Digital Craftsmanship
The Making of Incunabula, a Fully 3D Printed Wearable Dress

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Abstract. The paper discusses the possibilities for 3D printing to help overcome the historic schism between manual labour/craftsmanship versus technology, specifically its potential to enable digital craftsmanship. Firstly, It contextualizes digital craftsmanship and introduces debates relating to tooling, application and design strategies, in particular in the field of architecture. Secondly, the paper articulates digital craftsmanship's properties and associated strategies by discussing three examples of the author's work. Lastly, it draws attention to the confluence of these properties and agencies through an analysis of the design and 3D printing of a fully wearable dress, titled Incunabula.

Keywords: 3D printing · Digital craftsmanship

1 Digital Craftsmanship – Context

Since the beginning of modernism and the associated industrial revolution, the growing separation of form-making from material condition has been seen as opposed to craft production. Sennet's definition of a process in which the practitioner is deeply invested in the outcome and takes care to do excellent work was superseded [1]. A continuous development led to modernism's tenets such as form following function and concurrently concept associated with ancient craft, such as integrating material properties with construction methods were lost.

Accelerated by the digital revolution, this widening gap between form and matter eventually resulted in the failure of digital form [2]. At the same time, the questioning of form led to alternative design approaches that prioritized material-based design computation and to a re-thinking of craftsmanship in digital environments [3, 4].

Arguably, 3D printing technology has created and facilitated a new, material-based approach to design. It has become one of the core technologies in the burgeoning maker culture [5]. This marks an important change in how we articulate design and making and is widely seen as counter-acting an industry-led decline of craftsmanship by enabling the democratising process of individual making. Both ease of use and availability of soft- and hardware for 3D print, coupled with a marked decline in associated costs of such printing in recent years, has led to significant changes in the creative and design industries. Virtually all areas of design have been affected, from the sole-trader and domestic settings up to much larger scale like Academia or industry

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level. Not surprisingly, therefore, 3D printing has been called a disruptive technology and a ‘game changer’ by one of the most significant economic reports in the industry [6], making it evident that additive manufacturing will optimize existing manufacturing industries because of its flexibility. One such example is that 25 % of current Boeing airplane parts are being 3D printed, saving significant costs in material, time and weight. The technology facilitates alternative models of production and organization and also alternative models for start-ups that can have lower initial set-up costs and be able to rapidly produce high quality product that rival existing cost-intensive design to manufacturing methods. This phenomenon is creating a wealth of creativity in all sectors and across scales and is unarguably a catalyst for new developments and the optimization of existing processes.

However, within this digital revolution of designing and creating, making and manufacturing, it is important to acknowledge that the optimization of existing designs is still prevalent, as opposed to the design of completely new objects. This is exemplified by the number of 3D prints that are digital replicas of existing objects, uploaded onto democratized maker websites such as Thingyverse or Google warehouse [7]. This suggests that the current state of 3D printing favors a model of replication and the automation of previously criticized modernism, in contrast to any realization of 3D print’s potential to reactivate values and qualities of a craftsmanship.

In the fields of architecture and architectural research, the global discourse about digital craftsmanship is characterized by diametrically opposed views, but at the same time is applicable to other design disciplines. On the one hand, there is the thesis that digital craftsmanship translates as digital construction in architecture today, which continues an architectural tradition [8]. This leads to more sophisticated CAD/CAM procedures involving robotic arms and even UAVs, commonly referred to as drones, erecting brick walls in a new process of construction. This view favors a mechanistic approach and tool-based debate about craftsmanship that sees it as a coherent and planned method of constructing and managing digital production.

The opposite view, which highlights the level skillfulness needed to use 3D modeling tools is also referred to as digital craftsmanship and values what some may term digital bravado [9]. Remarkably, both views seem to only marginally take into account ideas of craftsmanship as a cultural heritage that has extensive relationships between art and technology.

The following examples illustrate the current polarized discussion surrounding digital craftsmanship and the properties associated with this craftmanship. In their work, Subdivided column, Dillenburger and Hansmeyer achieve a synthesis of formal and material properties through advanced use of altered subdivision algorithms, using 2D laser cutting technology to craft and assemble a series of large-scale columns made of cardboard. The result is a mesmerizing start of a much larger work of art in which the genesis of its immersive quality lies within its formal and material properties.

