Beyond Prototyping

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Abstract "Beyond Prototyping" is a research undertaking exploring the possibilities of algorithmically defined products that can be easily manufactured using digital fabrication techniques. Using interdisciplinary teaching between two universities and collaborations with small commercial studios as well as a series of product-service systems to evaluate the feasibility and appeal of such products, beyond prototyping proposes a vision of service model that sits between atelier and mass production. *Locatable*, *Ciphering* and *Highlight*, three case studies implemented as web and material services, chronicle the challenges and opportunities of such products. To evaluate their success, the services are offered to the public, who are subsequently sent surveys to reflect on the products. The case studies demonstrate that such products have potential to complement the current market with new business models.

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1 Motivation

The research undertaking "Beyond Prototyping" has its roots in a series of collaborations, and transdisciplinary activities in the Digital Media Design department of the Berlin University of the Arts (UdK Berlin) and Computer Graphics department at the Technische Universität Berlin (TU Berlin). Perhaps due to the inherently hybrid approach of digital media design, as a discipline that combines visual communications, electronics, computer science, product design, human factors and many other perspectives through embodied activity, we had already conducted collaborative experiments between the departments years prior to the establishment of the "Rethinking Prototyping" research project.

For example, a course offering "Computational Photography" was a course we jointly conducted, wherein the visual communications opportunities of photography was contrasted with the general transformation in society in which every mobile device was suddenly a camera, and where computers could increasingly better "see" pictures. These kinds of collaborations were always carefully crafted to have meaningful challenges and opportunities fitting the syllabi of an art and design programme as well as a computer science degree.

Digital media design, or with the new name of "New Media Studio" is a course, that is exploring the communication potential of new technological means, and questioning their role and impact in the culture. This questioning is best done by actively using and exploring the enabling capabilities, in a hands on fashion, prototyping new experiences, new services or criticizing the status quo, as well as showing warning examples of what might happen if the worst sides of the explored technology were to become the standard.

Also, leading to the "Beyond Prototyping" undertaking were a series of explorations in digital fabrication that occurred in the years prior, such as a course "Beauty of Data", which looked at the translation of "machine readable internet", or "Web 2.0", which examined physical artefacts with fabrication technologies. Suddenly, when the friends of social networks were turned to physical sculptures on a mantelpiece, or a mobile network's potential for tracking one's movements was visualised as a 3D volume, the new tangibility of all this, triggered a different kind of interest in the otherwise invisible digital aura we carry around us. Similarly, a course entitled "Indie Design" looked at how digital fabrication can enable an explosion of independent design labels that do not rely on large-scale production facilities such as a factory, and how new kinds of individualisation can be enabled by algorithmically defined aesthetics that are easily configured by end-users.

In summary, "Beyond Prototyping" stemmed from a long lasting collaboration and exploration of a field that would combine technological and design challenges in equal proportions that the Digital Media Design and Computer Graphics departments would be able to fulfil and realise, together.

2 Teaching

The previous work leading to the formulation of the "Beyond Prototyping" project used university teaching at masters level as a testing ground for broadly scoping out the possibilities of an emerging field. A semester theme for a studio class would be intensively explored in weekly seminars, discussions and hands on building of prototypes and scenarios. The advantage of this method was the open-endedness and broad scope, where within a relatively short period of time one can see a landscape of interesting complementary or contrasting areas that follow a common theme. These explorations, even though they manifest themselves in individual concrete design projects, highlight a way of thinking and propose a way of thinking about a subject. But due to the time constraints (basically extending only over a single semester at best), the depth and level of execution often stays at the level that could be much improved with more time.

Unfortunately, this time expenditure cannot be justified under the normal teaching syllabus. Some ideas get then developed further in the students' individual work, or in their graduation projects, but they hardly extend to transdisciplinary collaborations.

We developed a strategy, informed by previous collaborations, as well as the theme-driven studio works, where we would start with a broad scoping through class teaching. The results would stay quite open-ended, but then in parallel develop a series of in-depth projects that would guide the whole research project time frame of three years, becoming much more refined, real world services, going beyond prototyping.

Exhibition in the Cloud The first transdisciplinary teaching project we conducted, (which already started before the official launch date of the "Rethinking Prototyping" research project) was a collaboration between New York and Berlin:

> *Prototype: Exhibition in the Cloud* is an interdisciplinary collaboration between Parsons The New School for Design and the Berlin University of the Arts (UdK Berlin) which seeks to challenge and reinvent received notions of prototyping, extending its design and industrial origin to encompass artistic imagination.
>
> Invoking the image of cloud computing, "prototype" here means a state of constant transformation and becoming. Like a cloud, it is amorphous and malleable, unstable and precarious. Instead of achieving a functionalist goal-oriented objective, prototyping-in-the-cloud becomes a mechanism of repetition in difference; always self-renewing and regenerating, revealing its infinite potential through chance, adaptivity and ephemerality in materiality. To prototype therefore is to invent the unforeseeable, to cast a shape that is at the same time formless. To prototype is to imagine the ineffable and to create polymorphic manifestations that are at once crystallized and fleeting. It is as much a way of cultural intervention as a mode of formal exercise in which memories, histories, locations and relations are engendered, tested, reiterated and distributed—each a raw model of its own unique presence and by its own means. The exhibition adapts to the environment in which it is produced. With the cloud database serving as a structural platform for the project,

each material extension of the exhibition becomes a prototype in and of itself, and as such, a tangible experience.

The project is a collaboration that takes place between two geographical locations, using the cloud as a communication channel, tool and archival form for the exhibition. New York and Berlin are both centers of global cultural production and significant platforms for local artistic experimentation. The participants come from a spectrum of disciplines including Design and Technology, Communication Design, Interactive Design, Fine Arts, Photography and Illustration. In June 2012, thirteen Parsons students travelled to Berlin to participate in a weeklong workshop at the UdK Berlin. In November of 2012, a group of students from the Digital Media class at UdK Berlin travelled to New York to complete the project and install the first of several iterations. A second version of the exhibition will be downloaded from the cloud and take place in Berlin in January 2013. The content of the show will remain dynamic as the participants continue to upload new versions of their prototypes. Future iterations can then be downloaded at additional sites globally.[1]

The resulting projects were highlighting the challenges and opportunities in creating digitally defined, but physically constructed artworks. In this case, the aim was indeed to create artworks, rather than product series so that the range of works only partially met the core of the “Beyond Prototyping” vision.

The three resulting works are summarised below and serve to illustrate the project.

Attracting countries is a static/localized data-sculpture dealing with the topic of migration (Fig. 1) . The centre represents the country where the exhibition takes place. It points out how it influences adjacent or more distant countries. The idea is to demonstrate how many people immigrate to the centre country, and where they immigrate from.

The construction contains 100 threads attached to a Plexiglas ring. The end of each thread is connected to a needle that floats horizontally toward the centre of the ring. They represent the relative count of immigrants and are attracted by a magnet, which is the exhibition country. Each needle has a small but noticeable distance from the magnet, which represents the path the travellers have gone to get to their destination.

Stamp lamp connects emotionally to its owner by using his/her biometric signature in the design (Fig. 2).

Fingerprints are used as an input to modulate the design. In this manner, the object is inherently connected to its “creator”.

Most fingerprint identification systems do not look at the pattern of a fingerprint, but more commonly use certain points on the fingerprint for identification. These points are called minutiae, and their position to each other makes them unique. One kind of minutiae is called the bifurcations, meaning that one ridge on a fingerprint is divided into two ridges. These are the points that are in this case used to generate the form of the object.

[1] http://cloud.parsons.edu.

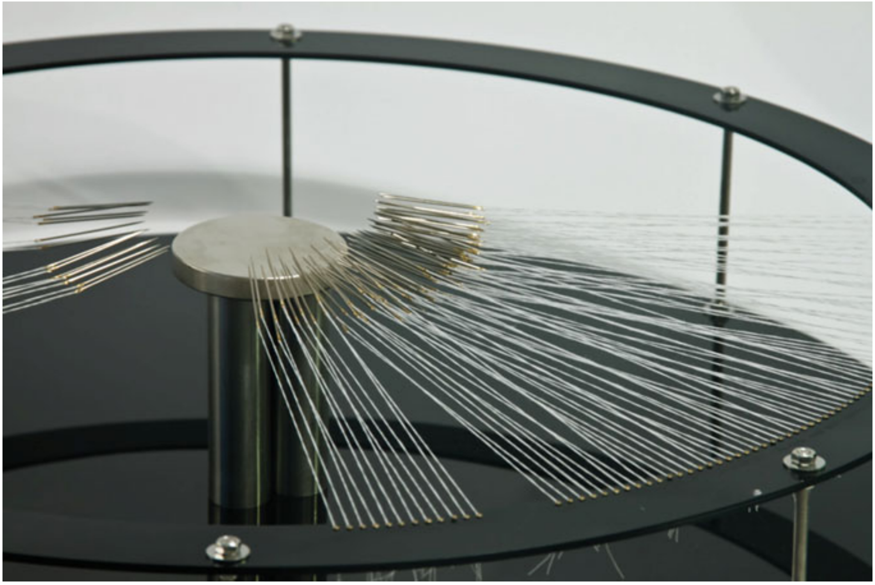

Fig. 1 ATTRACTING COUNTRIES by Felix Worseck

Fig. 2 STAMP LAMP by Gaspar Battha

The design itself and its generative process are strongly connected to the bifurcation minutiae. Using these “dividing” points according to their coordinates, the structure of the lamp is divided at the position of these points. This structural design is then pulled into three dimensions by a generative algorithm.

Signature piece is about the recording and reproducing of sensitive motion through the transformation of energy into movement (Fig. 3). A significantly simple device that can reproduce any one person’s scripted signature on site. Utilizing the Cloud signature piece is able to send its DNA anywhere it so chooses, encoding individual signatures into its design as it is produced. Using the DNA, individual exhibitors can produce the machine on site via any rapid prototyping method, thus making the availability of this machine limitless and exponential.

