin shoes (Nachtigall 2017).

System Challenges

Research into system design spans decades (Norman 1986). Software and stakeholders face challenges and opportunities as seen in the data flow of an UPPSS process. The system challenges can be observed when creating an overall picture of how the data and material interact in UPPSS (Nachtigall et al. 2018).

Saving and storing the data trail (SD) is often used in app design and social media design, not physical objects. Much like home health devices now track patient health (Habibović et al. 2018), designers of an UPPSS have an opportunity to record data at many points during the analysis, design, manufacture and use of the object. That data is shared and used with many stakeholders. This can be seen in the current way usage statistics are impacting software development (Dinner et al. 2015), in UPPSS data is created and stored for at least the product or service lifetime. Questions of data security and privacy become important as well (Wetzels et al. 2018)

Artisans make bespoke personalized shoes using implicit craftsmanship. When making shoes with data new challenges and opportunities for **quantity and scaling up (QS)** become possible. The form, behaviour and aesthetic can be understood as data. New opportunities emerge such as monitoring, control, optimization (Porter and Heppelmann 2015). Challenges include the costs of digital fabrication (Baumers 2016) and the integration of craft and technology to move from mass customization to mass personalization (Wang et al. 2017).

Self-directed machine learning has opened up the possibility of **comparing data (CD)** from predicting iterations and users. UPPSS is driven by generational (Reiss and Stricker 2013) and multi-user comparison via pattern recognition and machine learning (Bishop 2007) at a design system level (Yang 2018).

As UPPSS depends upon data as a material, **storing and decoding use (SU)** is fundamental to the iterative generations of an UPPSS. We see the importance of that data in data-enabled design (Bogers et al. 2016) as well as the lifespan nature in temporal composites (Valgarda et al. 2015). Hybrid Reassemblage (Zoran and Bucheley 2013) provides a unique window into the possibilities of generational iteration with materials.

Creating a service design game for UPPSS

Service Design games have been shown to drive innovation and knowledge creation (Hannula & Harviainen 2016). Especially when dealing with the challenges of integrating products in service systems (Hannula & Harviainen 2016). Card games have demonstrated their capacity to deal with large amounts of complex challenges (Lucero et al. 2013). The UPPSS game we created is intended to scale up a shoe-based personal crafting experience into a full-fledged UPPSS. The game was inspired by other design games already used in service design that deal with multiple stakeholder co-design sessions (Mattemäki 2014).

The game board was taken from the theoretical UPPSS model, representing the UPPSS phases and enabling transitions described in “Unpacking Solemaker into a model for UPPSS” (Nachtigall et al. 2019b). The game board is a circular system with phases of Co-Analyze, Co-Design, Co-Manufacture and Co-Use in the corners. Co-Analyze is the process of understanding the needs of the person in different forms of data, including multiple expert opinions. Co-Design in UPPSS is a generative process that algorithmically negotiates the parameters of the wearer to the design considerations of the object being made. Co-Manufacture is the process of fabricating the object being made, often in a distributed location geographically close to the wearer. Co-Use is process of using the object over its lifetime, with the data feeding forward into the system for all to use that data. Between the “Co-” phases are enabling transitions of encode, materialize, profile and monitor. Encode enables Co-Analyze to become Co-Design by making the data compatible with the parameters needed to generate. Materialize enables Co-Design to become Co-Manufacturing by making the data ready for digital manufacturing processes (which may be distributed). Profiling enables Co-Manufacturing to become Co-Use by remembering the data from all previous phases for later comparison and predicting the lifecycle of the object. Monitor enables Co-Use to become Co-Analyze by taking the data from the object and the behaviour and making it available for analysis.

Working with a graphic designer known for systems illustration (Zevi 2017), a series of icons that represented the domain of shoes were created, fig, 2. Cards representing stakeholders, objects, characteristics, phases, actions, and values were made. Each card had a simple icon and a word describing the icon with extra lines to fill in information from design actions and the data flow. The labels and illustrations were not set on stone, empty cards were added to encourage the addition of new icons and descriptions when needed, as suggested in “Efficiently Inefficient: Service Design Games as Innovation Tools“ (Hannula and Harviainen 2016).

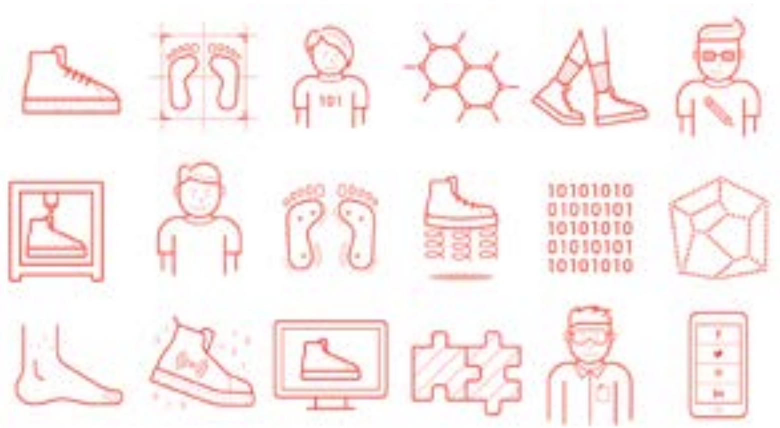

Figure 1. Icons created for the UPPSS game that describe stakeholders, objects, design considerations, phases, actions, and values in a general way that is modifiable.

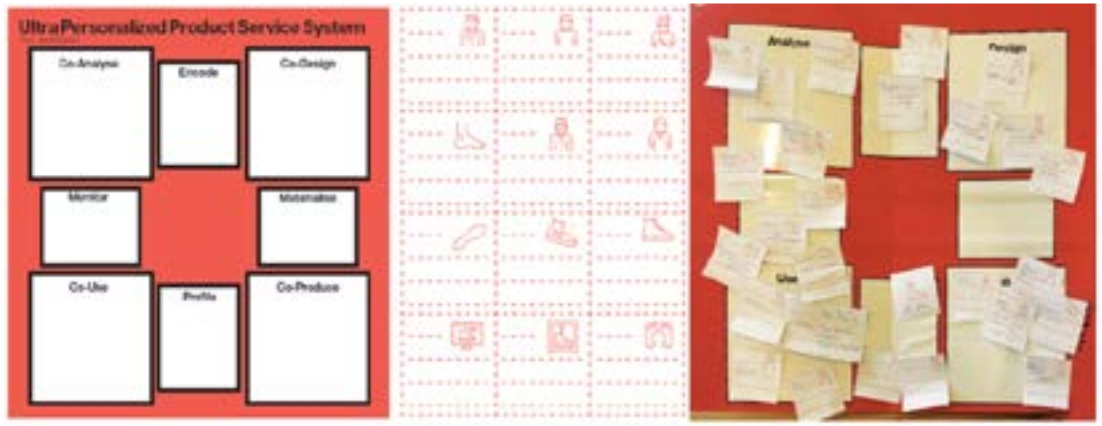

Figure 2. The UPPSS game board and cards being used to create Customer Journeys and Data Flows for an Ultra-Personalized shoe platform.

Based on the following questions players selected, named, modified and described their process on cards which later were placed onto the board (see fig 2 right):

1. Who is involved in the process?

2. What are the other objects involved in the processes areas? ie. foot, shoe, scanner, leather, sole.

3. What happens in between each phase? Where is the data? How does the data change (ie formats)?

4. How and when is the “fit” (physical, social, behavioural) of the shoe controlled?

5. Are there places when changing one aspect will break another? Add a negotiation card to that moment and quickly note what happens.

6. Consider the board as a system. What is difficult and what would make the process better? Identify challenges and opportunities in the product, service and the system.

7. Walk through the system again to see what can be streamlined, modified or changed.

8. Create a customer journey and data flow from the cards on the board.

Deploying the UPPSS game

A class of second and third-year bachelor students (n=16) from a three year industrial design program were selected to participate in this research. 8 were female, 8 were male. Their brief was to scale up bespoke shoe personalization into a

UPPSS.

Before the design game started, each participant made and wore a pair of digitally fabricated shoes. Then, the participants formed into groups and were asked to play the UPPSS game. Afterwards, with the findings from the game and a new version of the shoes (see figure 2), they created customer journeys and data flow diagrams (see figure 4). The final version of the shoes, customer journeys, and data flows were critiqued at the completion of an eight-week process. Participants then wrote a reflection which was coded by the researchers.

A first-person embodied perspective of shoemaking was important to support a meaningful learning and valuable reflections. Participants who engage in an experience can translate material usage to memory making (Tsai and van den Hoven 2018). Additionally, living with a prototype is key to understanding a research product (Desjardins and Wakkary 2016, Mackey et al. 2017). We choose the ONEDAY shoe toolkit deluxe version which has been shown to be an effective tool for understanding personalization (Nachtigall 2019a).

Fig 3. Examples of shoes personalized with digital craftsmanship and worn by participants using code based on the ONEDAY open source shoe toolkit.

Inter-Coder Classification Using an Interpretative Framework

To understand if the game helped participants create an UPPSS, we used an inter-coder agreement method previously used to classify research methods and purposes (Kjeldskov et al. 2012, Tetteroo et al. 2015, Nachtigall et al. 2018). Table 1 presents an interpretative framework based on previous work (Nachtigall et al, 2019) and related work. A short abbreviation was given to facilitate the coding process as a coding schema. Two coders (PhD candidates working within UPPSS) read each reflection and coded each sentence if one of the classifications was apparent. The coders also noted when a sentence was an exceptional or interesting example of the classification. Only one classification was allowed per sentence. It was possible for a sentence to have no classification. If more than one classification was present, the coders selected the classification that seemed more important in context. After classifying, the coders reviewed their classifications together. When disagreement was found, the classification was debated until a consensus was reached with no time constraint. Each coders' classification and the final agreement classification were recorded for analysis.

Table 2. A summary of classifications found in the reflections using inter-coder analysis

Results

From the reflections all 1474 sentences were considered from the participants' reflections (n=16). The classifications, Table 2, part of the interpretative framework, were found in 753 (51%) of the sentences. Product challenges represented 384 (51% of found classifications), service challenges represented 215 (29% of found classifications), and system challenges represented 154 (20% of found classifications) The individual challenges are reported in fig. 3. The inter-coder agreement for the classifications was 0.76 using Cohen's kappa. This is found to be sufficient reliability to draw the results (Munoz and Bangdiwala 1997). During the classification, sentences that exemplified the classification or were considered interesting were tagged for later. A representative sentence of each was selected as an exemplar, table 3.