A further example that attests to digital craftsmanship is their more recent work, Digital Grotesque, currently exhibited in the FRAAC, Orleans (2014). It presents the first fully 3D printed human scale environment using Voxeljet’s sand based 3D printing [10]. While it lacks detail and material sophistication compared to other 3D printed works, its scale and inclusive character are a milestone for the development of 3D printing as a form of craftsmanship in Architecture [11]. As the makers’ state, *A unique language of form is developed that transcends rationality and celebrates spatial expression: a digital exuberance* [12].

The term digital exuberance is a fitting term to describe the qualities of digital craftsmanship that they explore, specifically, the culturally articulated symmetrical arrangement, reminiscent of the baroque period allows speculation into a new craftsmanship led design in architecture to come.

While Dillenburger and Hansmeyer work at fully immersive scale and, through the use of algorithms, develop a homogenous quality of a total work of art, the works of Marjan Colletti, close the gap between optimization, technology and art. He advocates research by design into the digital grotesque and convoluted, as he describes it, and articulates craftsmanship within 3D print by addressing cultural values [13]. It is his culturally embedded understanding that differentiates his architectural approach to craftsmanship from making that depends upon a functionally oriented input-output objectivity. Colletti is not hindered by a simple input-output mechanistic approach but advocates the masterful use of all tools without restrictions to their genesis. He does this within a cultural framework of operation, for example allowing style periods from the baroque and Rococo to influence and characterize his works.

2 Digital Craftsmanship – Qualities

Three projects made by the author are now described in order to demonstrate procedures, references, techniques and strategies unique to digital craftsmanship. All of the following are governed by bringing together contemporary CAD techniques and CAD/CAM technologies with sensitivities to site and with culturally-specific design narratives, intuitive non-linear design processes, and historical architectural references. Here, the creator-craftsman takes on a multiplicity of roles, including architect, designer and cultural agitator and by so doing finally has the chance to overcome the fifteenth- and sixteenth-century separation between intellectual and manual labour. This model for being a digital craftsman also bridges the nineteenth-century gulf between automatic mechanization and poetic creation.

2.1 The Integration and Transition Between Actual Objects and Materiality and Digital Models in the form of 3D Scanning and the Implementation in a 3D Print Workflow

In 2006, we created and 3D printed a series of works titled, *Synthetic Syncretism*. The work argues for what, in theological research, is commonly referred to as the merging or synthesis of two entirely different cultural and religious frameworks into a hybrid belief system, known as a syncretic religion (examples of such include the Santeria in Cuba, a merging of Catholicism and Yoruba based religion, and many more). In the context of a digital craftsmanship, the syncretism between the craft and the digital is at the center of this work. The dichotomy between the direct physicality of manual craft and objects and the virtual nature of digital based work is epitomized in the work by using 3D scanning and the incorporation of physical, biological artefacts into the working process.

This body of work subsequently became the foundation for a series of explorations into the use of 3D printing as a new tool in the expression what we term today, digital craftsmanship. *Synthetic Syncretism* is a speculative architectural project that articulates, through the creation of a series of 3D printed objects, ranging in scale from model to prototype, a culturally embedded understanding of digital craftsmanship.

The project establishes a relationship between a culturally based craftsmanship and local narratives, rituals, biological remains and 3D printing. The starting point is a local burial culture in Havana, Cuba and hybrid religion, Santeria. Initial studies of this syncretic religion showed rituals centered on the dual worshipping of catholic Saints as deities in the Sanitarian religion. Visits to the local cemetery, the Necropolis de Cristobal Colon, revealed rituals including animal sacrifices with the physical bone remains of these found scattered in the graveyard. The fragments and traces of these rituals were collected by the author and brought back to London. The procedure of scanning the remains into a digital format compatible with 3D software did not exist at the time but is fairly standard today. The time intensive 3D scanning included the processing from point-cloud data into precise data mesh models with 0.1 mm tolerance. The resulting mesh data was operational using commonly available digital software platforms such as 3D Studio Max or equal mesh modelling software used in the animation industries (see. Fig. 1).

In the technical framework of the project *Synthetic Syncretism* and the debate around digital craftsmanship, the translation from actual biological fragments to a digital data set, is comparable with the creation of a mold for casting in sculpture or taking measurements during the design of a garment. The very fabric of the project stems from the rituals of its cultural background and the translation from the mortal physical remains to the scale-less, ephemeral digital is a significant step. The artwork expresses site specific narratives and simultaneously creates a cultural framework for 'reading' craftsmanship.

As one can see from the right side of the illustration (Fig. 1), in the next step the digital skeletal form is used as a starting point for digital mimicry and sculpting.