All three pieces described above were created as a hybrid between material knowledge of the fabrication (using mainly laser cutting as the physical tool). All of them required a considerable effort in the physical assembly, even if the algorithmic design process, once established, was easily adapted to different contexts.

This was a concrete experience about how the seeming lightness of digitality, transmitted through the “cloud” was confronted with the effort and expertise required in actually assembling and installing the individual works. The whole course was designed to bring the participating students together in Berlin as well as in New York—not only in the mechanical sense, but also in a physical one as well. Having this physical connection, and really knowing the people you are working with on a project proves that a mediated collaboration can be both effective and rewarding.

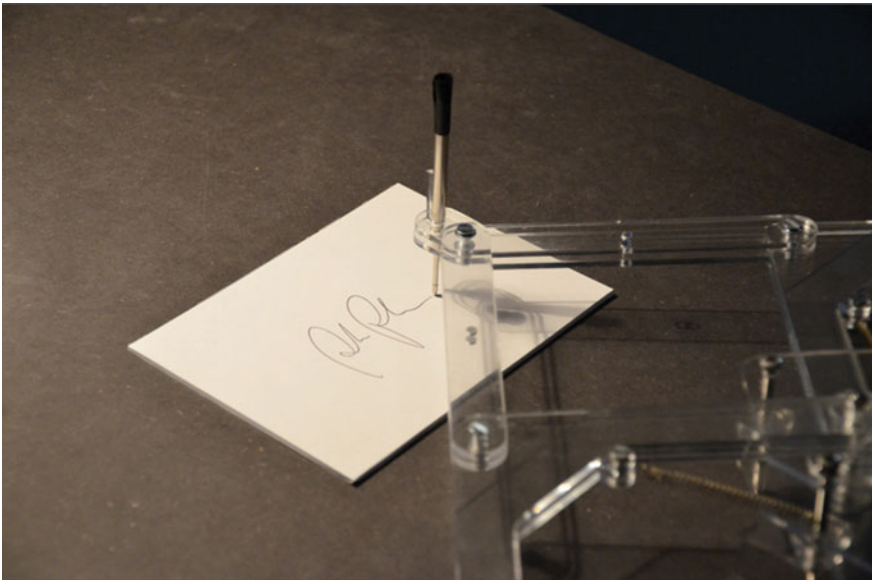

Fig. 3 SIGNATURE PIECE by Andreas Picker

The experience also highlighted the challenge of finding meaningful designs and striking aesthetics with a meaningful “configurability”, i.e. how to convert aspects of the design to parametric digital model where the form stays aesthetic with changeable narrative.

Ready/Made The next teaching offering between the UdK Berlin and TU Berlin focused on the threshold between mass manufactured goods with customisable parts through digital fabrication.

> The “Ready/Made” course looked at how rapid Prototyping Methods become more and more important in manufacturing products or product parts. Mass produced objects of high material variety and quality but with no individualised features coexist with highly customizable parts and objects limited by choice of material, size and surface quality. During the course students developed symbiotic relationships and computational models between a mass-produced and a customized object to create new ready/made hybrids that benefit from the best of both worlds using 3D printers, laser cutters and milling machines.

Since the course was offered as a part of the syllabi of the TU Berlin and the UdK Berlin, the challenge was to set course aims so as to be relevant to both career paths. Where the computer graphics department would expect developing ideas and solving the technical challenges within the realm of 3D geometry processing, either in capture or production, the UdK Berlin students’ would be challenged with developing believable concepts, compelling aesthetics and meaningful narrative, along with the technical solutions.

Invase is a platform that enables the conversion of normal drinking glasses to flower vases, where the user can easily configure the type of flower arrangement and match that with the base glass form (Fig. 4) . An algorithm then generates a 3D geometry that can be 3D printed and attached to the glass.

Screw lock presents a system for “physical password security” wherein a screw and matching screw key are generated from a passphrase (Fig. 5) . Hence, the product affixed with the screw lock can only be opened by the holder of the key, or broken in the process.

With *HeroMe* system one could replace the head of a toy action figure with a 3D scanned head, enabling one to transform the figurines to personal doubles (Fig. 6) . To facilitate this, a Microsoft Kinect generated point cloud was semi-automatically converted to an appendix that could be mounted on the otherwise mass-produced toy.

Techno Legacy The course “Techno Legacy” took a look back in time at the history of innovation, challenging students to closely study a particular historical innovation and convert it to a relevant enquiry in today’s digital context (Fig. 7). *“Mechanical Pi—In Memory of William Shanks*” is a machine that would mechanically operate an old calculator, using an algorithm that iteratively approaches to the value of pi in increasing number of decimal places.

Fig. 4 INVASE by Alyssa Trawkina and Marjam Fels

Fig. 5 SCREW LOCK by Gaspar Battha and Daniel Dalfovo

Kepler's Dream by Michael Burk and Ann-Katrin Krenz used 3D printing to create a fantastical abstract landscape inspired by the mystical world view of Johannes Kepler, made visible through an optical apparatus and mechanical gimbal, conjuring images from a medieval orrery (Fig. 8).

Fig. 6 HEROME by Nizar Ben Sassi and Robin Henniges

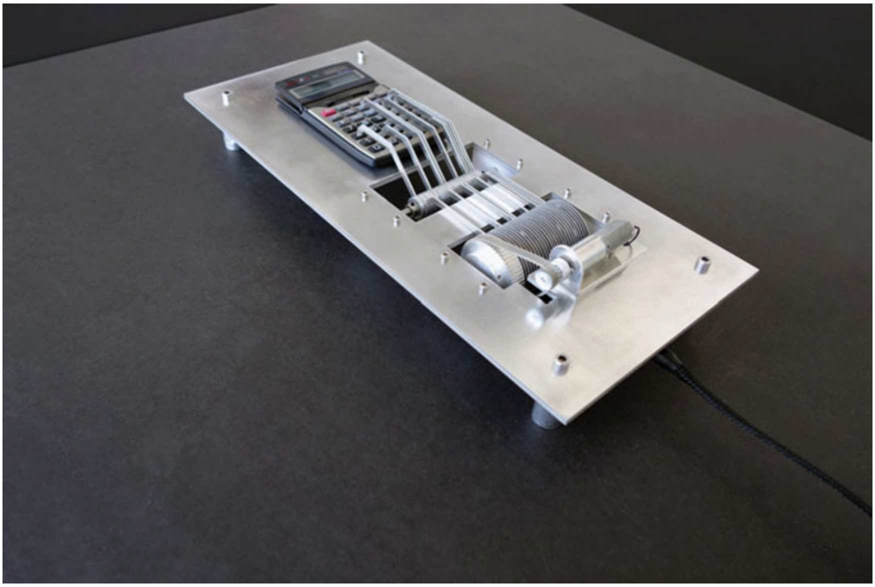

Fig. 7 MECHANICAL PI—IN MEMORY OF WILLIAM SHANKS by Florian Born and David Fröhlich

Fig. 8 KEPLER'S DREAM by Michael Burk and Ann-Katrin Krenz

Narrative Material Finally, the course "Narrative Material" explored a hard-coded meaning making into artefacts, as a counter reaction to the omnipresent screens in the public space, where the standardised form factor of a mass product dictates the aesthetics of the space. By creating spaces and objects that have the meaning physically encoded in them challenged the students to think hard about the message and the carrier to be seamlessly telling the same story.

Stephan Sunder-Plassmann created a park bench to remind the audience of the Nazi book burnings: A campaign conducted by the German Student Union to ceremonially burn books, in both Nazi Germany and Austria, by classical, liberal, anarchist, socialist, pacifist, communist, Jewish and other authors whose writings were viewed as subversive or whose ideologies undermined the National Socialist administration ideals (Fig. 9). "*Ort des Geschehens*" (The Place Where it Happened) recalls these crimes by linking the burnt books and persecuted authors at the actual place of event with a subtle memorial. A regular bench intended to be used as a place to sit, meet, think and read is slightly modified by implementing a barcode at the back. This code is the ISBN code of one specific publication, decodable using any conventional device, enabling the user to access any platform, which makes this book "readable" once again, and one is invited to sit down, read and reflect on the book at the actual place where it was burnt decades before.

These teaching projects served to guide and inform the "Beyond Prototyping" research efforts throughout the duration of the project, highlighting the technical challenges, aesthetic opportunities and simply inspirational case studies as to where to potentially apply digital fabrication as a part of a meaningful building process.

Fig. 9 ORT DES GESCHEHENS by Stephan Sunder-Plassmann

3 Case Studies

One of the motivations for the “Beyond Prototyping” research endeavour was the observation that the word “design” is often misused in supposedly interdisciplinary academic computer science communities such as Siggraph, TEI, CHI or UIST. Too often reduced to denote styling or used to justify otherwise unrelated fun, design is seen very differently depending on the perspective. This is certainly symmetrical in that any other discipline’s concisely defined terminology is surely abused outside the field. However, this “lack of seriousness” about design was one contributing factor to our motivation in employing design more centrally in the process, not only as a subject of enquiry, but also as the means for it.

So, where “Beyond Prototyping” attempts to take a closer look at the opportunities digital fabrication can provide in defining new kinds of products (through services) that enable users to have a considerable influence in the physical appearance and function of the product through an algorithmic translation of the design concept, we decided that the best way to research this would be to try to implement real, functional services that anyone could potentially use. The design concepts would not only have to be believable but also to actually exist as services, because the biggest advantage of digital fabrication is the capability of producing every single product as a unique piece. Hence, it would not be enough to speculate on the user's aspirations about a particular customised product, but instead, the products would be made so that one could truly reflect their impact and potential.

We developed a wide range of design concepts, focussing on different aspects of the fabrication:

- A simple production line, where the number of actors involved in the production would be to kept to a minimum.
- A network of Berlin based small studios and workshops that would together produce a high quality product as a service, choreographed by an online service.
- A service model, where a custom hardware-measuring instrument would be used to scan a space and create a fitting design for it.