Analysis

It's clear from the inter-coder analysis that the interpretive framework challenges were addressed by the students as reported in the results. All challenges had at least four classifications and as many as 179. We looked for the effects of the game itself in all of the challenges. The product challenges were best represented, but this could have been caused because the participants spent a significant amount of time and effort in making the shoes. The challenge of mechanical sensing material structures was the least represented. The concept that material "wear and tear" forms part of a computational system was difficult for the participants. Finding four reflections in the material sensing is still nominally sufficient. For example, p12 reflected "I also found that you can gain a lot of information about a persons' foot by looking at the shoes after wearing them for a certain amount of time." The presence of the game is also seen in other product challenges. For example AA P4 "Now the shoe is not as flexible and it still looks nice. I had to change my initial design a little bit to fit in with our shared service design."

We found the game in the service challenges as well. AS P1 wrote, "This game gave me the idea to let customers of the service platform play with the contrast by letting them change the density of the vector markings on the top of the upper and on the back". Moreover, the game leads to personalization as PU P9 wrote: "With this design, I wanted to create an ultra-personalized shoe in which design would not be obvious for everyone but would be very important and precious for a user himself."

The system challenges had the least classifications, but there is evidence of the role of the game. QS P16 wrote: "The main objective for our service system was to keep it modular but not too complicated. We made the data flow with the website in mind; we transformed all the functionalities from the site into data objects.". Dealing with the complexity of scaling up was not taught in the classes but became apparent in the reflection. Finally, the best evidence for the game was found in comparing data CD P6 - "The provided cards helped to create a general path for all of us."

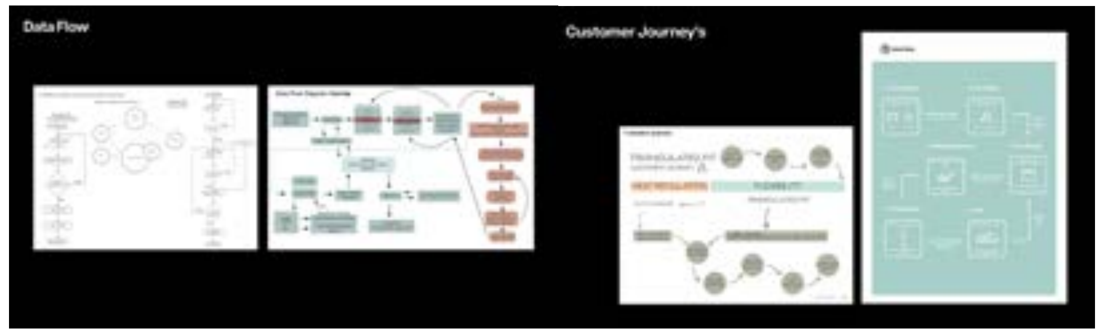

Figure. 4 Examples of Data Flow and Customer Journeys created by participants after playing the UPPSS game.

Discussion, Conclusions and Future Work

Working with data as a material is a complex challenge. It is especially true when we look to a future of complete product service systems that are personalized with that data. The UPPSS design game helped participants work together to create complete customer journeys and data flows that open up the gateway to future production systems. The cards allowed the participants to take the experience of digitally crafting a pair of shoes and scale it into a PSS platform. One of the teams was so successful that members went on to build the website P-16 "To illustrate our service and learn more about implementing processing.js, Daan and I created a website." It is also interesting to note that in many of the reflections, the game influenced either the product, service or system levels or multiple of them at the same time. AA P4 - "Now the shoe is not as flexible and it still looks nice. I had to change my initial design a little bit to fit in with our shared service design."

Product Challenges / Learnings	Service Challenges / Learnings	System Challenges / Learnings
AA Exemplar: "Now the shoe is not as flexible and it still looks nice. I had to change my initial design a little bit to fit in with our shared service design." -P4	RB Exemplar: "After this the feet are scanned, pressure and 3D, to gain data about the feet and make a perfect shoe." -P12	SS Exemplar: "There you can create an account that manages the customer's current and old shoe designs, number of walked steps and unlocked designs." - P6
AA Interesting: "I learned a lot of basics for using mathematical functions to generate form, but I am not yet able to create these alone from scratch." -P5	RB Interesting: "It will start measuring (the foot) with an app on your phone as soon as you wake up and start your first activity." -P14	SS Interesting: "Most of the sketches that had already been made could be implemented in the Processing.js sketch directly."- P3
MM Exemplar: "In the beginning ... and while trying to make some material explorations with some scrap leather, I faced a lot of problems with setting up the proper functions for the laser cutter and despite asking for help every time a new error was there." -P6	PU Exemplar: "When the customer is fully finished with designing, they will see a realistic render of what the design will look like." - P3	QS Exemplar: "The main objective for our service system was to keep it modular but not too complicated. We made the dataflow with the website in mind; we transformed all the functionalities from the site into data objects." -P16
MM Interesting: "For the actual realization, another material would be needed." -P3	PU Interesting: With this design, I wanted to create an ultra-personalized shoe in which design would not be obvious for everyone but would be very important and precious for a user himself. - P9	QS Interesting: 'Doing this felt like a more 'professional' approach then I am used to, because in previous projects I never integrated my Processing code into a system, by allowing the code to be integrated into a system, it feels more like a 'finished' product." - P1
SB Exemplar: "With different densities, materials, placements and stitches I could see what would suit best for this project." - P4	UB Exemplar: "In order to get a good impression of the differences with my normal sneakers and to find possible design opportunities, I wore the shoes for four full days." - P13	CD Exemplar: "In the meantime sensor data from the pressure sensors on the uppers are compared to the optimal values for people with comparable features (weight, hight, shoe size, etc.)."-P5
SB Interesting: "Code can be very abstract and designers need to know what will happen to the real material if they manipulate the code." - P5	UB Interesting: "With my hands I could feel that there actually was more resistance in the heel, the place where the cells were smaller." - P8	CD Interesting: "When the customer is ready for ordering the shoe, the metadata is imported and it will check if they have walked enough steps in order to really order it." - P4
MS Exemplar: "I also found that you can gain a lot of information about a persons' foot by looking at the shoes after wearing them for a certain amount of time." - P12	AS Exemplar: "This game gave me the idea to let customers of the service platform play with the contrast by letting them change the density of the vector markings on the top of the upper and on the back." - P1	SD Exemplar: "I made sure that the output of the code is a pdf file that can be sent to a laser cutter immediately, without the need of changing the scale or removing things in Adobe Illustrator." -P1
MS Interesting: Also, the option of a printable paper model to check what size the customer needs, will be available. - P8	AS Interesting: "Even when the shoe has already been received and worn, there is an option of sending the shoe back to enhance its design" -P12	SD Interesting: "By making the service, I learned more about all the taken steps and required data." - P3

Table 3. A summary of sentences that the coders indicated were exemplary or interesting.

The results show the potential of digital craftsmanship to support the making of future production systems like UPPSS. The data and algorithms became a fluid part of the designer's toolkit. Starting from a material, moving to a product, and then to a PSS, allowed participants to have a clear mental picture of how the process would change the shoe they had made. In the future, exploring the qualities of craft (Wensveen et al. 2016) and how they specifically relate to UPPSS may reveal even a greater understanding of the game, the interpretative framework used to analyze it, and about what digital craftsmanship is.

The game captured some elements of stakeholder relationships that the interpretive framework did not encompass. Service design emerged from the relationship of people with computational things but has been shown to understand stakeholder interaction (Blomberg and Evenson 2016). Future work into the UPPSS, the game, and other future systems should look to better capture these interactions and define stakeholder roles better. This could include templates for the dataflow and customer journey that might allow for greater analysis.

The UPPSS board itself represented a static framework. It needed to be more dynamic allowing for the changing of the board (system) itself. We saw the frustration in a few of the reflections P15 - "Without having the group service platform, my customer journey probably would have been completely different." In the future, the Co-Analyze, Encoding, Co-Design, Materialize, Co-Manufacture, Profiling, Co-Use and Monitoring phases could be in independent boxes allowing participants to manipulate the system framework. This would have helped participants like P6 who said "The design will be updated and again send back to the customer." indicating a possible different process.

Data was challenging for the participants. The concept that materials can make data as part of the process was difficult to find in the reflections. This was tied to the fact that the circularity of bringing the data from the shoe back in the process was poorly represented. The game allowed conceptually detailed and contextually rich first-person experiences. We look forward to adding actions to the UPPSS game to address qualities such as sustainability that may help participants make the process more circular resulting in iterative shoes.

Finally, we couldn't find any other examples that used an inter-coder analysis of personal reflections based on design action. The data to validate the game was created using this method and lead to effective research. It showed the transmission of the ideas of UPPSS and digital craftsmanship directly, although it was key to capture the exemplars and interesting quotes that informed the analysis.

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8.2 Critical Reflection

A workshop or project with shoemakers would provide insights as to the skills, knowledge and attitudes needed to digitally craft such a system.

Limitations of the work

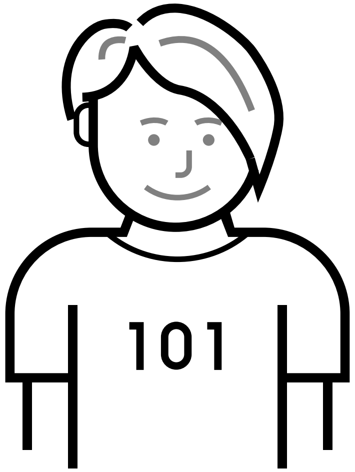
This project was performed with bachelor's-level industrial-design students who have all completed classes in calculus, computer programming, physical prototyping, and physics. It is unknown if these skills are required by a craftsperson who is intent on creating UPPSS. As noted in Chapter 1, I too have had classes and experience in all of the subjects. It is unclear if others would be capable of realizing such a system.

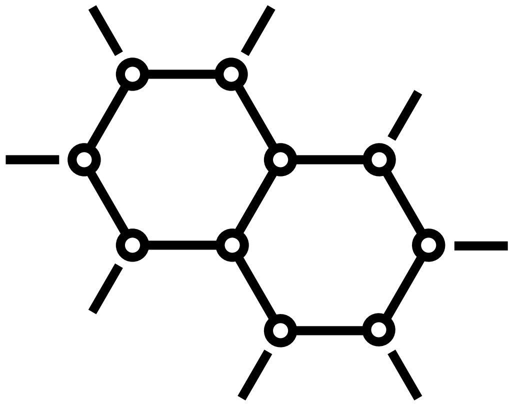
How was this different from a traditional bespoke shoe?