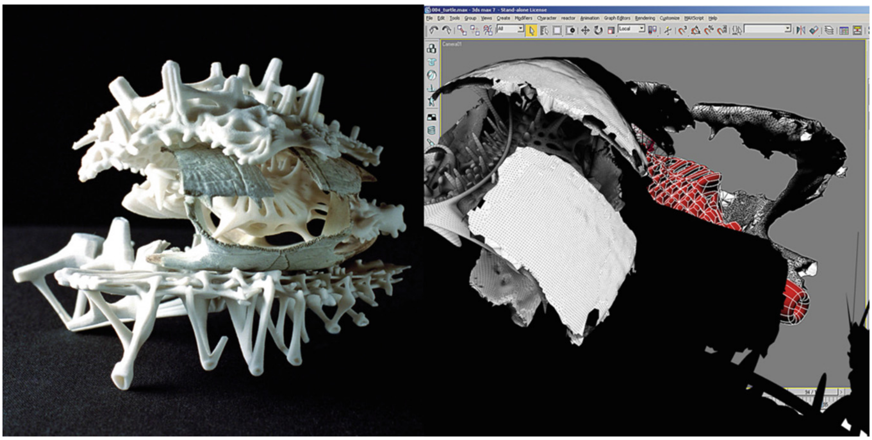

Fig. 1. 3D Scan of found tortoise shell and 3D Print using artificial sandstone by Z-corp within the bone structure of the tortoise shell.

Through a process similar to the physical building up of a clay model, yet relating to the existing digital scan, the added sculpture is 3D modeled along the digital bone structures to form vessels, embedded within the virtual data of the skeletal remains. In the case of the tortoise shell (Fig. 1), the process also included the de-construction of the individual bone segments to fit newly 3D printed organs and vessels back into the naturally grown shell and its later re-construction.

2.2 The Changed Relationship Between Materials and Tooling and Resulting Collaborative Designs that Would not be Able to be Produced Using Processes Other Than 3D Printing

In the framework of a competition, organized by the Sir John Soane Museum in London, we collaborated with a recent jewelry graduate from the Royal College of Art, Silvia Weidenbach, to create the work GLOW (Fig. 2). The work is a new translation of the traditional relationship between hand and intellect as a feedback mechanism in craft, and shows the advantages such a digital translation might yield. The work was entirely conceived using Computer Aided Design (CAD) packages and no model was built and no physicality was tested before the final 3D print. This complete transition from physical to digital form might be seen as a controversial form of digital craftsmanship. As Richard Sennett puts it:

> "*Every good Craftsman conducts a Dialogue between concrete practices and thinking, this Dialogue evolves into sustaining habits, and these habits establish a rhythm between problem solving and problem finding* [1] ".

Thus the continuous dialogue between material properties, the manual and intellectual feedback, defines craft and seemingly stands in opposition to the lack of materiality within such digital crafting. When articulating craft, the interface or tool is a

Fig. 2. 'GLOW' commissioned by the Sir John Soane Museum and in collaboration with Silvia Weidenbach.

vital part of craftsmanship and was the main problem in the translation, is that the traditional craft of Ms. Weidenbach was incompatible with standard interface tools and computer peripherals such as the mouse and keyboard. To address this, using the facilities of the Royal College of Art, we replaced the 2D mouse interface with a haptic device by Geomagics [14]. This interface tool facilitates fully 3D free movement and feedback via a controlled robotic arm. Through registering the resistance of the digital material which is shown on the screen in front of Ms Weidenbach, and through allowing full 3D movement, we translated the haptic feedback inherent to the traditional material approach and translated her experience of the craft of traditional jewelry as part of our collaboration. Through these changes to interface and tool, we extended traditional techniques like symmetry to expand the traditional craft.

GLOW is a symmetrical mirrored object that, by breaking the object in half at the designed break points becomes 2 necklaces. The object can only be produced using 3D printing as the action of breaking the object releases complete 3D printed chains for both necklaces that are stored in the interior of the previously closed object (Fig. 2).

2.3 The Ability to Articulate and Craft Non-related Data Sets Within a Set Cultural Referential Framework, Resulting in a Hybrid Non-scalar, yet Referential Construct

Through the work, Contoured Embodiment (Fig. 3), we explore the potential of digital craftsmanship to transcend the scale and origin of scanned objects and its ability to translate and graft different data-sets within a specific cultural framework.