These different approaches required a highly transdisciplinary set of skills beyond the research project staff, so we collaborated closely from the very beginning with a number of experts in cabinet making, 3D milling, online service development and materials to guide our designs to be as realistic and as high in quality as possible.

This dialogue, which took place in various workshop visits, informal discussions and process tests, were paramount to designing not only a concept, or a prototype, but a realistic design, with a functional service to realise it.

The three design concepts, explained below in detail were the following:

- *Locatable*: a table top with a street map grid engraved on its surface, chosen by the user through an intuitive web service from the global openstreetmap[2] database, and produced through three Berlin based small studios.
- *Ciphering*: a 3D printed precious metal ring that encodes four digits on the surface as selected by the customer on its website.
- *Highlight*: a generative lampshade that is made with the help of custom lamp socket mount 3D scanner and an accompanying web service that enables an intuitive design of desired light distribution.

3.1 Locatable—Balancing Between the Craft and the Computational

Beyond process optimisation, digitally fabricated products promise personalisation and customisation in form, function or meaning. Designing such objects, the entire system needs to be considered as a whole: The interface and the parameters the users may access and the manufacturing process between machines and manual workshops constitute a network that enables quality in design and in realisation, which supersedes the possibilities of each step alone. Designing in the real world with small workshops as a methodology, a case study of a mass customised table is

[2]https://www.openstreetmap.org.

presented, “Locatable”, with strong aesthetics, meaning and function, illustrating the potential of combining digital fabrication with traditional crafts (Fig. 10).

Introduction Digital fabrication is the focus of a lot of attention presently. The proliferation of 3D printing technologies through ever more affordable printers, as well as flexible and efficient online services is hugely influential in forming how the new generation of designers are thinking about design. 3D printing, which has first been profiled as prototyping, has maintained the focus mainly in the form over other material qualities. This has focused the development in ever-increasing abstraction between the digital and the material, where the printers can print more complex shapes, defined by the digital models, where the users have to think less and less about how the actual manufacturing takes place, how the machines actually work and if the manufactured object works in the real world. Yet, given this new accessibility, the 3D prints are increasingly expected to become the final products, as described by Hague et al. (2003), and Gershenfield (2008, pp. 3, 42, 79).

However, much of the quality of our products stem from their materiality: haptic feel, texture, weight, temperature and even resonant sound, all being qualities that are a key factor in the quality of a product of traditional handicraft and manual manufacturing, not only in terms of useful knowledge, but also as a motivation to design and create a product as discussed by Sennett (2008, pp. 163, 196–198). These qualities are often lost in the digital abstraction (ibid., pp. 59–65) and we often accept these shortcomings without question, as we have become accustomed to what is possible with these techniques. Many digital fabrication processes can

Fig. 10 Detailed view of a finished LOCATABLE depicting Schöneberg area in Berlin

manipulate a broader range of raw material than additive manufacturing methods: Laser cutting and 3D milling lets one process a broad range of material, but requires much more from the workshop and maintenance of the machines and does not fit well with the vision of the desktop 3D printer at home. These processes are already used quite commonly in small series or even mass production, but their intrinsic customisability is not so commonly applied. (For example, every individual item can be different without accruing any additional costs in adjusting the manufacturing process: one only needs to change the tool path).

This research presents a way of combining the digital malleability and the deep knowledge of the material. It defines a way of designing and producing high quality customised products that leverage the traditional handicrafts skills together with the digital algorithmic manipulation. The design process is a form of a dialogue in defining the meaning, the narrative, the aesthetics, the interface, the manufacturing process and choice of materials within the constraints of the meaningful, controllable, affordable and manufacturable.

Prior Work Pioneers in this field, such as *Nervous System,*[3] *Unto This Last*[4] or *Fluid Forms*[5] have been developing products for rapid manufacturing for several years. Nervous System design studio has been exploring the formal possibilities of rapid manufacturing in designing with biological forms, generated by algorithms and converted to jewellery. Albeit some of their designs are user customisable, their work is mainly designed by the designers using software, and the final forms are then fixed as final designs that the customers can buy in different sizes. Their striking aesthetics is only possible through the new manufacturing techniques, and their biological narrative is a meaning that works beautifully.

Fluid Forms designs focus on the personalising aspect of production on demand, such as 3D printed rings, where the inside hides a relief of a finger print, a 3D milled fruit bowl with an exaggerated elevation map of an area of the user's choosing, or a clock face that is laser cut in the shape of a city map—all instances which leverage the user's projection of meaning onto the objects. This personal narrative defines the object more than any functional aspect of the design.

Unto This Last[6] creates customised furniture, and performs the making process as a robotic ballet at the studio's workshop and showroom hybrid. Using 3D milling, *Unto This Last* creates functional objects that have been optimised for the manufacturing process with striking aesthetics. The different modular components, such as joints are easily combined, dimensions adjusted, and produced on demand, fitted to the customer's spatial constraints. Due to the 3D milling as a process, the choice of material is much broader than when relying on 3D printing, and the physical dimensions are much larger, making the creation of functional furniture possible.

[3]Nervous System, http://n-e-r-v-o-u-s.com/ Accessed 20 April 2015.

[4]Unto This Last, http://www.untothislast.co.uk/ Accessed 20 April 2015.

[5]Fluid Forms http://www.fluid-forms.com/Accessed 20 April 2015.

[6]http://www.untothislast.co.uk/.

Vision As the above examples illustrate, the manufacturing method is a central part of the aesthetic potential of any artefact. Designing the form finding and manufacturing process are both essential parts of the design. Instead of trying to constrain the work to a rapid manufacturing process that one might be able to print at home, there is a great potential in designing a network of services, be it through software, robotic manufacturing or even a handicrafts workshop, working together as an ecosystem, partially applying the principle of peer production to the production of physical products, as proposed by Reichwald and Piller (2009, p. 72), but with a greater emphasis on distributed manufacturing resources. This type of system-level thinking enables a balance to be struck between material qualities, dimensions, personalisation and the infusion of meaning, all (hopefully) within the constraints of the affordable and the manufacturable.

Seeing system design as an inseparable part of the work, the real world is used as a research method. Instead of using a good number of workshops and machines in different departments of our university, the design is done with small workshops and studios in the city that subsequently define our production network and implicitly operate within the constraints of a real world context.

A Case Study: Locatable Locatable is a dining table with a street network carved and filled with resin on it. It is meant to be ordered online with a simple interface, where one only has to specify a single address. The address defines the cutout area from the OpenStreetMap database, which is sent to a 3D milling studio. The tool bit has been previously defined for optimal aesthetic, and the vacuum table under the milling machine makes it extremely easy and fast to carve the street network on a wooden board. Once ready, the board is transported to another woodworking studio close-by, where the grooves are filled with epoxy resin and subsequently sanded for the final aesthetic, before sent to the client.

A map as a motif is useful and aesthetically appealing at the same time, a location is often emotionally charged, and both present an optimal content for personalised product. The idea stemmed from the observation from everyday life, where daily events and near future plans are often discussed in front of a wall mount map. Most of the time, these discussions do not include specific street address searches due to the familiarity of the place, but instead, the map reference is giving broad visual backdrop that illustrates distances and puts the plans in context. Hence, an abstracted, but relevant map of an area where one is located was deemed as desirable for creating a sense of attachment to the product as described by Auclair et al. (2005), and an ideal context was thought to be informal breakfast or dinner discussions at home. A table top surface fits this scenario very well, but had a central requirement of good haptic and aesthetic quality.

The interface through which one can define the final table online was kept very restrictive on purpose: The entering of the address is the only interaction possibility, resulting in an abstract preview of the cutout. The reason for this was to control the aesthetic, as defined by the designer. It was designed to let the user enter something personal and meaningful into the object without the possibility of inelegant and unforeseen outcome resulting in either a fall-off in user experience as mentioned by

Auclair et al. (2005) or complications in the production process as discussed by Willis et al. (2011). A limited number of parameters also promised better means to optimize the overall production workflow (Fig. 11).

To prototype this service, all aspects of design were worked on iteratively, in close collaboration with a team of experts: An online interface was designed to keep the interaction flow as smooth as possible, and provide the data needed for the milling in an easy to use format for the workshop, and to estimate the total length of the routing needed to keep the production speed realistic. In the milling workshop different milling bits, routing speeds, carve depths and vector terminations were explored to find the optimal aesthetic that is ideal for many different layouts of streets and still able to be produced within reasonable machining time.

In a similar fashion, different resins and inks, as well as the manual sanding process were tested and reviewed with the experts to come up with a high quality handcrafted aesthetic that still kept the man-hours to the minimum, and hence in turn make the production of the whole table a realistic proposal.