Data is used as a design material. A service system that scales up is created allowing several of the actions taken by the bespoke craftsperson to be handled by an algorithm or prospectively machine learning. This allows the craftsperson to advance the system and how fit changes in terms of aesthetics of fashion, behavior of interactivity, and topology of form.

Impact

The design game is being taught in design courses at three universities across Europe.





9 Contribution, Discussion and Future Work

An ultra-personalized product service system (UPPSS) for bespoke shoes can be designed and constructed, but it requires craftsmanship including ubiety to make it work. As seen in the previous chapters, craftsmanship is a digital craftsmanship of the data. and algorithms as much as it is a traditional craftsmanship of the “rubber” and leather used to make the shoe.

This chapter summarizes the findings and research questions of the papers presented in Chapters 4–8. The research question presented in Chapter 1 was, "How to craft ultra-personalized products, services, and systems through emerging digital technologies?" The research contributes a new understanding of the data–material relationship needed to craft an UPPSS. The research extends the theoretical model for ultra-personalized products and systems (Ahsmann 2016) followed with twelve challenges with insights. The discussion reflects upon the process and possible future work.

Chapter 1 established my personal background and the importance of this research. The chapter concluded with the research question above and a guide to the structure of this thesis. Chapter 2 situated the challenge of ultra-personalization in emerging digital technology and craftsmanship. Chapter 3 provided a portfolio of the conceptually rich artifacts created in the practice of this thesis and a guide to the methodology.

Chapter 4 asked: Can a shoe be personalized using current digital-fabrication technologies? It can, but it was found that this requires identifying and negotiating design considerations. The paper confirmed that the form, behavior, and aesthetic of a shoe could be personalized using a craftsmanship approach to the digital technologies.

Chapter 5 took a different approach and asked: Will a wearer personalize their shoe if they make the shoe themselves? They will, depending upon the quality of the tools and materials. An additional finding was that makers will develop a craftsmanship with those tools and materials.

Chapter 6 built upon the previous chapters and asked: Can shoes be constructed using the wearer's data to be ultra-personalized? It is shown that they can by making a pair of shoes with data, and that the same 3D-printed structures used to personalize the form, behavior and aesthetic could also generate data for future shoes. These findings were based upon 272 conceptually rich artifacts that explored many of the possible trajectories of the design space.

Chapter 7 collected everything we could find from the Solemaker project, and in examining this material asked: Can reflecting upon the conceptually rich artifacts improve theory? Yes, the artifacts can be annotated in groups that can be used to inform a theoretical model. A new expanded theoretical model of a ultra-personalized product service system emerged.

Chapter 8 asks: Can the knowledge be transferred to others using a design game? By analyzing the reflections of a class of students, I show which concepts of the research transfer easily and which are more difficult, yet all transfer as the students created UPPSS.

9.1 Contributions

In responding to the research question "How to craft ultra-personalized products, services, and systems through emerging digital technologies?", four contributions are summarized below.

Tools and techniques for personalization are provided in Chapters 4–8 and come together to form an expanded UPPSS theoretical model.

The thesis provides an example of an expansive RtD exploration which expands on methods into exemplars, toolkits, autoethnographies, annotated portfolios, and design games.

A new perspective of how to craft and design using a data material relationship perspective (data as a material) is described and shown to be useful to non experts in the form of a design game.

Future challenges for ultra personalization are identified.

9.1.1 Expanded UPPSS Theoretical Model

This thesis contributes tools and techniques for personalization in the methods presented in each chapter and an expanded theoretical model for UPPSS, as shown in Figure 28. Crafting the system with data as a material showed that are four enabling transitions as shown in chapters 7 and 8. Through addressing a series of challenges (specified below) with craftl, an expanded theoretical model emerged.

The expanded UPPSS model is capable of supporting designers in crafting data–material relationship that realize product service systems and enable ultra-personalization. In this model there are four phases that become circular as the system makes data to make more shoes. These key phases are co-analyze, co-design, co-manufacture, and co-use.

Co-Analyze - The process in which stakeholders use data to understand the specific design considerations of the user (wearer).

Co-Design - The process in which stakeholders craft algorithms to parametrically generate personalized shoe design specific to the design considerations of the user (wearer).

Co-Manufacture - The process in which stakeholders craft digital fabrication of the design by adjusting machines, physical material and data as a material to the specific thing being made.

Co-Use- The process in which stakeholders craft the object by using it and the data it is generating.

Crafting the larger UPPSS system requires enabling transitions that support a data - material relationship: encoding, materializing, profiling, and monitoring.

Encoding allows co-analyze to become co-design by transforming the data of design considerations into simple parameters that can be used in generative algorithms .

Materializing allows co-design to become co-manufacturing by transforming the data of the designed form into a physical material.

Profiling allows co-manufacture to become co-use by remembering the state of the physical material including the specifics of the digital fabrication process in a data form before it the object is used.

Monitoring allows co-use to become co-analyze by comparing the profiled data to the current physical object that is converted into data providing data for co-analyze.

The example described in chapter 6 shows how a foot is scanned and data is encoded for generative design. The design data is then materialized for co-manufacture in a specific digital fabrication setting and the shoe is manufactured. The data from the manufacturing should then be saved as a profile to compare to later co-use. As the shoe is co-used and monitored while used to provide personalized data that can be co-analyzed when the the next shoe is needed.

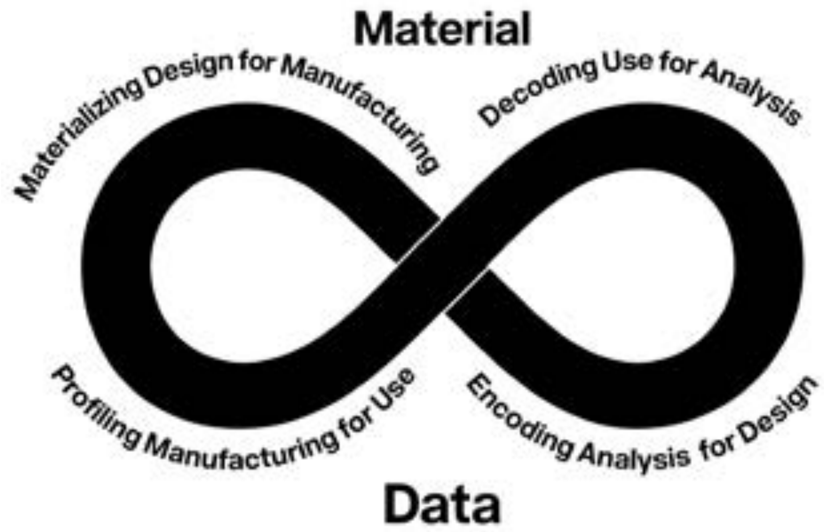


Figure 27. The material-data relationship depicting the transitions between a data state and physical material state. The shoe is sometimes a physical thing, while at other times it is a data thing.

9.1.2 Detailed Exploration Using Craft in Expansive RtD

This dissertation in itself is an autoethnographic expansive RtD exploration. It details how craft was used to understand a possible future of personalization. Chapters 4–8 and appendices each take design methodology and expand that methodology for the crafting of shoes, services and systems. Chapter 4 describes the challenges of making an exemplar UPPSS shoe using off the shelf technology which can also be found in popular culture[47] . Chapter 5 describes the creation and deployment of a toolkit for co-manufacturing. Chapter 6 describes a multi stakeholder design project on how to craft a full UPPSS system with multiple stakeholders. Chapter 7 details an annotated portfolio made with 276 samples, artifacts and research products to inform theory from the result of practice. Chapter 8 describes how that theory was validated by making a design game where untrained undergraduate students made their own products (shoes), service (data-flow) and system (customer journey).

9.1.3 Data–Material Relationship

There is a data–material relationship in UPPSS. There are times when a shoe is data and times when it is material. Chapter 5 concluded that “The ‘computation’ of HCI can occur in the process or service instead of in the artifact. We see opportunities for computing to occur over the lifetime of an artifact in the form of use (wear and tear) and user experience in the ONEDAY systemic and service aspects.” The role of the craftsperson is to understand the data when confronted with the material and the material when confronted with the data. This is supported in the conclusion from Chapter 4: “The complexity of ultra-personalization also shows the need for a system to gather information about the user to create better design considerations”.

In the UPPSS cycle of Analyze, Design, Manufacture, and Use, the shoe shifts between data or

47 https://www.dezeen.com/2015/10/20/troy-nachtigall-pauline-van-dongen-leonie-tenthof-van-noorden-3d-printed-high-heels-more-comfortable-than-normal-shoes/

material in an iterative lifecycle. Through processes of transition (encoding, materializing, profiling, and monitoring) the shoe transforms between data and material as described in Chapter 6:

(UPPSS) is achieved by encoding data and encoding materials in ways that remember how the thing was made and used. We show how a product service system can support iterative personalization by subdividing the complexity of the lifetime The collection of data across the lifetime of the shoe opens up possibilities for post-human concerns such as sustainability, not only over the lifetime of a shoe, but in multiple shoe over multiple lifetimes. The ability to use data as a designer provides new frontiers for hybrid craft, allowing designers to consider the why of the object, not just the how.

Figure 28 provides a model of the cycle of the iterative personalization needed to craft data–material relationships in ultra-personalized shoe manufacturing. This is embodied in the EVA moccasin featured in Chapter 7.

Chapter 8 concludes that the knowledge of data–material relationships is transferable: The results show the potential of digital craftsmanship to support the making of future production systems like UPPSS. The data and algorithms became a fluid part of the designer's toolkit. Starting from a material, moving to a product, and then to a product service system on page 138.

The conclusions of the previous chapters come together to illustrate the important, integral, and iterative relationship between material and data that emerges in the practice and digital craftsmanship required to support UPPSS. If craftsmanship embodies the embodied practice, then the craftsmanship of an UPPSS is a multi-stakeholder experience. The designer crafts a system that can encode the analysis of the scientist and materialize it into physical object. The engineer crafts a system of manufacturing where the materialization makes an object as a data material profile for use. The wearer takes that shoe (which is also a profile) and crafts that shoe into data by using the shoe. The scientist crafts the data into an encoding that the designer can use.

9.1.4 Challenges for Ultra-Personalization

In Chapters 6–8 a series of challenges and opportunities for future UPPSS are identified and detailed. While a few of these are only applicable for wearables (clothing), most apply nearly all UPPS systems already proposed. Three levels of challenges, Product, Service and System were identified in the Chapter 7 and validated in Chapter 8. These levels of challenge are separated to make the challenges operational for the creation of UPPSS as detailed in Chapter 8. Crafting for each of these challenges together builds a cratsmanship of UPPSS.