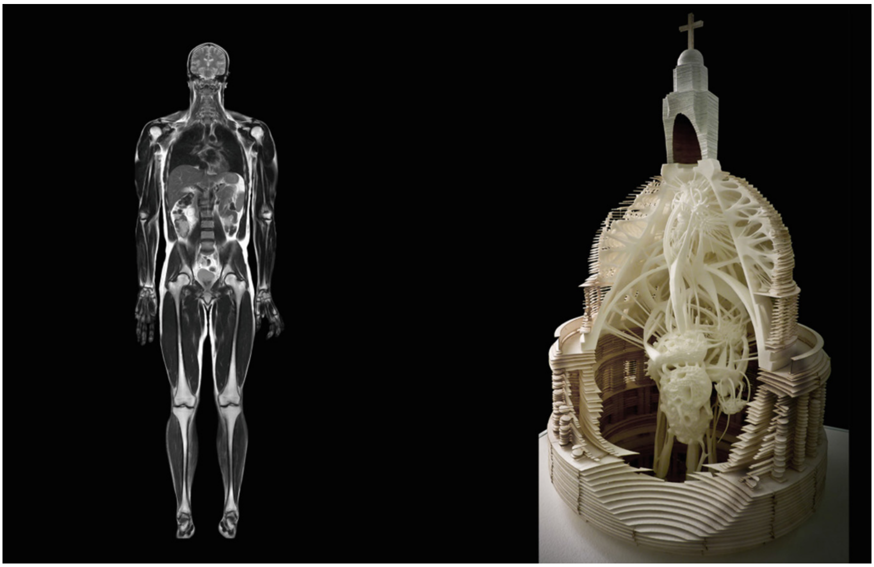

Fig. 3. Author's Magnetic Resonance Image Scan and the work Contoured embodiment using the Author's MRI Scanned data in a model of St Paul's Cathedral in London.

By contrast to the previous that introduced procedures to scan the surface of an object and translate it into a shell like 3D model, Contoured Embodiment uses Magnetic Resonance Image Scans of the author's own body. These scans have the advantage of creating volumetric data sets in the sense that they are creating not a surface driven model, but one using Voxels to articulate spatial and material density [15].

The work uses the author's heart in the cultural framework of the iconography of the Catholic Sacred Heart of Jesus, it places the biologically-derived artefact into the cultural context of the ecclesial architecture of Sir Christopher Wren's baroque masterpiece, St Paul's Cathedral. The resulting gradient voxel data of the author's own body becomes a digital embodiment that bridges between iconography, structure, scale and biology. This work transfers the volumetric medical data of the human body, re-articulating scale and properties. Through imitation and the crafting of ventricular connections it fits the biological artefact with surgical precision into the architectural model of St. Paul's Cathedral. The architecture of the ecclesial space, often compared to the corpus Christi, becomes the garment of a translated embodied data set.

3 Incunabula - A Dress Using Digital Craftsmanship

The London College of Fashion's invitation to respond, from the perspective of fashion, to Rem Koolhaas's brief, Absorbing Modernity: 1914 – 2014, offered an ideal opportunity to test some of the ideas and methods that are referred to as properties of digital craftsmanship and the amalgamation of craft as a technique and digital manufacturing. In particular, the questioning of Modernity as a dominant force in design today was a key element in the design of the dress, which was designed as an evolution and translation from the traditional hand-craftsmanship of Irish crochet techniques into 3D printed technologies. It required the transfer from an intricate textile design, based on a single thread, into a volumetric manufacturing technique without the loss of historic context. At the same time the work had to be achieved without the replication of a technique and design to make a different material, as criticized by the author in the first part of the paper. Koolhaas's oppositional argument to modernity resulted in the building of a false suspended office ceiling beneath a Venetian dome. It resolutely visualises the contradiction between art and engineering and the dilemma of a craftsmanship in modernity. Against the background of that debate, the hybrid design of Incunabula poses the question about the relationship between art and technology in the framework of digital craftsmanship.

Incunabula differs tremendously to other 3D printed fashion designs, in its materiality as well as in the techniques and craftsmanship used to produce the dress. Currently, wearable design that is 3D printed is commonly designed in two ways. One, seen in some of the works of Iris van Herpen and Daniel Widrig, uses a shell like print that allows very little flexibility but a great detail [16]. The second type of design differs to the first in that it is able to be flexible, via a subdivided approach. When looking at existing 3D printed fashion, particularly in regard to the recent published work, Kinematic Dress, by Nervous System, supported by Shapeways [17], one can see that the designs rely on mechanical connections such as hinges or chainmail-like

Fig. 4. Stills of the film made by SHOWstudio from the dress Incunabula http://showstudio.com/project/1914_now.

arrangements. Both approaches are based on the fact that, to date, very little 3D printable substrates or filaments exist that combine the material properties of fibers, specifically to be flexible yet strong enough not to rip apart under stress.