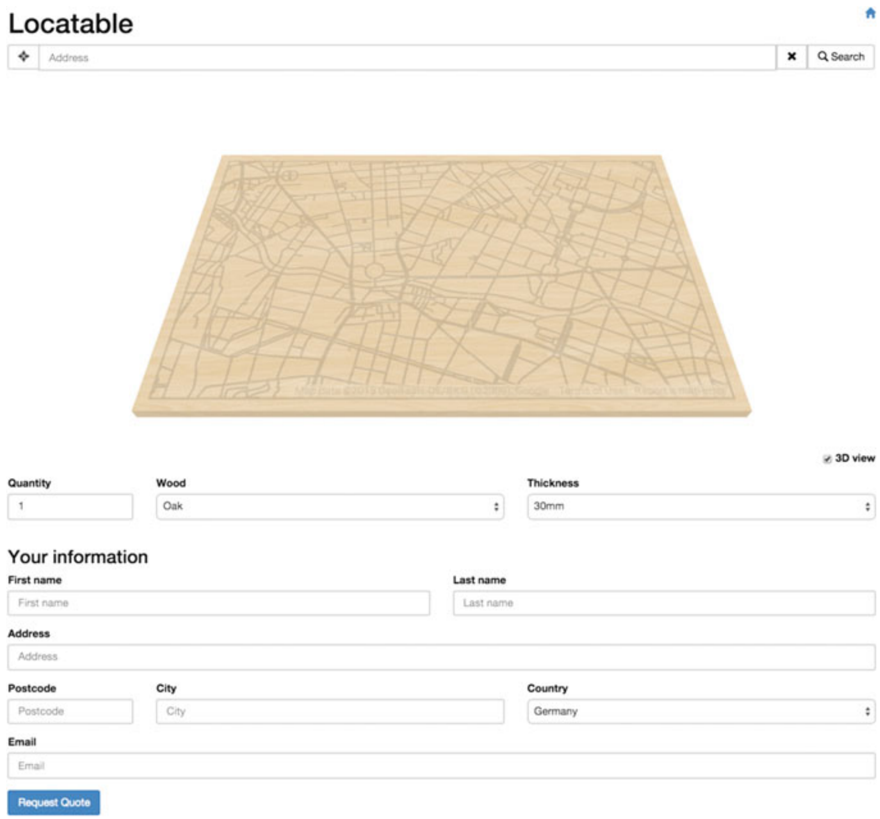

Fig. 11 Screenshot of the LOCATABLE order interface

A central question to the design process was the feasibility of the idea. This included the manufacturing and material costs, and the perceived value added from the end-user's point of view. To this end, it was decided to firstly push the concept to the extreme using an icon of cheap mass manufacturing as the base for our design, the Björkudden table from Ikea. We then carved our customisation layer on top, creating a dissonance between the mass manufactured object and the personalised service layer (Fig. 12).

The table was displayed to the general public as a part of the Berlin "Lange Nacht der Wissenschaften" (Long Night of the Sciences) event in the city, and a simple survey was conducted, asking the visitors to evaluate the table. The study was conducted only to give us an indication of the perceived value, and due to the nature of the event, we could not attract people to fill in complex forms, so the questionnaire was reduced to 3 simple questions:

1. What would you pay for the base product without engraving?
2. What would you pay for a generic engraving that you cannot choose?
3. What would you pay for a table with customised engraving that you can define?

The answers (N = 29) ranged significantly in evaluating the base product price, but overall, the difference between the base and the personalised was almost 100 %, albeit it did vary substantially (271 % sd = 191 %). In other words, our informal study suggests that people were willing to pay double for a table with a street map

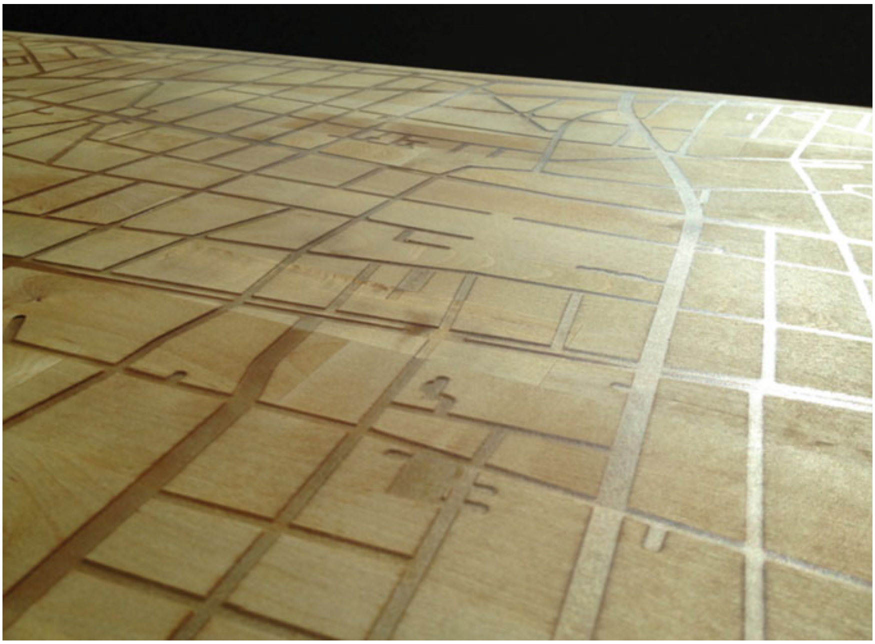

Fig. 12 Close-up of the first finished table

carved and cast on it than the same table without the customisation. This indicative evidence would make the customisation feasible with our process for the mid price range upwards.

What many visitors noted was that once the base table was identified as an Ikea table, the value of the customisation was starkly reduced. The aura of the product was always seen as the combined value of the base product together with the personalisation, and the attached narrative. This experience led to the decision that using a mass manufactured base product makes little sense, as the meaning associated with the product conflicts with that of digital manufacturing.

Reflection The prototype in this process was on one hand the 3D milled, resin cast and manually sanded Ikea table showing the coordinates of the research group's offices, but on the other hand a manufacturing system that consists of a web component where one can define the design and order the table, the material supplier (and ordering process), the 3D milling studio and the woodworking studio for the different steps in the manufacturing.

Designing together with the experts in the studios proved an immeasurably positive benefit for coming up with the high quality aesthetics as well as providing direct indication of the feasibility of the process, how it would integrate in the everyday of the workshops and how much time it would take to actually produce the table.

Confronting the general public with the final result very much involved the pleasing quality of the table, where a transparent resin cast creates subtle ambivalence between the shadows of the grooves and the smooth haptic feeling. This reminds one of the importance of manifesting ideas in a physical space where these material nuances are extremely important in the final experience. It is easy to forget them in the complexity of software and process optimisation, as well as when concentrating on the narrative and the meaning from a more rational perspective.

Further Work Locatable was the first concept that was played through in the real world, and had tangible feedback from the everyday audience for the work. In parallel, various additional concepts are being developed that attempt to strike a balance between the narrative power for the individual, the manufacturing process mixing digital fabrication and manual processes and the definition of the system enabling the interactions. However, the feasibility of this approach is still highly specific and limited to a narrow range of products. As the pioneers in the field, *Fluid Forms*, *Unto This Last* and *Nervous System* all demonstrate, finding the meaning beyond the purely aesthetic is still a very difficult balance to strike. *Fluid Form's* focus on the personal story, at the expense of functionality, *Unto This Last's* focus on the spectacle of manufacturing, and use of 3D milled aesthetics, without additional narrative, and *Nervous System's* complex forms as aesthetics, but with very few meaningful personalisations all highlight the challenges of finding the right balance.

This text demonstrates the feasibility of a service and a network of production steps that may consist of the new or the traditional that together make possible aesthetics that cannot be yielded with digital fabrication alone. The network can serve as a design tool in the prototyping phase and be used for production as well. In case of increasing demand, and given a well-designed and well-documented workflow, the network can be extended easily to provide more production capacity by adding nodes, namely workshops and digital manufacturing studios.

The design process is far beyond simply form-finding, and is a balancing act between which aspects to limit and those that it makes sense to leave open to end-user manipulation. With the right mix, it is possible to find striking customisable products that can provide functional added value to the end-users and that are also feasible in smaller-scale production, and still beyond the safe haven of a university research project: designing in the real world.

3.2 Ciphering—Sense of Ownership of Generative 3D Printed Artefacts

This text looks at the infusion of meaning in digital fabrication processes. We analyse how non-expert consumers identify themselves with digitally manufactured products and whether the embedding of personal content can change their perception of a particular product. We present a case study of a customisable, digitally fabricated ring—*Ciphering*—which encodes personal information into a physical object. Through a website, the user can enter four digits (such as a date, for example), which are then encoded in the physical shape of the ring and only legible when held in front of a light source in a particular way.

In order to analyse the sense of ownership of this product, as well as to understand its appeal, we conducted interviews and surveys with customers. Instead of paying subjects to take part in the study—as is commonly the case in academic contexts—the design was implemented as a functional online service where people customised and purchased the ring. In this way, we could collect users' reflections in a real scenario, which was much more useful than speculating on an imaginary service. The study suggested that the narrative aspect, along with the sense of authorship, were central to the identification with this product. Additionally, we found that the meaningfulness of the parameters that customers can control, as well as the level of impact they have on the physical design, are both important aspects to take into consideration when designing a digitally manufactured product, and can allow the users to identify better with it.

Introduction Without question, the advance of additive manufacturing is changing the way we think about products: In manufacturing processes, it is possible to produce parts in quantities from one to several thousand, depending on the demand. In the design aspects, with no more tooling constraints, designers are free to create new shapes that were impossible to manufacture before (Campbell 2006). In fact, a growing number of companies are investing in systems using additive manufacturing (Wohlers and Caffrey 2013). Only in the past decade or so, this industry has developed notably from a mere prototyping tool to a real manufacturing system, able to produce complex high-performance outputs, such as aircraft parts (LaMonica 2013).

Along with the advancements in the area of industry, this technology is also creating dramatic changes in the way users perceive and relate to products. This can be observed in the proliferation of the so-called "maker" culture, as well as new formats of creating and sharing products, such as Fab Labs. These small-scale workshops equipped with computer controlled tools use digital fabrication to democratise manufacturing technologies previously available only for expensive mass production (Menichinelli 2011). Distributed manufacturing—a decentralised system using a network of geographically dispersed facilities—is also one of the phenomena developed hand in hand with information technology.

Other exciting aspects of this field are the newly available possibilities in the customisation of products. Customisation is the process of taking a general product design concept and tailoring it to the needs of a specific customer (Carter 2013). Customisation can be handled very easily in additive manufacturing in contrast to conventional manufacturing processes (Campbell 2006; Nambiar 2009). Since every product made with additive manufacturing can be unique, taking individual customers needs into account becomes possible while keeping mass production efficiency at the same time. This use of flexible computer-aided manufacturing systems for producing custom output is called mass customisation. The concept is attributed to Stan Davis in Future Perfect in 1987, but more recently, Tseng and Jiao proposed another definition. Tseng et al. (1996) define mass customisation as producing goods and services to meet individual customer's needs with near mass production efficiency. This possibility for the consumer to influence in the creation process of the product and become its own designer seems truly revolutionary (Carter 2013).