Product challenges

Ultra-personalization requires using algorithms to negotiate the design considerations.

Ultra-personalization requires deep understanding of digital fabrication as data is often misinterpreted when materialized.

Ultra-personalization requires understanding precision as a balance between the physical material and data material.

Ultra-personalization requires data created from the object, which can be done with mechanical structures

Service challenges

Ultra-personalization requires understanding the behavior of the individual.

Ultra-personalization requires new methods for gathering data often done by observing the physical material.

Ultra-personalizing the product for the user can require personalizing the sensor for the user.

Ultra-personalization requires predicting how the product will be used by the individual.

System challenges

Ultra-personalization requires saving and storing data trails.

Ultra-personalization requires decoding those data trails into temporal composites for materialization.

Ultra-personalization requires comparing the data material between iterations and users.

Ultra-personalization requires quantity and scaling up.

9.2 Discussion

9.2.1 UPPSS from Craftsmanship

Craftsmanship is essential in an UPPSS for shoes because crafting a shoe UPPSS supports all of the ubiquitous outliers that occur. In scanning more than 400 feet (Solemaker), distributing co-manufacturing around the world (ONEDAY) and having students build UPPSS in teams based upon a personal shoemaking experience (Digital Craftsmanship), a common understanding developed: personalization attracts the outliers. Personalization attracts outliers because mass manufacturing is already tailored to the masses. ONEDAY attracted those who wanted their own style. Solemaker also attracted people who need dynamic behaviors such as runners, dancers, and various professional sports players. Solemaker also attracted people with orthopedic problems (who are very willing to share very disturbing personal details). Additionally, personalization requires small incremental change for fashion, not large systemic change. UPPSS needs to be capable of such incremental change.

The moment a shoe system uses the word "personalization," it is inundated with all of the people who have foot problems, specific behaviours, and wild stylistic ideas. Crafting an UPPSS asks, What is the scale and scope of users that are to be supported? An UPPSS for a single user wearing the shoes for a single event is laborious, but systematically simple (Project J). As the system scales up in scope, the system tends to face generalization to support the plethora of users unless craft supports the personalization of the system. However, UPPSS may require that shoe data is first gathered before personal shoes are made. This system would begin in the use phase. This thesis remains limited in that it only explored entry to the system via the analysis phase. Future work that explores alternative entry points and a reshuffling of the phases and transitions is warranted.

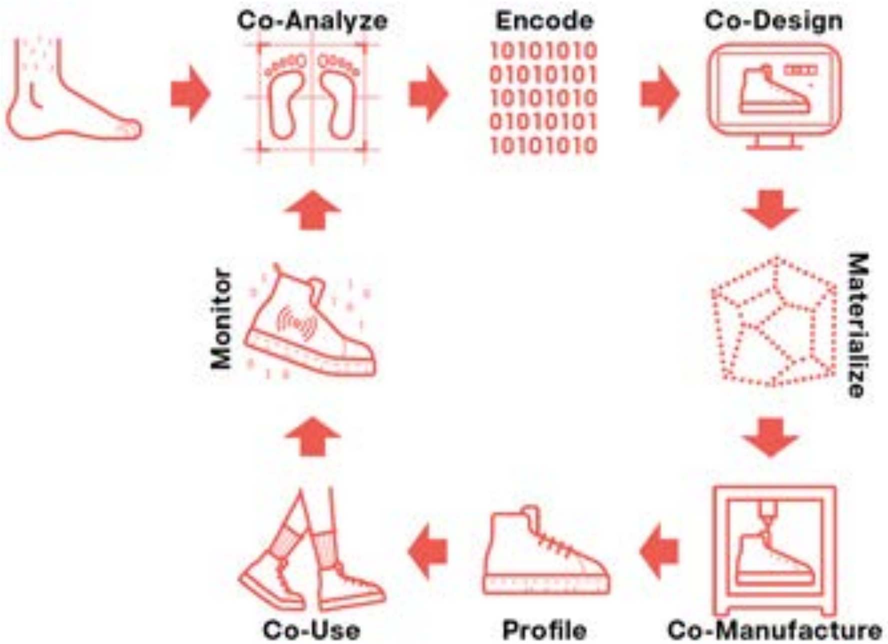


Figure 28. The UPPSS Model from Chapter 7 which includes phases of Co-Analyze, Co-Design, Co-Manufacture, and Co-Use. Between the phases are enabling transitions that allow the designer to create systems of ultra-personalized design.

9.2.2 UPPSS will cost less, eventually.

For the person with odd shaped feet the system will cost less. The person who a perfect size EU 41 and can always find their size on sale will probably pay around the same. Why is this? Craftsmanship is understanding G-code and machines as they relate to the movement of the foot. The system is only as smart as the craftsperson behind the system, what UPPSS allows is more stakeholders to be engaged in the system. When done on a large scale, UPPSS likely allows for the cost of a personalized shoe to come down as the expertise required becomes embodied in the system. The more that system is capable of accepting input by different stakeholders, the more it is capable of embodying specific kinds of craftsmanship. The designs of the designer, the analysis of the scientist, the materialization of the engineer, and the literally embodied experience of the wearer all come together as data in the system.

Yet, It can also be surmised that the economic law of diminishing returns will enforce a limit to how much craftsmanship is possible per pair of shoes. Much like was seen in Project J, it was possible to make a personalized pair of shoes for a single evening, but the fact that it took three designers three months of work to realize that shoe would be economically difficult in the current economies.

Additionally, the ebb and flow of fashion in its current seasonal machinations would require digital craftsmanship to adjust the generation of the calculated material for the specific style that the shoe will be used. Moreover, creating the UPPSS system requires a significant amount of programming. Ramping up the UPPS system is certainly expensive, but I expect it is to be profitable within five years and fundamental in ten years. Seen as a product, the UPPSS shoe may seem initially expensive, but as a long-term product–service system it becomes quite reasonable as shoes become more personalized.

Moreover, the data set of an UPPSS, when it contains enough users, is a valuable resource. Not only can that data be used to make shoes for the constituents of the UPPSS system, it can be used to make better shoes for society as a whole. The aggregate data that shows how people move over a lifetime opens up interesting possibilities. If the data set can show how knee replacement can be affected by the shoes it is easy to imagine that insurance companies may insist that the UPPSS shoe be used. Data being used for the fit can already be seen in the Vivo-Barefoot website with the online tool Fit finder[48].

The result of an UPPSS is not complete automation

What is proposed here is not a way station on the way to complete automation, but a system that supports the personalization of a vast majority of wearers alongside a culture of craftspeople to support the rest. Data from all of these users support the developing robustness of UPPSS. This was seen in ONEDAY (Chapter 5). Yet, what was found in Project J (Chapter 4) and Solemaker is that there is a need for intervention when the system needs a particular fit (a particular aesthetic, an outlier foot, or walking problems). The UPPSS system requires co-design in the software not only for the wearer but for the designers, stylists, podiatrists, orthopedists and possibly others. The system asks, Can a system be made that supports multiple stakeholders in the same and different roles? Can that system support ongoing craftsmanship and the changing requirements of that craftsmanship?

Industrial designers traditionally work with a brief to complete a project. Yet much as we see in social design, design stakeholders in UPPSS become long-term partners. In fact, ultra-personalization needs the human touch; craftsmanship deals with the ubiety. We found in the ONEDAY project that indeed personalization works better when it is expensive and using quality material. The craftsmanship of the bespoke shoemaker is a key part of the success of the shoe. People are sometimes skeptical of the value of technology which causes friction in the scaling up of an UPPSS. Hand craftsmanship can solves this at a cost.

9.2.3 Algorithms and digital manufacturing don't kill traditional craft

UPPSS can enrich or even create new digital craftsmanship in traditional and legacy craft. Starting in 2005 digital craftsmanship was incubated in the maker community and codified starting in 2009 by the Fab Academy. These communities went beyond understanding the means of production into local digital fabrication. Both communities embraced understanding new means of production started by answering how and what, but now look at the why and questions of sustainability.

To accomplish this, the communities who want to craft in this new way face challenges and opportunities. What was done in this thesis was make tools and techniques for myself that translate to others so that they can develop the skills, knowledge, and attitude required for the craftsmanship needed in emerging technologies. Moreover, the distributed nature of data, code, and software allows for alliances of bespoke and handmade shoemakers worldwide. The software could be made to help the shoemaker deal with the data of fit while keeping their own signature style. While this research took more of a first-person perspective, distributing this idea

48 https://www.vivobarefoot.com/dk/mens/active/primus-knit-mens?colour=Mood%20Indigo

with machine learning–enabled software seems to promise even more emergent technology.

A new kind of shœ designer that understands algorithms and technical systems emerges.

This designer can design the lifetime of the shoe (or multiple lifetimes of multiple shoes). At the same time the designer creates tools for working side by side with automation. An example other than myself is Francis Bitonti who in his recent book compares tools to programming syntax:

3D printers are capable of producing so much variety because they run on a discrete additive logic. It is a generic non-specific tool, capable of self-replication. 3D printers present us with a methodology for thinking about materials and assemblies as a set of discretized operations that inform a manipulation of matter that is much closer to how we manipulate software; and as a result, assembly of physical form and material differentiation no longer fall on the tool but on the manipulation of a codified language. This is a paradigm shift. This means materials are now shaped by linguistic constructs (computer programing languages), rather than formations of other materials. (Bitonti 2019)

But more than this, there are suggestions in the projects of this thesis that machine-learning AIs could develop their own form of craftsmanship and join the UPPSS as stakeholders of various capacities.

9.2.4 The Data–Material Relationship

What was gained from crafting hundreds of samples, swatches, sensors and shoes? There was a materiality of data, and data of materiality that supported the understanding of data–material relationship. The shoe is made from data that was created from the person. The shoe makes data to be used in the creation of a new shoe.

Materiality of data

In the research, a craftsmanship approach was applied to the emerging new technologies of digital fabrication. New tools, techniques, and software are detailed in Chapters 5–7. Numerous samples, swatches, sensors and shoes were created throughout the project. The research as papers and artifacts show that data can be materialized into shoes by taking a craftsmanship approach to data, algorithms and digital fabrication. This approach is supported by Dourish in his argument for the materiality of data in The Stuff of Bits:

I argue that software and digital information—the ultimate “virtual” objects, the poster children for the triumph of bits over atoms—have a material dimension in the interactional processes of their construction and use. Programmers understand the ways in which digital structures can resist their will, every bit as much as clay, wood, or stone. (Dourish, 2017)

The shoe, as a concept, came to be seen in its data form in Chapters 5–7. We could see the shoe as arrays of Cartesian points inside the software, or in scan data of the footstep that would serve as the parameters to generate a shoe. The data is encoded from the footstep and materialized into the shoe. In Chapters 4 and 5 this data was hidden inside the black box of technology, while in Chapters 6 and 8 I came to know that data intimately through writing software and embroidering footstep sensors.