When approached to design the dress and to collaborate with Joris Debo, Creative Director of Materialise, we faced the challenge of completely re-inventing this tried and tested typology, as the material we would use is a flexible thermo-polymer that combine the above mentioned properties of flexibility and strength. The result is a multi-layered main fabric, with the addition of a large interlocked bib, referencing the common use of Irish Crochet to be implemented into wedding gowns at the time, as well as the addition of articulated arms that would eventually be used to connect the 3D printed fabric to a pleated organza (Fig. 4).

3.1 Geometric Design of the Pattern and Relation to the Bending in Two Directions

To design a fabric using a flexible material meant that, instead of an arrangement of static elements that are interwoven as described, Incunabula uses a balance between the material's own flexibility and a multilayered textile design to generate flexibility in two directions. It uses two interlocking and articulated layers of material, imitating the base structure of a crochet and the interwoven details and floral patterns.

The first layer of the fabric uses the idea of a multidirectional base grid of cells that are elongated hexagons. The individual grid cells start at the top of the garment, arranged at a 45 degree angle and change with every row till they are orthogonal. The idea behind the dress is to express verticality in the fabric by rotating each individual cell row by row by 5 degrees. (Figure 6 right side) The cell size also changes in a

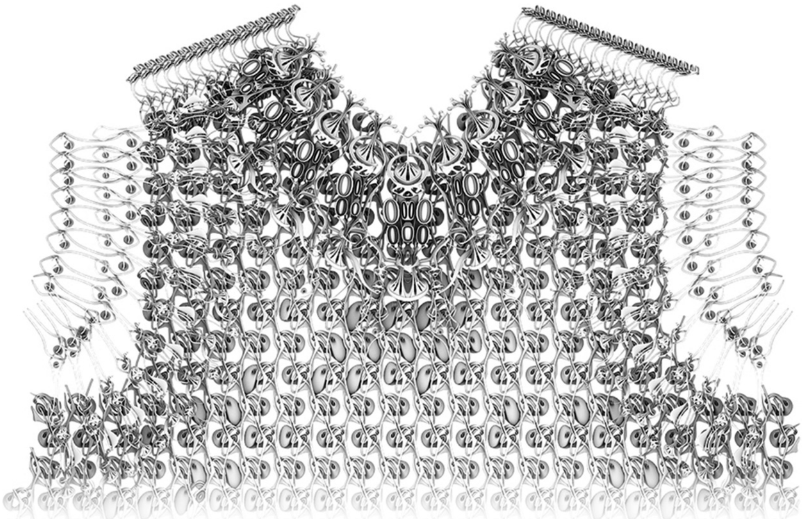

Fig. 5. Complete upper part of the overlaid 3D printed fabric layers including the bib and arms

continuous gradient, cells are vertically connected, yet only in the last third of the dress are they also partially horizontally connected (Fig. 5). We will refer to this first layer of the garment as the matrix (a). This matrix is able to achieve visually the same continuity as we can see in the crochet techniques of the time, yet it also allows a high degree of flexibility that shapes the dress according to the human body. The arrangement of connections vertically, yet not horizontally, allows the smallest curves of the body to be described, while also allowing the design to stretch and alter the visibility through the crochet-like material.

The second layer, matrix (b), is constructed as a series of 3 different sized, interconnected volumetric dots. The dots are designed to have a main body that is changing in size, a hook to connect to matrix (a), similar to Velcro-tape, and a connecting stem leading to a secondary grid. While the material is a flexible 3D print, it contains enough flexibility, yet toughness for these hooks to be interlocked with the hexagonal grid of matrix (a). The difference in sizes of the elements expresses the idea of creating transparency and opacity through variation of the sizes and thus allows the fabric to be more porous where the size of the hook is smaller and appear more opaque at locations and areas with the larger hooks. Additionally, the dots are similar to the described cells of matrix (a), rotating clock and anti-clockwise, row by row, imitating the gradual shift common to crochet techniques. Furthermore, the grid connecting the dots also rotates from a 45 degree oriented grid, connecting the dots, to a parallel grid at the end of the dress as shown in Fig. 6 sample A, B and C. In conclusion, we articulated variety and diversity through the introduction of rotating and mirroring elements and additionally created ornamental diversity, through the different sizing of the dots. We extended the possibility of articulating these even further by connecting the dots with a layered sub-matrix (Fig. 6).