The advantages of mass customisation as a viable business strategy had been widely discussed (Piller 2005). For some time, the opportunities of mass customisation has been acknowledged as fundamentally positive by theoretical and empirical studies, and some companies are already having a degree of success employing this model. On the other hand, many companies have also failed in their attempts to implement it and large-scale mass customisation operations are still limited to a few examples (Harzer 2013).

One of the reasons for this, according to Piller (2005) is that most of today's offerings focus only on style, although in fact this option may be the least appealing to consumers. This problem is quite evident in many of the existing generative products using mass customisation strategies today. In areas like jewellery, for example, the customisation parameters that are accessible to the user seem often arbitrary; one can change the amplitude of a curve on a surface, radius of the bevel or choose a predefined selection of patterns. These parameters have little value for the user and hardly allow him or her to project a personal meaning into them. At the other extreme, many products provide the possibility of entering letters and create personalised cufflinks or pendants, or upload a picture to be embossed on the face of a ring, for example. In these cases, there is an attempt to introduce personal content, but being able to see the letters/images directly on the surface of the product is predictable; beyond the choice of the font or thickness of the lines, not much is actually designed.

Although mass customisation can increase the value of a product, this is not always necessarily the case. In fact, many mass customisation products do not create enough additional value for customers compared to their alternatives (Piller 2005; Squire et al. 2004). And as Campbell (2006) states, there is very little point in customising a product feature that will not add value. Therefore, one of the biggest challenges of the mass customisation field is to find meaningful parameters to customise, according to real needs and desires of users. We believe that design can play a vital role in recognising these motivations, creating products that are both meaningful and engaging.

Towards Meaningful Customization Every artefact we use already inherently bears a degree of cultural meaning embedded in its aesthetics and functionality (Siefkes 2012). Tables, for example, facilitate social gatherings and serve as a meeting point; rings often signify events, people, or affiliations. Therefore, the understanding of the cultural aspects of artefacts, as well as their functions and affordances, is fundamental for designing mass-customised products. Once the design goes along with these cultural and functional aspects, the customisation does not only make the process of buying the product easier, yet can actually enhance the experience of using it. This is exemplified in different prototypes designed as part of the "Beyond Prototyping" research project. One of the prototypes that serves as a study case for this paper is *Ciphering*, a digitally fabricated ring (Grimaldi et al. 2013).

Rings are interesting objects in terms of customisation because of their long tradition of hand-made production, as well as their small size, which makes them feasible to produce with digital manufacturing tools. The custom of giving and receiving rings dates back over 6000 years. As other types of jewellery, it has different cultural functions: it is used as a marker of personal or social status, as a signifier of some form of affiliation, or as a symbol of personal meaning. It often symbolises group membership or status. One of the aspects we found more interesting when designing a ring was the twofold affordance that this object possesses, allowing two different functions: On the inside, it carries an intimate piece of information—normally personalised in the form of a name or a date engraved inside—which can be seen only by the user. On the outside, visible to other people, the shape expresses its value in a symbolic form.

Ciphering: The Narrative Potential With this in mind, we have developed Ciphering, a digitally fabricated ring that encodes personal information into a physical object. In order to customise the ring, a user can enter four digits—a date, for example. In contrast to other generative jewellery, the digits are encoded in the physical shape of the ring and only legible when the ring is held in front of a light source in a particular way. In this manner, the ring keeps the two different functions: a personal message on the one side and a distinct aesthetic on the other (Fig. 13).

Since Ciphering provides users the possibility of designing a product according to a date—which represents a personal event—it most probably evokes emotions and personal memories in the user. This strong narrative aspect can play an

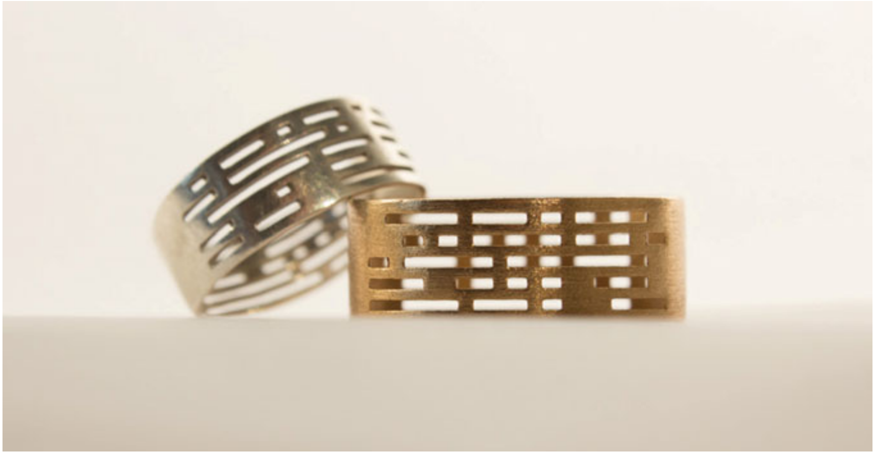

Fig. 13 A pair of finished CIPHERING rings in different materials

important role in how users identify with this product and contribute to their sense of ownership. In order to understand this phenomenon more in depth and recognise the narrative potential of Ciphering, we look at the theoretical framework proposed by Grimaldi et al. (2013). In the paper "Narratives in design", they analyse the different definitions of narrative as well as the roles and functions of narratives in products and design processes.

Grimaldi et al. also show how the narrative can contribute to the value of a product. This is exemplified by the project Significant Objects from Rob Walker and Joshua Glenn, which aimed to measure the added value that an accompanying story adds to an object (Glenn et al. 2012). In this project, they purchased cheap objects at flea markets and then ask writers to write an accompanying story for them. The objects were then sold on eBay with the attached story to verify the increase in value (for example a glass that was bought for $0.50 was subsequently sold for $50). As Grimaldi explains, the buyers were not purchasing the story, freely available online, but simply the object which acquired meaning through the story (Grimaldi et al. 2013).

We believe that one most important aspects that makes Ciphering valuable and appealing is in fact the narrative, as the customisation of the product is connected to a personal story. At the same time, we believe that the traditional narrative aspects of rings is enhanced, since Ciphering not only activates remembered or associated stories in the user, as rings normally do, but also includes the narrative as part of the design of the object.

Ciphering: The Service The customisation of Ciphering is done through a website (http://ciphering.me), which enables the ergonomic and material customisation of the product in a very easy and intuitive fashion. As the design concept is not obvious, a large portion of the content on the page explains the concept through 3D

Fig. 14 CIPHERING website. http://ciphering.me/

renderings, photographic and video documentation as well as schematic illustrations. These are essential, especially since the customer cannot physically examine the ring, as would be the case in a traditional shop (Fig. 14).

All the information the customer can enter is done through simple text entry or choosing an option from a pull-down menu. These variables fundamentally affect the design of the resulting ring, but are exposed as precise choices for the customer. The entered parameters are piped to an OpenSCAD service that generates the solid 3D geometry ready for 3D printing. The four digits are converted to a five-pixel font, and scattered through the ring walls from a single vantage point. All the surrounding pixels are then randomly distributed either to the front or the back wall of the ring, disguising the digits into a pixel pattern. Only by looking through the ring from the projection vantage point, the pixel grids align, exposing the entered digits (Fig. 15).

The generated 3D model of the ring is automatically uploaded to a 3D printing service portal, from where the customer subsequently receives a confirmation email, when the geometry is processed and rendered for a realistic 3D preview. The customer can then see the final price (based on the choice of material and the total material volume of the ring) and order the product. The production and delivery, depending on the material, takes between 2 weeks and 1 month (Fig. 16).

A significant challenge of the service system was that the customer could not immediately try the ring on to gauge its ergonomic fit. This problem of uncertainty

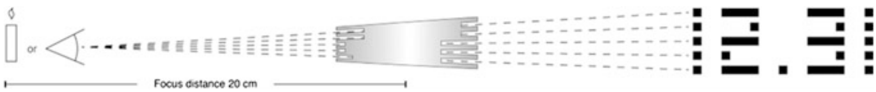

Fig. 15 How Ciphering works. http://ciphering.me/

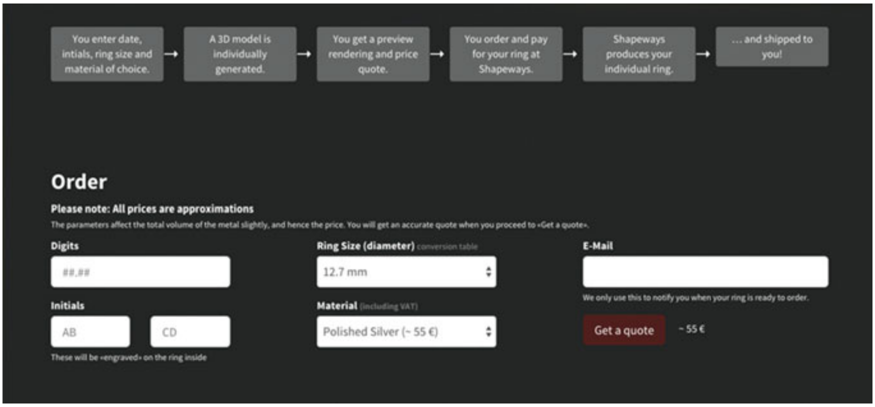

Fig. 16 Online configurator. http://ciphering.me/

was already devised in mass customisation systems and in many cases presents a disadvantage (Piller 2005). But for us it was interesting the way customers tried to overcome this problem: many went to a local jeweller just to measure the correct size. Alternatively, some have asked to have the ring produced in cheap plastic to confirm the fit before ordering the precious metal version. This of course delayed delivery of the product even further, which for many kinds of products would not be acceptable. However, since rings are acquired to represent an event planned well ahead of time or in retrospect, they are less problematic than other types of products.