Data of materiality

This research argues that to make a personalized shoe we needed personal data, and to generate that personal data we needed a personalized sensor. In building personalized sensors to put inside the shoe we realized that we didn’t need the electronics to build a sensor: the shoe was already an expression of materialized data, and in this we saw the shoe itself as data.

Part of the practice of 3D printing is watching the geometries materialize. Thousands of hours were spent printing, writing the code, and watching it print. This led to seeing the shoe itself as the data that made the structures that formed it (in outsoles, internal support structures, sidewalls, and uppers). As I wore the shoes, I realized that data was changed by walking in it. It was rubbing off onto the ground and the internal structures were breaking. Abrasion and breaking was shown to be part of a computational system, where wearing the shoe would change the shoe and provide data for generative parameters for future shoes, as shown in Chapters 6 and 7.

When the shoe is newly printed, it is in a way an expression of personalized data with mechanical sensors that ask questions about use, in that way it is a profile as a physical representation of the use in that moment of time. A mass-produced shoe sole is a generic estimation of what a general populace needs. The printed sole is a calculated hypothesis of what the user needs from ultra-personalization. Designed for an individual, the new shoe remains untested as to whether it works for the individual (in form, behavior, and aesthetic) . Wearing the shoes tests that hypothesis. Chapter 6 presented this closing of the loop of ultra-personalization, and introduced the term “iterative personalization.”

Precision holds the key

In “On the Philosophy of Slow Technology”, it was noted that one possible strategy of slow technology is “to replace digital precision with textile imprecision. Instead of trying to mimic the traditional computational devices in textile constructions, we take the inherent imprecision as a starting point and open up for interface slowness and complexity” (Hallnäs 2015). I found that instead of it being a question of precision and imprecision, it was a question of different types of precision, first between electronic precision and the 3D-printing precision, then in the printed structures for different design considerations. The tolerances and attention to detail required to negotiate the design considerations took different amounts of time and concentration. The craftsmanship of creating a data–material relationship requires bringing together and accepting incongruities in different types of precision. Electronics and 3D printing have different expected ranges of precision. The geometries printed inside the shoe have a specific range of precision. The data from the foot scanner and the data used as parameters for the design software also have a specific range of precision.

The precision of the structures used to control the interactivity and form of the shoes was controlled by the 3D printer, which in turn was controlled by the software used to generate the G-code for the printer. As seen in Project J (presented in Chapter 5), using off-the-shelf software and hardware necessitated working with the precision of the chosen hardware and software. Solemaker (presented in Chapters 6 and 7) demonstrated what was possible when modifying the 3D printer and writing the software oneself. In Chapter 8, many of the students found their own precision in terms of mathematical complexity and level of machine control needed to materialize their shoes. This is best illustrated in the reflections classified as standardizing material behavior (SB) and manufacturing misinterpretations (MM) in Chapter 8 where the results of digital

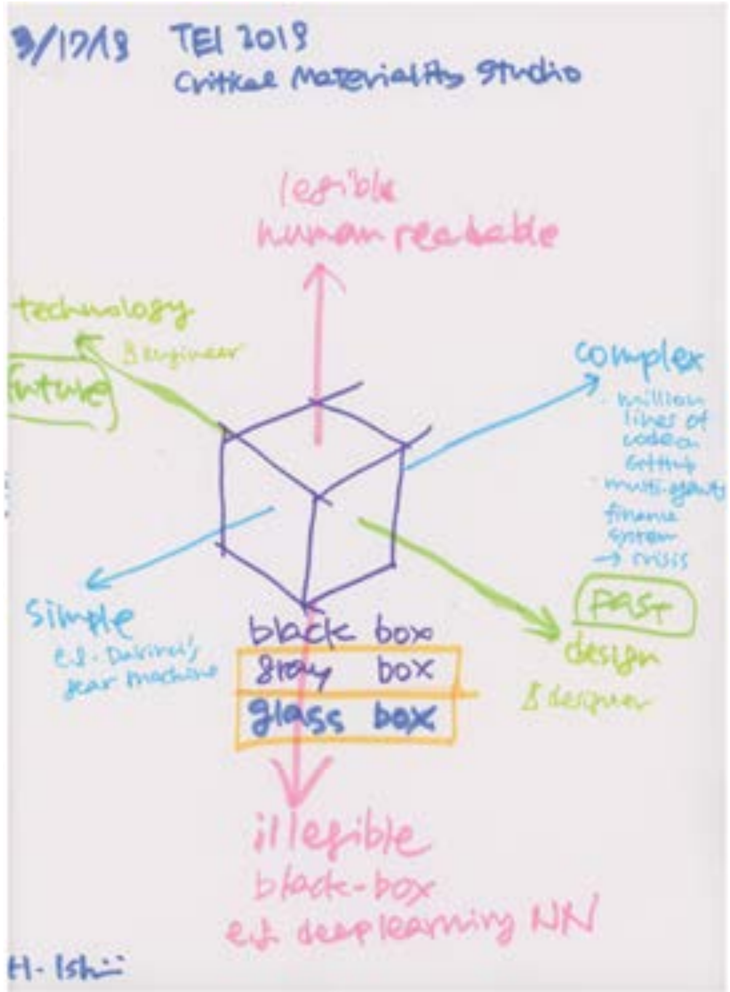


Figure 30. A box representing three axes of the challenges of making things with data. Illustration by Hiroshi Iishi.

fabrication did not meet the expectations of the designer.

When personalizing using data in product service systems, the thing being made is both data and material at different moments. Looking at the lifetime of the thing allows for the design of more personalized future things that are capable of creating increasingly precise data.

9.2.5 Machine learning and UPPSS

It was clear when 400 feet were scanned as part of the Solemaker project that there was a possibility for machine learning to predict past use, future use, and use not covered by the sensing systems by comparing the data of all the systems users. To get there, craftspeople capable of working with the data material relationship are fundamental.

Technology is often described in economics as the unknown thing happening inside a "black box" (Morgen and Rosenburg 1982) , The black box is a metaphor to discuss what happens inside software that is not understood by the user (Tomico 2018). The need to use craftsmanship to work with data is challenged by the complexity of machine learning. Hiroshi Ishii, HCI professor at MIT, illustrated this space at the Critical Materiality workshop (Berzowska et al. 2019) as a multidimensional cube where design struggles with engineering, simplicity with complexity and the comprehensible with the black box (as shown in Figure 30). The black box lies on the axes of simplicity–complexity, legibility–illegibility, and past–future. The box represents the point where the machine learning becomes a part of the craftsmanship. In the experience of this RtD research, opening the black box (or making it transparent) required approaching it from both sides simultaneously. Craftsmanship and technology were needed to see inside the box. Simplicity and complexity were both needed to address the shoe. Simple structures informed complex systems for example. Not only are both needed, but they inform each other as well.

Addressing data as a glass box opens the UPPSS of this thesis to participatory design. Instead of the countless hours (or at least one day) needed to train a wearer in shoe design, the user could be presented with a website full of shoes, much like what they currently see on shoe e-commerce websites. That site could offer not only shoe choices, but information as to what data was being used and how it connected to expressions of the design considerations. Moreover, genetic algorithms, or a "motor schema of digital gothic" (Spuybroek 2016, 37), that generate variations of shoes from the same data could enable new artistic expressions as an agent in participatory design. The data of how a person walks over a lifetime, the data of thousands of users, and the data of a closet of shoes, is a large quantity of data. If data is like clay, a material that is shaped and molded to make a shoe, machine learning might be a tool that can sculpt fine details.

That said, after executing these projects, a roadmap for using data to understand a user's lifetime becomes apparent. As machine learning develops, the challenges and opportunities found in Solemaker can be addressed by artificial intelligence. This is already being seen in the machine-learning solver plugins for software packages such is MatLab. Licensing for the solvers can cost hundreds of thousands of euros yearly. However, there are needs of the user that are outside of what is possible using quantitative data. Creating a UPPSS demonstrated that there is an opportunity for co-design and machine learning to be used simultaneously. Is machine learning simply a new kind craftsman? It certainly embodies the embodied experience of the digital craftsman. The dark secret of machine learning is that actual human beings (often paid terrible wages in third-world countries) have provided the "machine intelligence" that drives systems.

9.2.6 A computer-science perspective

In conversations with computer scientists, Solemaker was often compared to a silicon compiler (or hardware compilation). Silicon compilers are a kind of software that take user specifications and creates integrated circuits (IC) of microchips by generating logic gates in silicon. The ICs are then used for electronic computation. These started off as fairly simple circuits, and eventually grew into the complex processors of modern computing. The Solemaker shoes are similar to a silicon compiler in that they use parameters to generate the shoe with sensing structures. The structures break and abrade in ways that "compute" with cycles of use (footsteps). That information is used to make the next pair of shoes in a continuing and iterative process.

The computation that the shoe is doing is a simple calculation. The question the shoe might answer is, "Does this shoe fit in the way we expected over its lifetime?" In the novel The Hitchhiker's Guide to the Galaxy (Adams 1981) the Earth is created as a computer to answer "the Ultimate

Question of Life, the Universe, and Everything." The answer that came back was a parameter: 42. While the joke runs much deeper, the idea that the earth is a computational device that delivers a parameter inspires this work.

The shoes with their sensing structures are much like the computer in the novel in that they are also made to answer a single question. The shoes are unlike the computers in offices, homes and pockets that are made to answer almost any question from anywhere all the time. The result of this shoe use is a set of parameters that were created as a temporal composite, as described in Chapter 6.

The shoe-as-computer is actually a research product that allows it to ask certain situated questions rather than general questions. This shoe as computer answered many questions, such as: Can we make data? Can we see where the person is repeatedly applying weight? More work is needed to tell how long the wearer has worn the shoes, and to develop geometric structures that provide information about foot sheer and more specific repeated movements for even greater personalization.

Is this wearable technology?