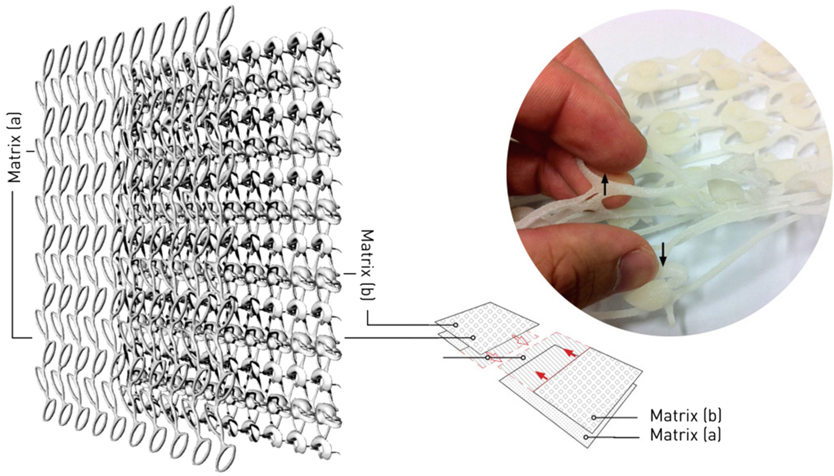

Fig. 6. Construction of the multi-layered 3D printed fabric using vertical and lateral connectivity to achieve flexibility and diversity.

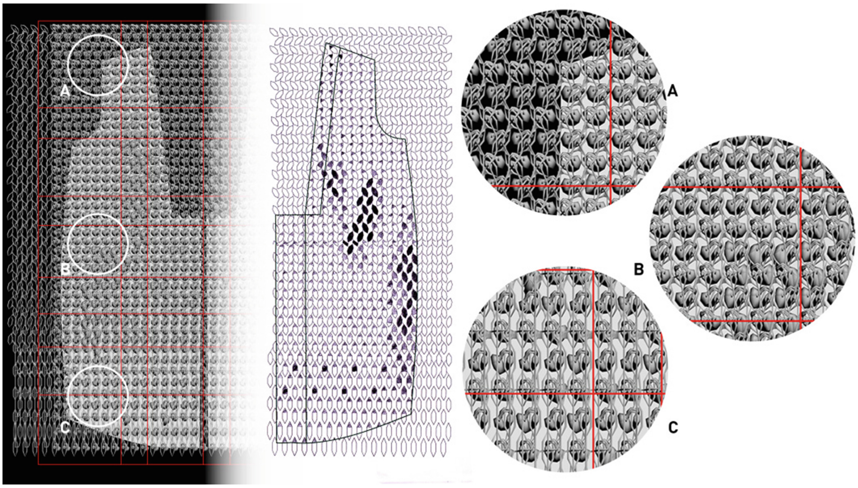

Fig. 7. Combined illustration of Alexandra Verschueren's sketch and translations into the grid matrix (a) and (b), excerpts of the rotating grid cells and dot articulation.

3.2 Production and Assembly

A further reason for this multi-layered approach in the design of a 3D printed fabric that translates the values and properties of Irish Crochet techniques, lies within the machining and associated building box sizes. At the current level of technology, it is not yet feasible to produce large-scale versions of 3D printers for a high definition print. The maximum build envelope in the machine we used, the EOS FORMIGA P110, is 200 mm × 250 mm with a maximum building height of 330 mm. In order not to have to stich the various pieces together using a thread, we developed a system of overlaying pieces of separated matrix (a) and (b) (Fig. 5). This allowed us, through the horizontal disconnection of matrix (a) and the ability to reconnect using the hooks within matrix (b), to create a fabric that behaves assembled as if being 3D printed in one go. It furthermore helped to work economically as well as ecologically (through the minimization of off-cut material). The pieces were 3D printed and assembled using a precise catalogue overlapping elements (Fig. 6, left side) (Fig. 7).

3.3 Conclusion

In conclusion, the dress is an experiment in translating the traditional and highly intricate craftsmanship of specific textile construction to the precision and material properties of a 3D printed craft. While acknowledging the qualities of the craft of Irish crochet, the author does not attempt to imitate or create a replica as seen often in 3D printing, yet attempts to design according to the material and digital constraints in as much as described by Sennet's work on the idea and construction of craftsmanship and thus constitutes a work in the field of digital craftsmanship.

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