User Survey In order to analyse the appeal and the meaningfulness of this product, we conducted interviews and surveys with the users. For this purpose, the design was implemented as a functional online service through which anyone could buy the product. As opposed to traditional user-studies, in which the subjects are paid to take part, we conducted this study with real customers. Individual users' motivations vary from person to person when they buying a product. We believe that user's reflections about their experiences in this real scenario carry much more weight than in a fictional scenario. Hence, making a real service available was the key to understand the true value of this product.

Designing the product, making it available and running the service were all parts of a system, and they would not make sense if they were not interconnected. By creating this fully working system in a concrete case, we were able to focus on the real experience, instead of posing questions or speculating. This process allowed us to understand which kind of aspects should be considered when designing digitally manufactured products.

The website went online in March 2014. The site was used (people filling their customisation details and asking for a quote) 367 times in 9 months. Thirty-two people bought a ring at an average price of $76 (prices ranged from $28 to $303, according to the materials used). Eleven customers filled the online questionnaire, which was sent by email. The questionnaire was structured in three parts: in the first part, participants had to enter general demographic information as well as answer a few key questions, such as whether they had experience buying jewellery online before, and what they found interesting about Ciphering, for example. The second part focused on their connection to the product and the meaning of the encoded message. The last part assessed their experience of using the ring.

Results Most of the participants (91 %), only half of whom has never bought jewellery online before, found the price fair or definitely affordable. 73 % of the users who answered the survey had bought the ring. The ones who did not buy it, reported that it was mostly because they were not planning to buy it in the first place or because they were not sure if it would fit their finger. But all agreed that the most appealing or interesting feature about Ciphering was the concept.

From the ones who bought the ring, all reported that the numbers had a special meaning for them and were related to personal events (such as graduation, engagement and marriage). 73 % of the participants reported that the ring was especially made for them and 45 % replied that they took part in the design of the ring by encoding the numbers. To the question of who they considered to be the designer/s of the ring (with a choice between: themselves, the designer, the programmer, or a computer) half responded themselves (in conjunction with another figure).

The different properties of the ring in order of importance across all respondents who bought the ring were the following:

- One can encode its own meaning
- Every ring is unique
- The numbers are “hidden” (not visible unless you know how to see them)
- The process is fun
- The materials are of good quality
- It is produced on demand
- The ring is created by a computer algorithm

Discussion Clearly the most important feature of this product was not the perception that it was designed by an algorithm, but rather the ability to participate in the design process by encoding a personal piece of information and seeing its significant impact on the physical form of the ring. The lack of interest in the algorithm and the focus on the uniqueness of the ring and the encoding of a personal story suggests that it is both the narrative aspect and the authorship of the user-as-designer that makes this customisation valuable. Of course, the automation of this process was enabled by the algorithmic design, but it was not perceived as *the* prominent characteristic.

With respect to the narrative aspects, all the participants said that the numbers had a special meaning for them and mentioned life events in order to explain why, confirming that the narrative plays an important role in the value of this product. Regarding the authorship, all participants described the experience of purchasing the product with words like "fun" or "exciting", which underscored the fact that they were involved in the process and that they feel positive about the experience.

Surprisingly, some participants responded that felt that they personally took part in the design of the ring (together with either the computer or the programmer). This reveals a new way that customers relate to products and a shifting role of the designer. Furthermore, many users contacted us to ask for additional customisation to match their individual needs.

For purposes of understanding these phenomena, we looked more in depth at these aspects through different theoretical frameworks of mass customisation: we analysed the experience the customers described through the sense of ownership, the customer co-design experience and the "I Designed It Myself" effect. Through these concepts, we explored how the level of involvement in making Ciphering could have enhanced the enjoyment of the process and the likelihood of bonding with it.

Sense of Authorship While the value of the outcome is important in mass customisation, many studies have highlighted the role of the experience itself in the perceived value of these products. Studies have shown that apart from the benefits that consumers get from mass-customised products, for example in reflecting their personal preferences, they also may derive benefits from the customisation process itself, that is, the activity of doing something by themselves is perceived by many consumers as self-rewarding and they experience joy during the co-designing task as a result of the fulfilment of a rewarding, artistic, and creative act (Mourlas and Germanakos 2009).

Merle et al. (2010) argue that from the consumer's point of view, the experience of co-design can have a positive influence on the overall value of mass customisation. They demonstrate that apart from an efficient customisation, there are complementary mechanisms that create perceived value in these products. Thus they identify two global components: (i) the product—with three dimensions: utilitarian value, uniqueness, and self-expressiveness—and (ii) the experience—with two dimensions: hedonic and creative achievement.

Piller (2005) also highlights the importance of the experience along with the outcome and explains that products that are co-designed may also provide symbolic (intrinsic and social) benefits for the customer. This co-design experience generates a sense of creativity and enjoyment in the user, in the accomplishment of a task. Another benefit of the co-design experience is the sense of ownership, which plays an important role in the evaluation of self-designed products (Turner et al. 2011). Mourlas (2009) describes the benefits of "pride of authorship". In this effect, the positive outcome of having created a satisfactory product on their own, instead of buying a standard off-the-shelf item, gives consumers positive feedback creating a feeling of pride. In this way, consumers would value the mass-customised product more than an identical off-the-shelf product.

Similarly, Franke et al. (2010) describe this phenomenon as the "I-design-it-myself" effect, when the value ascribed by individuals to a self-designed object incrementally stems from the fact that they feel they were the originators of the object. They explain that the economic value of self-designed products has often been attributed to two factors: preference fit achieved (which should be as high as possible) and design effort (which should be as low as possible). However, they suggest a third factor, which is "the awareness of being the creator of the product design". In their studies, they present evidence that the I-designed-it-myself effect creates economic value for the customer: Participants have the opportunity to design different products, enabling different degrees of design freedom and choices between self-designed items and standard ones. First, they demonstrate the I-designed-it-myself effect by showing that individuals are willing to pay more for a product when they are the originators of the design. Secondly, they confirm that the feeling of accomplishment acts as a mediator of this effect (Franke et al. 2010).[7]

In the context of the *Locatable* development as described above, we also found suggestive evidence for the same increase in the perceived value.

In summary, the frameworks described in this section can be useful for explaining the sense of authorship that users felt in making Ciphering, as well as their enjoyment in the process. They can also explain why, apart from the narrative aspect of the product, users felt a special connection with it. Although the customisation offered them the possibility to express certain level of creativity, we observed that users even felt comfortable enough to actually get in touch with us and ask for extra customisation. This phenomenon, in which users feel the need to customise over the default possibilities that were offered to them, not only confirms the sense of authorship they developed, but it might go beyond. We believe that these requests present an interesting case for mass customisation, as it demonstrates that, by being in the middle between mass production and an atelier service, customers can use the advantages of both.

Between Mass Production and Atelier Service In order to design an online configurator that is easy to use, many aspects of the design had to be pre-determined and unchangeable, whereas in a manual design process, they could have been easily changed. For example, the 3D printing resolution limits, as well as structural constraints in encoding the pattern onto the ring meant that a maximum of five (ascii) letters in five-pixel high font could be encoded on the surface. Defined by this limit, the design was then constrained to two digits separated by a dot, instead of a five-letter ASCII letter pattern. The interface thus seemed most suitable for encoding a date onto the ring.

However, several customers, after playing around with the online configurator, decided to contact us directly and request features not readily available through the website. For example, a group of graduating mathematic students from Swedish university wanted a memento of their studies, and thus asked if they could shift the dot in the configuration to encode the first three decimals of π onto the ring. Another customer couple asked to emboss the year on the outside, and engrave another date with year on the inside, the numbers symbolising the time they met and

[7]Shapeways Waveform Earrings. In: Shapeways.com. http://shpws.me/ClWa. Accessed 28 April 2015.

the wedding date. Several customers also wrote back suggesting expanding the design concept to other forms of jewellery. We found this very interesting, as it seems that these customers were using their own creative ideas to adapt the product to their needs, going beyond what the online platform offered. This direct customer exchange much resembles a consultation with an atelier service.

Commissioning an atelier to design an object, be it interior or jewellery, means that the client is hiring an expert to first understand the needs and desires of the client and then translate them to a satisfying experience. Purchasing a mass-produced product, on the other hand, means choosing between ready-made options that implicitly are also available to many other people. Thus, the broader aim of the "Beyond Prototyping" research project, to which Ciphering belongs, is to explore the opportunities that algorithmic design and digital fabrication can bring in between atelier service and Mass Production.

Ciphering provides a service that embodies the design language of a designer, but manifests itself in a bespoke unique instance through the interaction of the client on the web service, generating a unique design based on the meaningful parameters provided. Hence, the design work is done once, but is adaptive to each individual purchase. Since the data entry and the production are both automated to a great extent, the costs for such parametric designs are significantly below the prices of an atelier service and simultaneously accessible to a wider audience. Furthermore, special requests were easier to accommodate than in a one-off design process, since the production pipeline was already set up and the rest of the system could be readily used for the production. In this scenario, the configuration, which enabled affordable but personal products, encouraged some customers to consult the designer, perhaps creating an even stronger sense of ownership of the product through this dialogue.

Conclusion Digital fabrication is still a niche market. However, it offers new possibilities for both users and producers and can make a product more appealing and personal. In this text, we have argued that design can play a vital role in recognising users motivations and have analysed the appeal of these products through the concrete case study of a digitally manufactured ring. The data collected from our survey demonstrated that in addition to the uniqueness of the shape, the two most important aspects for users were: (i) the embedding of a personal story, and (ii) their involvement in the creation process, leading to a sense of authorship. This suggests that the physical shape (which 3D printers can easily create) and the production advantages that this technology offers are only a small part of the meaningfulness of these products.