This way of using the shoe as a research product is part of a larger system of calculation that challenges what wearable technology is. I argue that a data–material relationship is a new form of wearable technology. While wearable technology is founded upon the idea of integrating textiles and electronics, the use of computational and programmable materials questions the electronic nature of wearable technology. The idea of systems of ultra-personalization using computational materials has already caused quite a bit of debate at the International Symposium on Wearable Computers. This revolved around the EVA Moccasin shoe detailed in the portfolio and demonstrator in Chapter 6. Questions of systems like those of cybernetics (Ashby 1961) on inputs and outputs emerge inside of the product service system as computational digital fabrication creates computational structures (in a form of computational craftsmanship). Emergent in wearable technology is the vision of Neil Gershenfeld in When Things Start to Think, that he would be successful "if the computer disappears and the world becomes our interface" (Gershenfeld 1999). If materials are sensors then everything is in a way a computer.

This UPPSS system of shoe computing is supported by slow technology as it focuses "on slowness of appearance (materialization, manifestation) and presence—the slow materialization and design presence of form (F)" and "focus on aesthetics of material and use simple basic tools of modern technology—the clear and simple design presence of material (M)" (Hallnäs and Redström 2001). The appreciation, presence, material, and tools are shown in the work to come from craftsmanship and show the importance of craftsmanship in contributing to our understanding of slow technology.

Meanwhile, computation in slow technology is subject to laws such as the EU General Data Protection Regulation which protects privacy and this creates security concerns. The shoe sole explicitly asks a specific question about a specific user and cannot easily give up unintended data about the user. The research asks new questions as well including, "Can all the data about a user be stored in the shoe in places such as the aesthetic?" The pattern on the outside of the shoe could be an encoding of the user data much like generative art is data driven. What would it mean to have less data stored on external servers, and more data stored in the object itself?

9.3 Implications

9.3.1 Implications for craft and craftsmanship

Craftsmanship-as-making is informing the thing being made about its relationship with the people and other things around it. Part of craftsmanship's role is situating a technology into the everyday, not just mastering a technology. As new technologies emerge they have not yet found their place in the everyday. The technology of ultra-personalization provides the means to make individual things for individual people. But these technologies have been seen before in mass customization, though mass customization lacked sufficient levels of craftsmanship. All the models of mass personalization and mass individualization that were encountered in this research failed to address craftsmanship.

The UPPSS raises the questions "Do we need to rethink what the design process is?" and "Where and when is the craftsmanship?" Ubietous products need craftsmanship. The addition of data as a material that can be designed will force the questions "Who is doing the craftsmanship?" and "How did the craftsmanship emerge?" What happens when the shoemaker becomes part of a product service system algorithm, the software, the wearer's data, the designer, the medical doctor, or the technician? How did each of these apply craftsmanship to the product, service, and system? These could soon be learning systems where algorithms can craft themselves. If data is the material, the algorithm is already a craftsperson. Craftsmanship is emergent in the code of the software and the hardware. What is the craftsmanship in the hand of the algorithm? What is the eye for detail of machine learning? Machine learning certainly loves to scrutinize the details. What is design when the algorithms that transform the data become better at transforming the algorithm themselves?

Maybe the answer is this: new technologies create new kinds of craftsmanship. New kinds of craftsmanship create space for future technology. Craftsmanship makes things that envelope the knowledge in a physical and data form. In creating the new technology, craftsmanship embodies that knowledge as a single trajectory. Many craftspeople working together create the trajectories needed to create that design space. More research is needed into groups of craftspeople and how they work together with data–material.

In On Craftsmanship, Frayling lists a series of qualities of craft, such as "Crafts can be made with machines and maybe even by them, if numerically-controlled technology goes on improving" (Frayling 2012, 119). The data–material relationships in ultra-personalization support and expand these qualities. This research started to confront the idea of blending technology and craftsmanship by using the term hybrid craft. Hybrid craft combines two disparate fields (one of these fields is always understood to be "technology") in a multidisciplinary understanding. A better term is digital craftsmanship, which allows for the question, "What is the craftsmanship of an artifact and in which ways do digital tools change how I materialize the thing?" Digital craftsmanship represents the interdisciplinary knowledge that comes from crafting with new technologies. What seems to be emergent is a form of computational craftsmanship (Frankjær and Dalsgaard 2018) . The data–material relationship takes computational craftsmanship of things to be simultaneously a computational system and a shoe.

I hope that it is clear at this point that craftsmanship belongs to the new craft as well as the legacy craft. Tomico would argue that "the only difference between crafts and technology is the moment in time from where you look at them" (Tomico 2018). Yet I would argue that a vital part of industrial design is the craftsmanship of new and emerging technologies. When a new technol-

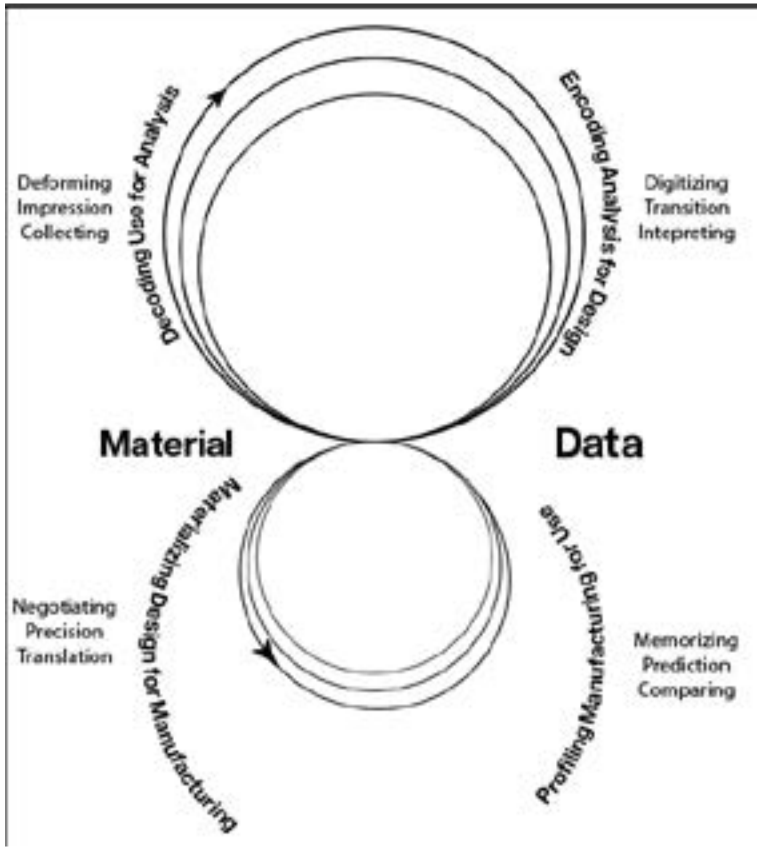


Figure 29. A theoretical onion-skin model of the data-material.

ogy emerges, industrial design research should look at it from a perspective of craftsmanship to determine the specifics of these qualities of this specific technology. Hybrid, digital, and computational craftsmanship allow for a specific perspective of craftsmanship. The future is sure to hold many new technologies. Can we speculate now on what bio craftsmanship, wicked textile craftsmanship, cell-free craftsmanship, and probably even speculative craftsmanship are? There is even a possibility of time-travel craftsmanship. No matter the kind of craftsmanship, the competency for the industrial designer and design researcher is craftsmanship. Design is different from anthropology or archaeology in this sense, in that the technologies worked with are from the future, very often only barely (and sometimes not even) possible when we lay our hands upon the material for the first time.

Reflecting upon the challenges from Chapters 6–8 that contribute to understanding how to make an UPPSS:

Craftsmanship can be a first-hand understanding of algorithms and physical materials transformed with digital manufacturing technology capable of interpreting both.

To accomplish this, digital craftsmanship does the following:

Craftsmanship is understanding the behavior of programmed materials.

Craftsmanship is creating data with emerging technologies: electronically, mechanically, and possibly biologically or temporally.

Craftsmanship is predicting how an artifact that makes data will be used.

Craftsmanship is developing new ways to create and save data, along with the limitations of those methods.

Craftsmanship is understanding how to scale up technology while keeping the artifact personalized.

Craftsmanship is preparing personalized data for machine learning.

Craftsmanship is iteratively personalizing lifetimes of objects.

Craftsmanship is thinking systematically and materially at the same time.

Craftsmanship is delving into the black box until it is no longer black.

Most importantly, craftsmanship is designing a system for ubiety.

9.3.2 Implications for industrial design

Ultra-personalization challenges the mass manufacturing foundations of industrial design. Industrial design provided efficiency and accessibility that brought clothes, furniture, food, and housing to the masses in the 1800s. Industrial design in the Bauhaus school embraced the craftsmanship of the technology. This PhD thesis argues that the craftsmanship of every new technology must be investigated to realize the full potential of that technology. But using data as a design material also creates the possibility that software-design models might also be applied to the making of things. Not only does software design enables rapid development of "versions," it allows the adaptive and responsive nature of UX design to create a personalized tangible UX.

In creating a loop of iterative personalization and this change in data–material relationship, a way of challenging mass manufacturing seems to be emerging. The phases of a UPPSS are marked by transitions that transform the data into material and vice-versa. Unlike digital twinning, where a data model and physical objects are supposedly mirrored, in this model the data takes on a material form, and the material takes on a data form, which changes depending on when in the lifecycle it is being observed. For example, the data of a UPPSS hold the possibility of revealing how shoe use over time relates to medical concerns such as knee- or hip replacement. A future where personalized shoes are mandated by health insurance becomes seemingly imminent.

To the craftsperson working with the data–material relationship, there is little difference in working with data or material, because they are simply expressions of different moments of the iterative loop shown in Figure 29. But this model only considers one pair of shoes. What happens when considering a whole closet of shoes? People own different shoes bought at different times. Shoes last for different amounts of time depending upon material and style. An onion skin of iteration occurs where multiple pairs of shoes are part of the slow technology that is occuring, as shown in Figure 29. A single sensorized shoe could possibly inform many shoes, or many shoes could inform all future shoes. The data from a high heel could inform elements of the same wearer's running sneakers. There are even possibilities that the shoe could inform a system of other garments and accessories, such as a handbag, as to what the wearer needs and wants.

One limitation of this work is the assumption that craft is design. I argue this in the approach and method. Personally, I choose not to enter into the ongoing discussion of what design is and is not. Craft is important to how I do design work, and has been shown to be important to HCI

I dream of a future where digital manufacturing allows the aesthetics, form, and the behavior of almost anything to be generated with data. The specific and ubietous world of an individual creates opportunities to design iterative lifetimes of things for that person. The things we wear, like shoes, become designed around the lifetime of a user. The trajectories of those designs will change over time, offering a space for art and engineering to blend. UPPSSs and designing with data hold the capacity to shift the foundations that the mass-manufacturing system design was built upon.

A future emerges where things are made individually, made to fit a multitude of needs, desires, and post-human drivers. Beyond a shoe compiler there is an opportunity for chair compilers, car compilers, and home compilers. The roles surrounding the idea of designer, maker, and programmer change, but what all of these have in common is a craftsmanship of understanding the thing that is being made and the programmable material it is being made with. When this research started in 2014, the idea that we could program things was in its infancy. I hope that this work will guide others. In the future, I envision physical things that will be like software: updateable and personalized.

However, a limitation of this work is that greater attention was given to the analysis, encoding, materialization, and manufacture. The other phases and transitions of profiling, use, and monitoring, did not become as evident until the work presented in Chapter 7. Future work should concentrate on the profiling, use, and monitoring. The original theoretical UPPS model has also changed[49] organically since it was employed in this research adding a phase of "collecting" which is very much like monitoring.

9.3.3 Implications for UPPS

If a company is willing to accept that the object will fail for a percentage of the population then the UPPSS can become completely automated. The company will need to accept the wrath of those users on social media. That wrath was already seen in the small scale projects of this thesis. But what the thesis proposes is a different model than that seen in other work into mass customization, mass personalization, mass individualization, and UPPS. Create a new kind of craftsperson who treats data as a design material.

There is a need to craft a system that makes the employees in large shoe companies passionate about what they are doing. In the practice of this thesis, I have had the pleasure of having my Wearable Senses Lab visited by some of the largest shoe companies in the world. It has also been my pleasure to later visit these companies and see them implementing some of the ideas of this thesis. One of the largest shoe companies on the planet implemented an internal maker space to help bring together people from various silos and create a sense of craftsmanship, seen

49 http://www.upps.nl/nl/ontwerpproces/

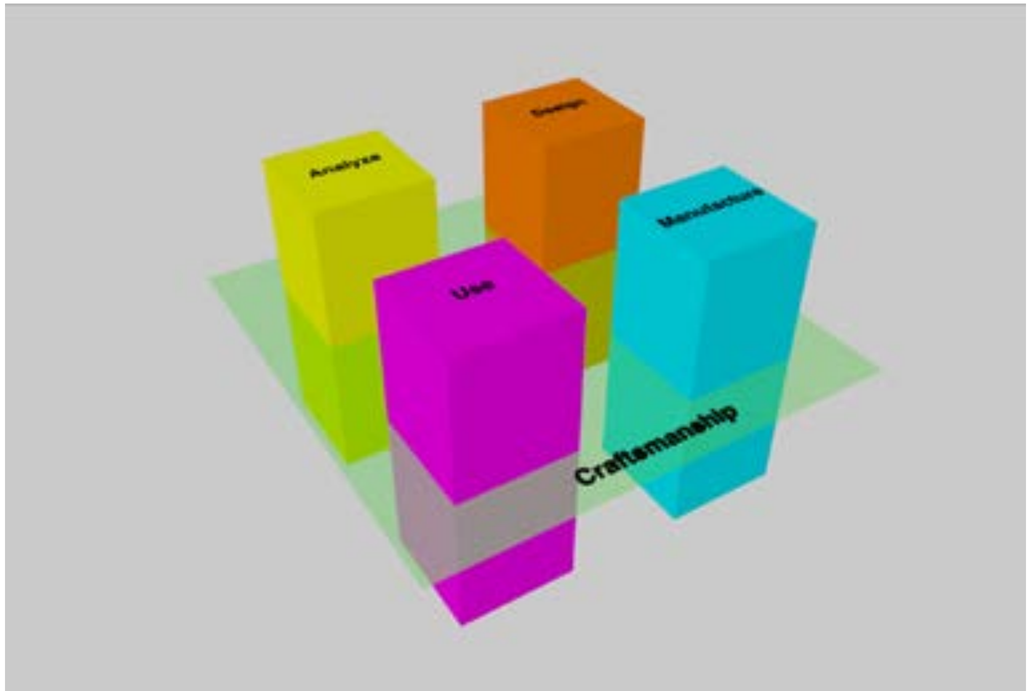


Figure 29. Craftsmanship being used on a systemic level.

in Figure 30. In these spaces ideas of personalization and sustainability have flourished.

Key to the results seen is this dissertation is crafting a system from material. This is different from the traditional engineering idea of first developing the system then finding the service, the product, and the materials to make it. Crafting is having a deep understanding of the material that you were about to transform. That material has inherent affordances. Building from the material ensures that the system can support the design space the material affords.

To accomplish this, many of the students "apprenticed" with me in the Wearable Senses Lab. They have found their way into shoe companies and projects that implemented the ideas from this thesis into their projects. What is unique to these individuals is that they do not see objects in the way that traditional designers see the object. These designers see the data–material relationship of the object. They see the shoe as a hybrid of materials with textures and colors that are also formulas conjoined into algorithms that parametrically generate unique instances of shoes.

Another key to making an effective UPPSS is making a system that can create unique instances and learn from outliers. Craftsmanship is needed in UPPSS when the shoe is changed or improved: a new material, a new technology, fashion changes, new sources of data (if only outlier users). These changes, especially emerging technologies and changes in style, happen so often that it seems that craftsmanship will always be needed. In fact, a designer capable of digital craftsmanship who understands the material (including digital material) in the scope of the larger system becomes an active ongoing team member, not just a consultant for a project. It can be surmised that there is a limit to improving each iterative personalization of the shoe, if only because the limits of the physical universe apply.

Craftsmanship can happen on different scales. This can be a very focused craftsmanship that happens inside the individual phases of the product or service. Craftsmanship can occur on the system level as well. Craftsmanship makes the system by creating it from a deep understanding of the data material relationship needed in the things and services an UPPSS creates.

Craftsmanship can happen on the scale of a single person in their garage up to multinational companies deploying production worldwide. At these scales and those in between the craftsperson develops the system and its component parts to personalized for the ubietous context they find the wearer and other stakeholders in. Craftsmanship helps the creators of an UPPSS system peer deeply into the role and responsibilities of the stakeholders that will come to maintain the system of UPPSS.

Once the system is crafted, craftsmanship can be used to make incremental changes to the system. At the same time, craftsmanship can be used to understand how changes at the product of service level affect the system level. Moreover, it allows for an understanding of not only the scientific qualities but of the artistic qualities of the UPPSS which make the roles of the stakeholders fulfilling and interesting. Most importantly, craftsmanship helps the system to scale while remaining personalized.

9.4 Future Work:

9.4.1 The Future is Distributed

What dœs UPPSS mean for the future? How do we get there?

First of all, realizing an UPPSS requires a new kind of stakeholder. Design, engineering, and many other disciplines are founded on the idea of making one thing that works for as many people as possible. Ubiquity and ambiguity (Gaver et al. 2003) being the hallmarks of such design. Look no further than the iPhone in your pocket to see how this socio-technical utopia has triumphed. Yet realizing ultra-personalized products requires a different socio-technical utopia: ubiety.

The ideal of an UPPSS is ubiety: making things for a specific place. UPPSS makes things for individual people in specific places at a specific time of their life. Instead of making an object that works for the greatest number of people, UPPSS asks that we might create millions and billions of designs for millions or billions of people.

To design for this ubiety means that stakeholders need to understand the society and culture that the UPPSS is being deployed into. What are the shapes of shoes in Barcelona? How do the materials of Norway differ from those of Italy? Design must lead from the craftsperson who adapts their product and practice to the individual in every project and subsequent iterations.

This ubiety vision of design started by Bill Buxton asks many more questions. How does branding work in an UPPSS system? What is the role of marketing? What are the economics of such a system? How do we maintain the role of the form language of a brand? Can the identity of the brand and the individual be merged? Or is fashion aspirational, thus friction between the user's current image and aspirational image needs to be considered. Is there an uncanny valley, the phenomenon where computer-generated people cause a sense of unease, in this generative form language? The answers to these questions lie outside the scope of this thesis, yet at the same time need answered to truly realize an UPPSS.

Teaching stakeholders to create an UPPSS requires distributed education so that the stakeholder is working with the materials, form, behaviors, and aesthetics of the wearers that surround them. The students who succeeded the most in the digital craftsmanship project were those who came to the wearable senses lab and worked alongside me to shape the data into things. Many of them continued on in internships, final projects, finding jobs, and founding companies based on the research into UPPSS. This first-hand experience alongside the theory seems vital to mastering data material and UPPSS

The Fab Academy (including the education programs known as the Bio Academy[50] and the Textile Academy[51]) has already created a distributed education model. In this certification students work with a local mentor at the machine while taking joint classes with people all over the world on a weekly basis. Class time is not only lecture, it is featuring the students work that is interesting. Each student documents their work on the Academy website, making replication easy. The fabrication courses deal with the materialization, co-manufacturing, and co-design of the UPPSS system. What is needed to realize UPPSS is a similar academy that teaches the data–material relationship in the phases and transitions of UPPSS.

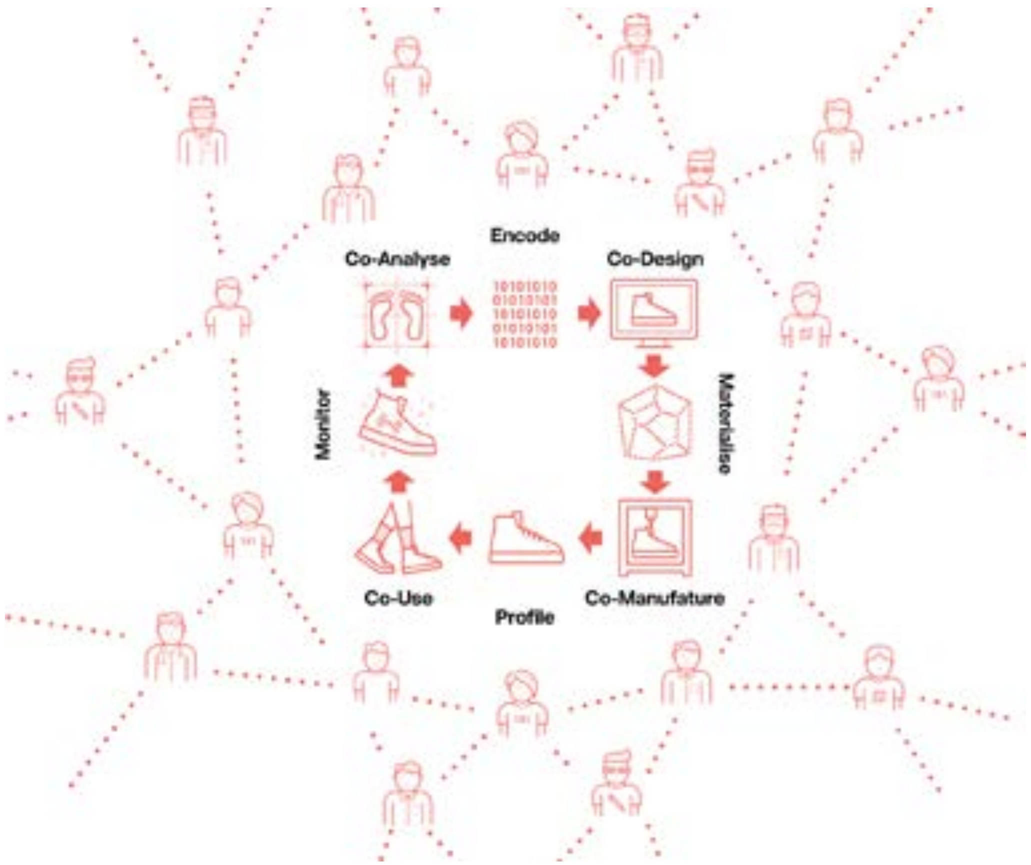


Figure 32. How many stakeholders could be part of an UPPSS

50 http://academany.org/bioacademy/
51 https://textile-academy.org/

Perhaps what is needed is an academy of co-analysis, co-use, encoding, profiling, and monitoring? What is the academy of the circular and iterative product service lifetimes that develop? Is this a new academy at all or an expansion of the infrastructure that the Fab Academy already has made? Will these challenges be addressed by the open-source vision or will a company like Adidas realize UPPSS with their speed factory and the local shoe collections under the brand Adidas Originals?