Furthermore, we argued that the narrative aspects of objects should be taken into account when designing these products: by understanding their cultural connotation, as well as its narrative potential, it is possible to find meaningful parameters for customisation and enhance the experience of using them. We have also highlighted the importance of the process along with the outcome. We showed that the ability to influence the shape of a product by introducing personal content is perceived by the user as a self-rewarding activity and brings a sense of pride and fulfilment. The level of involvement in making Ciphering has potentially enhanced the enjoyment of creating the product and the likelihood of bonding with it.

Therefore, we claim that the user's ability to partially design this product by introducing personal and meaningful data has contributed to developing a sense of authorship and increased the value of the product. Furthermore, the desire of users to customise more than what was offered to them suggested that there are fertile grounds for exploring new opportunities in between atelier services and mass production.

Future Work In contrast to many other customisable jewellery pieces, Ciphering combines the literal meaning encoding with the aesthetic configuration. The fact that the literal meaning can be deciphered in the object was an essential part of the design concept. We have demonstrated that the engagement in the process creates a strong sense of ownership of the product, but further work is required to discover how important the deciphering act actually is for the user. One can argue that many of the benefits of Ciphering also apply to generative products that cannot be "deciphered" afterwards, be it encoding an audio recording[8] or GPS coordinates to polygon mesh.[9] Hence, a further study is needed to clarify how important the functional aspect of the customisation is in relation to the personal engagement.

Furthermore, since the concept is automated as production pipeline and the design is in the algorithm, we intend to study the monetary value of the immaterial, for example with the pay-as-you-want model, to find the difference between the manufacturing and the narrative, when clustered between the customised, pre-configured or hand-made.

We continue to explore further opportunities in between atelier services and mass production through concrete working study cases in the form of usable tools, which facilitate the dialogue between users and designers. Together with two additional prototypes, the research project "Beyond Prototyping" explores not only how the designer's aesthetics and the users' needs are brought together with the help of custom hardware and software, but also what kind of new service models are best suited for mediating this interaction.

3.3 Highlight—A Generative Lampshade

Highlight is a digital fabrication service that creates custom designed lampshades. Each lamp is customized to a specific space and allows the user to direct the light to particular areas in the room. This way, the service combines the uniqueness of an atelier solution with the advantages of a mass-production process.

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[8]See Footnote 7.

[9]Meshu. In: Meshu. http://meshu.io. Accessed 28 April 2015.

Fig. 17 An instance of HIGHLIGHT installed in a room

Every space we live in is different: not only its architecture, but also the way we arrange it according to our needs. When it comes to light, one might want to have a spotlight at the couch table, illuminate a piece of art on the wall, or highlight a specific feature in the architecture of the room. With this in mind, we developed Highlight, a digital fabrication service that creates custom-designed lampshades, allowing users to direct the light to areas they feel important.

The era of digital fabrication brought new customization possibilities. Using algorithms, designers are able to generate products according to specific needs of users. In this line, designing objects that respond to every interior seems like an obvious step. However, this process has always remained challenging, as it requires designing new tools and systems as well as blending the physical with the digital. With this project, we address this challenge and demonstrate that with the assistance of technology, the designer's aesthetic can be adapted to a user's personal needs (Figs. 17 and 18).

Description The system consists of three core components: a custom built 3D scanner, a web-based generative software system and a 3D printing service. Initially, the user receives the 3D scanner as a loan. The scanner can be screwed directly into the existing lamp socket of the room and operated through the light switch. After the room is scanned, the users can see a 3D representation of the room in a web-based application and decide to which areas the light will be directed. From these data, the shape of the lamp is automatically generated and ready to be printed. Once installed in the room, the lampshade creates a special atmosphere, combining both diffused and direct lighting into one single object (Fig. 19).

Fig. 18 The directed illumination on the walls from HIGHLIGHT lamp

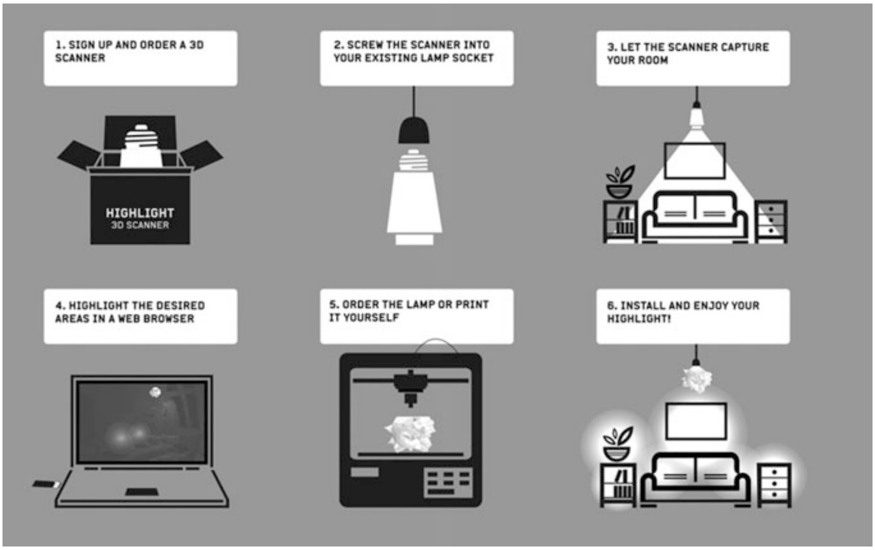

Fig. 19 A service description of the HIGHLIGHT system

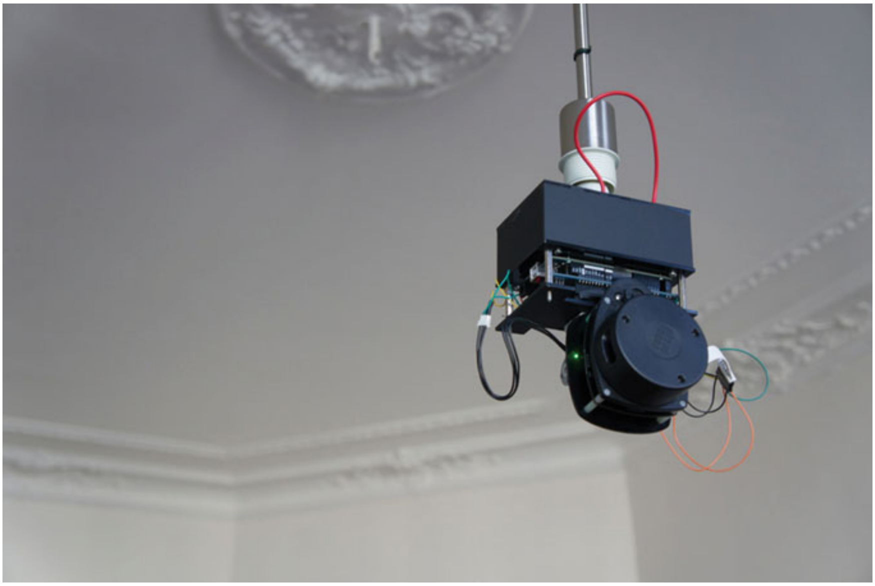

Fig. 20 Scanner installed to the lamp socket for 3D scanning of the room

Highlight takes advantage not only of the aesthetic and functional possibilities of digital fabrication, but also presents a new paradigm as a service, bringing together the uniqueness of an atelier solution with the advantages of a mass-production process. For example, since a 3D scanner is an expensive piece of hardware, it is provided to the users on a short time loan (Fig. 20).

Another big advantage of this service is the fact that a 3D preview of the lamp is generated in real time. The opportunity to see the lamp in the real context gives a better understanding of how the product will work than when buying it in a shop. This last point is of even greater importance when buying 3D printable products. In this case, one cannot even see the real object, but only a model, broadening the sense of proportion and scale. Hence, by connecting the model with the space for which it is designed, the product becomes more "tangible" (Fig. 21).

The intuitive browser interface is designed to allow users creativity and freedom. By using a "painting tool" as an interaction affordance, users can easily focus on the desired effect. The visual quality of the 3D point cloud both provides an implicit freedom to highlight the features of the space and at the same time also presents an easy-to-operate digital environment. The scanning of the room and its visualization in 3D serves as a design tool for users in a way for which they have never had access before. This offers them the ability to use their creativity and presents them with the opportunity to perceive their domestic spaces in a refreshing way.

The object has a strong narrative and performative aspect from a user's experiential point of view. In the process of "making", this object becomes meaningful and personal, and as a result, every lamp is strongly connected to the person who

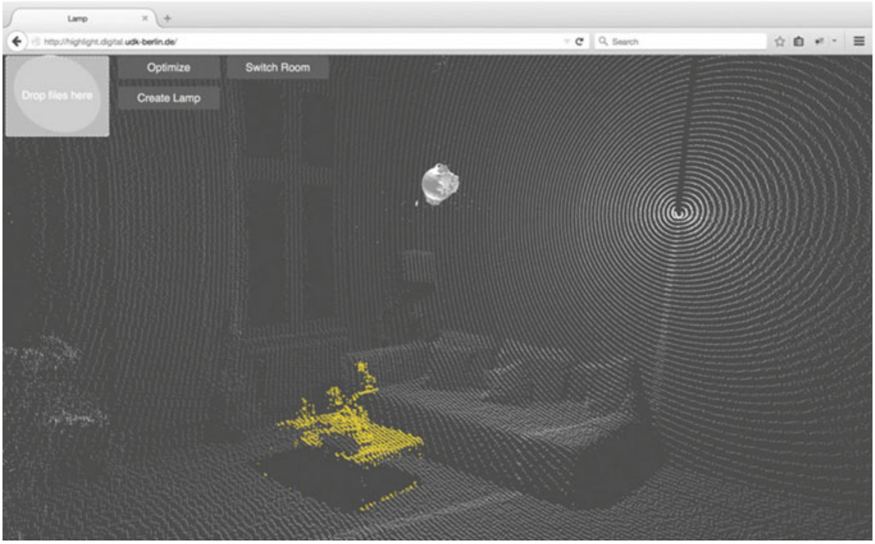

Fig. 21 The web interface for intuitively design the lighting based on the 3D scan

created it and the space it inhabits. The product is not simply a single object anymore, but goes well beyond this, including the whole process, from planning to realization.