No matter which ideas are implemented, they build upon the vision of Fab City[52] (Diez and Posada 2013) where city states create all the things that are needed for their community. Yet the data flows from one city state to those all over the world. Tomas Diez of the Fab City project called Solemaker an example of a single product of the Fab City during Barcelona Tech Day[53] at the Elisava[54] School of design and Engineering. Will users accept this idea of things made locally, personally for them? Will they accept their stakeholder role in the system and help craft data with their movement and social expression in these shoes?

Ubiety in UPPSS requires a new understanding of the relationships that the stakeholders operate within. Traditional production takes a vertical model where silos such as business tells design what to design, design tells engineers what to produce, and so on. Service design brings these stakeholders into a horizontal relationship where responsibility is shared. UPPSS creates networks of each product, closets of products and individual wearers, as illustrated in Figure 29. The idea from social science of propinquity, the relationships or kinships that form between people, may best describe what develops in UPPSS. Alternatively, Ron Wakkary have recently used the term constituency to describe this phenomenon at his keynote during the EKSIG '19 conference[55].

UPPSS as data–material relationships creates an opportunity to redistribute the value of manufacturing and allows a rethinking of work. Crafting with material suggests these things, but data allows new, decentralized ways of working. The propinquity of the stakeholders can describe the socio-technical systems of production invite new stakeholders worldwide to participate in the process as the data is made available. This creates a new community of digital craftspeople not limited to a physical place. In fact, the craftsperson may not be a person at all.

The possibility of algorithms to act as a craftsperson stakeholder is not only emergent, it is already a reality. Genysis.cloud, by fashion designer Francis Bitonti, is an API that provides generative design techniques for 3D applications. More work is needed to understand the nuance of the propinquity between stakeholders such as designers, podiatrists, fabricators, influencers, and machine-learning algorithms.

What is missing for this collaborative system is a simple legal framework that supports the collaboration of many, some who may be algorithms, in making a shoe. Crowdfunding sites only allow for individuals to legally use their service. There is an opportunity to facilitate small (tens to hundreds), medium (thousands), and large (tens of thousands and up) series of shoe productions with changing stakeholders between iterative lifetimes.

Finally, does all this lead us simply back to a reality of craft production only with data added? No, what UPPSS represents is a system that can handle both ubiquity and ubiety. The practitioners who engage in UPPSS are able of realizing magnitudes more shoes as the data of individual adds to the understanding of the multiple facets of fit. The data-material that is the shoe, creates a specific place to design the ubiquity of the system and the ubiety of the product.

52 https://fab.city/
53 https://www.elisava.net/en/calendar/tech-day-2019-barcelona-local-tech
54 https://www.elisava.net/en
55 http://www.eksig2019.com/home/speakers/

Summary

Fashion designers often dream of a past when everyone wore personalized clothing and accessories handmade by skilled artisans. This idea is a myth; personalized attire (often classified as bespoke or tailored) has always been a luxury limited by financial means. Nevertheless, what if this fabled age of mass personalization could be made future real? What if the hands of an artisan and the bits of technology come together to realize a hybrid-crafted shoe? In the research, algorithms blend with craftsmanship to parametrically generate specific shoes for specific people. Implicit, bespoke traditions of shoemaking merge with explicit tangible expressions of data. The possibilities of personalization broaden as craftsmanship is applied to new technology. Shoes have many types of personalization: fitted (insoles are added to a finished shoe), tailored (shoes are made for an individual using an existing base form, a last), and bespoke (a last is created to the wearer). Digital fabrication weaves the ubiety of data with physical material behaviors. While data has been often used to make software, digital fabrication allows the making of products for the individual, moving outside of mass production systems.

Current literature and practice has shown how data can drive material properties, form, and behavior using algorithms. This approach provides the opportunity to rethink these shoe design personalization processes, which work with measurements that could be considered parametric data from the wearer. This PhD research, situated in shoe design (as a branch of accessories design and generally fashion design), explores the emergence of Ultra-Personalized Product Service Systems (UPPSS). In an UPPSS, shoes are not only personalized by parameters, but also generate data for the next pair of shoes. Thus, creating the possibility of a system of iterative personalization over multiple shoe lifetimes, changing the way shoes are made, worn, analyzed, and designed: user data is analyzed for parameters to generate shoes algorithmically, shoes can be digitally manufactured in new ways in a multitude of places, multiple users' data is profiled (and compared) anticipating needs and experiences, shoes become increasingly personalized over time.

The research asks the question: "How to craft ultra-personalized products, services, and systems through emerging digital technologies?" In order to understand the complexity of UPPSS as a future production system, an autoethnographic expansive research-through-design (RtD) approach was adopted. A series of projects realized hundreds of sample artifacts based on code, including a few finished shoes as research products. This PhD thesis consists of five key papers which address the following questions:

1. Can fabrication support the personalization of products? How does shoe personalization happen in shoemaking when the end user is involved? (ONEDAY Shoes: A Maker Toolkit to Understand the Role of Co-Manufacturing in Personalization, TEI 2019 (Nachtigall et al. 2019))

2. What new design considerations emerge when digital fabricating personalized shoes? How do we negotiate parametric data based on these design considerations? (Towards Ultra Personalized 4D Printed Shoes, CHI 2018 (Nachtigall et al. 2018))

3. What kind of new UPPSS models can be developed from RtD practice? How do we unpack them based on the collection of samples and research products developed? (Unpacking Solemaker into a Model for UPPSS, RtD 2019 (Nachtigall et al. 2019))

4. What data material relationships emerge in UPPSS when closing the iterative personalization loop? What are the main challenges faced in the specific case application domain of shoe design and what did we learn from them? (Encoding Materials and Data for Iterative Personalization, CHI 2019 (Nachtigall et al. 2019))

5. Can we support designers to transition to UPPSS by means of a design game? How does the UPPSS model support addressing the challenges faced in this research? (From Personal to Ultra-Personalized, EKSIG 2019 (Nachtigall et al. 2019))

The research details the digitally crafted research products and samples that were used as a vehicle of inquiry to understand what is required to close the loop of iterative personalization. The contribution of the research is summarized as tools and techniques for personalization (2, 3, 4), detailed exploration of materialization (1,3,4), a new understanding of the relationship between data and materials (1,3,4), and future challenges for iterative ultra-personalization(4, 5). The thesis concludes with recommendations for the future of digital fabrication for ultra-personalization.

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T. Nachtigall, P. van Dongen (14 September 2015) Prinsjesdag – Project J, Presentation of 3D Printed Shoes, Dress, Hat and Bag, The Hague, Netherlands, 24-10-2015

P.van Dongen, T. Nachtigall (17-25 October 2015) "Project J Between" Mind The Steps, Dutch Design Week, Eindhoven, Netherlands, 25-10-2015

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O. Tomico, T. Nachtigall, P. Vonk (27 November 2015) Textile and Technology Workshop, Wearable Senses Lab, TU/Eindhoven, Eindhoven, Netherlands, 27-11-2015

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Curriculum Vitae

Photo: Bart van Overbeeke

Troy Robert Nachtigall was born in Belle Fourche, South Dakota, The United States of America on the 7th of December, 1977. He studied Fashion Design at the Fashion Institute of Technology of the State University of New York. He received his AAS diploma in 2006 and in 2018 his master's degree in Industrial Design from Eindhoven University of Technology with the project EU Stimulus "Multi-Material 3D Printing" project alongside partners Philips Lighting, TNO, DoMicro and PWC. As part of his studies, Troy spent a year at Polimoda in Florence, Italy. Troy remained in Florence to work for fashion brands Emilio Cavallini, and in the design studio of Hugo Boss, Calvin Klein and many others. Troy continued by opening his studio, creating fashion projects for brands Panerai, Nolita, Dan Ward, and others.

Troy started PhD research at Eindhoven University of Technology as part of the ArcInTexETN Marie Skłodowska-Curie Horizon 2020 action in 2015 with results presented in this dissertation. During his doctoral research, Troy supported education in the Industrial Design Wearable Sense Lab and Crafting Everyday Soft Things educational squad as a lecturer and coach. His research continued as a visiting researcher at the Design Research Lab of the Universität der Künste (UdK) Berlin and at Phillips Lighting. The research included courses at the Universität der Künste Berlin, Royal College of Art (RCA) in London, Harriot Watt University in Scotland, Swedish School of Textiles (HB), Phillips, Phillips Lighting, Signify, TU/e and the Vilnius Accademy of Arts. Additionally, dissemination presentations were held at the National Fine Arts museum of Taiwan, ISIA Firenze, Sapienza Rome, RCA, UdK, HB, Phillips Lighting, Signify, TU/e, Maker Faire Eindhoven, and others. The results have been exhibited at worldwide at exhibitions, museums and conferences including the "Fashioning Technology" exhibit in Perth, a design exhibition award at the International Symposium of Wearable Computing in Honolulu, publications at the ACM CHI Conference on Human Factors in Computing Systems conference in Glasgow, and a grant from Design United to exhibit in multiple design weeks including Eindhoven and Dubai.