In summary, the research project explores the possibilities of designing in an existing space in a tightly coupled way, where the designer's aesthetics and the users' needs are brought together with the assistance of custom hardware and software. The resulting striking and functional digitally fabricated artefact fits seamlessly in its context. The first iteration of the idea is a lampshade generator, but the concept easily translates to various other aspects of spatial design: from furniture to space dividers, wall surface materials to acoustic elements, and beyond.

Technical Details In order to scan the room in 3D from the location of a lamp socket, we developed a custom piece of hardware. Combining Robopeak's "RPLIDAR 360 Degree Laser Scanner" with a "Dynamixel Robot Servo", it is possible to conduct a volumetric scan of the room. A specially designed power converter provides power supply directly from the lamp socket, enabling a cable free installation of the scanner. The hardware is controlled by an Arduino based system custom software that saves the data on an SD card for easy handling.

The user can upload the data to a custom website, which converts the data into a point cloud. This serves as the basis of the user interaction, navigating a virtual representation of the room and selecting areas that should be illuminated. The software runs on the client side and is a custom solution built with THREE.js/WebGL/HTML5. This cross platform application generates the geometry of the lamp that can be viewed in real time and is exportable for 3D printing as an STL file.

Extending Highlight While scanning users' room offers benefits in terms of costs and ease of setup, it is potentially difficult for users to imagine the final result of the custom made lamp. Therefore, we extended the simulated approach by providing users with a physical lamp shape that can change the permeability of its sides. The individual sides can be manually controlled using custom software, offering users the possibility to create different light situations on demand.

We created two different prototypes of controllable lamps, with increasing geometric complexity to fulfil users' needs. The first lamp is created from a laser cut acrylic glass frame and 10 individually controllable sides from liquid crystal shutter panels. The second prototype consists of a laser cut base and 24 controllable faces, each being created from polymer dispersed liquid crystal (PDLC) switchable diffuser. The shutter panels and the switchable diffuser alter their transparency when voltage is applied (Fig. 22).

Description The lamps serve as a "live preview" for users on how different light situations will appear with their custom made lamps. The lamp is screwed into existing light sockets and can then be controlled using a smartphone or desktop application. Users can model their lighting environment, highlighting parts of their room or physical objects. The light setting can easily be maintained for later fabrication of non-dynamic lamp shapes. The physicality of light change provides users with a one-to-one mapping of their imagined lighting environment and the

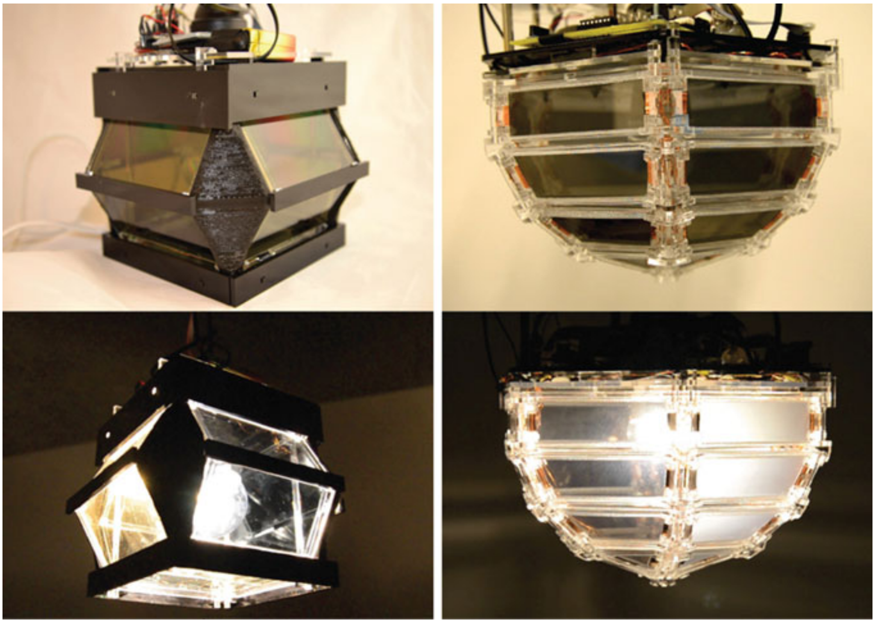

Fig. 22 Two different, complex geometric prototypes were created; a lamp with 10 LC shutter panels (*left*), and a lamp with 24 faces from PDLC switchable diffuser (*right*). Each face of the lamp can be controlled individually when voltage is applied (*bottom*)

later fabricated lamp. This eliminates the need for the creation of a virtual room as well as indirect manipulation of room light via the digital model. Manipulation is direct and users can also choose to explore light under different conditions of daylight or night.

While it would be possible to provide users with the dynamic version of the lamps, this is not necessary since users can use the device one time to decide the preferred lighting and manufacture a permanent lamp shade reproducing their favourite lighting environments. Additionally, this highly reduces costs. As with the simulation-based version of Highlight, users are provided with an expensive hardware for individualisation, which can later be exchanged for more cost-effective, manufactured versions (Fig. 23).

Technical Details The individual faces of both lamps are attached to a laser cut acrylic glass frame. The LC shutter panels are fixed in size and shape, therefore

Fig. 23 Users can control the individual faces of the lamp to create desired lighting situations

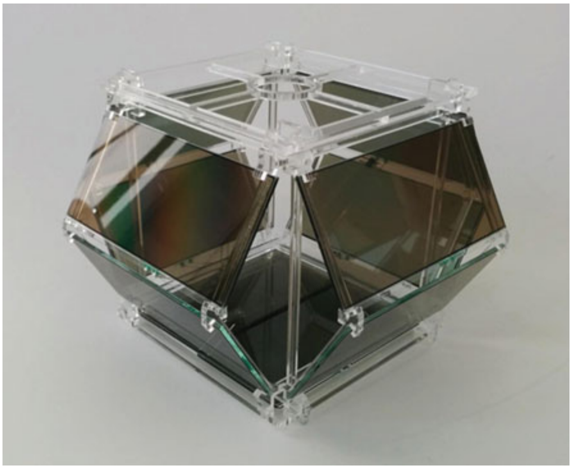

Fig. 24 The LC shutter panels are mounted on an acrylic glass frame and connected to custom circuitry

allowing for creation of a limited variety in terms of lamp shape. The panels are actuated with 3–5 VDC and can alter their transparency from transparent (0 VDC, 50 % light transmittance) to completely opaque (5 VDC) continuously. This makes the panels especially suitable for controlling light permeability.

The second prototype consists of 24 faces of switchable diffuser, a material that turns transparent when voltage is applied (110 VAC). The material consists of two layers of conductive transparent material (ITO) with liquid crystals sandwiched in-between. This makes the material feasible to cut in arbitrary shapes using a laser cutter. We create 4 different shapes of switchable diffuser and enclose them in housing for protection and improved mounting. The custom circuitry controlling the voltage is created using a microcontroller, also including Bluetooth for remote control. Users literally connect their smartphone to the lamp to control it. The desired lighting environment could then potentially be saved and uploaded for manufacturing of the lamp (Fig. 24).

4 Beyond "Beyond Prototyping"

The great number of ideas and functional prototypes stemming from the courses taught during the research project, as well as the three case studies developed to functional services, present a vision for algorithmically defined products where the dialogue between the designer, the manufacturing process and the customer can be structured differently than before. Five years after the first discussions leading to the subsequent research proposal and the beginning of the project, today, many startups and more established players are developing ideas in a similar vein. 3D printing services are increasingly ubiquitous in creating small-batch products for the growing market, yet the algorithmically defined, customisable objects remain a tiny minority comparatively. Our research is very much aligned with this, having realised how difficult it is to find elegant design ideas where the customisation remains meaningful, not simply a manifestation of the latest technological trend or the mere capability of being able to do so, but something that is meaningful to the customer in more timeless manner.

On the other hand, many furniture startups are connecting local manufacturers as a network of actors for enabling local production in on-demand basis. In this field, also, the parametrically defined objects remain limited.

The case studies developed as a part of “Beyond Prototyping” are ready to be taken beyond the research and implemented as startups or integrated as designs with existing manufacturers. Meanwhile, the approach to use on-demand productions as a research tool whereby the audience are more invested in the designs has proven a useful tool for taking design more seriously in the academic context, not only as a subject of study, but as a proactive method of enquiry. To setup such working systems requires much more effort than prototypical one-offs, but provide more credibility in analysing prospective consumer responses.

The challenges in developing these systems we faced were considerable: On one hand, as with any software relying on public APIs of online services, we had to keep on updating the code so that it would stay compatible with the service providers. On the other hand, in integrating with small studios’ daily work, the research project tended to have less of a priority than the client’s orders, and hence finding time and space for the development was always a challenge. But these challenges were essential in creating a more realistic designs that would not only work “in principle”, but also in practice, and through this practice, the prospective consumers, and hence our research subjects, could interact with the systems and share their insights with us.

In the end, out of the three concepts, only one, Ciphering is currently fully functional, as the Locatable network of participants still requires considerable human effort in coordinating everything, and in similar vein, the Highlight concept has the prerequisite of shipping of the scanner to the prospective clients, also demanding continuous human involvement. Ciphering, as it has been streamlined to directly interface with the 3D printing service Shapeways, can operate autonomously. In this case, even though there still is considerable human involvement, it takes place under the auspices of the Shapeways organisation, and does not involve any action from within the research team.

We feel that everyone involved, the students, faculty, research assistants, the small Berlin workshops and perhaps the wider design community as well have all learnt a lot through this project, and we remain grateful for this opportunity.

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