Modular Approach to Designing 3D Printed Products: Custom HCI Design and Fabrication of Functional Products

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Abstract. Alongside bringing about new ways to make products, additive manufacturing (commonly referred to as 3d printing) opens up new ways to design them. This article explores a *speculative model and vision between HCI and Industrial design*, where the use of modular and modifiable 'CAD' parts coupled with intelligent systems could be used within lay user/retail settings to enable non-designers to create custom functional objects, with limit prior knowledge. Leading to design outputs that can be fabricated by on-site and on-demand additive manufacturing technologies. This article reports on a design workshop where cycling enthusiasts, supported by industrial designers, utilised, configured and modified a range of 'CAD parts' to create custom-made functional objects for additive manufacture. The study findings indicate the practicalities and challenges of implementing an 'HCI system' for the production of novel functional objects by novice designers, and signposts further investigation.

The article yields value to HCI researchers through design-led opportunities, based on technological review and workshop insights; developing sustainable, resilient and independent manufacture. The combination of digital manufacture, design opportunity and intelligent HCI systems offer; new HCI models, distribution, design file access, standards compliance, unique Intellectual Property and building functioning customised parts. The (current) Covid-19 context, reaffirms the researches study offering new and agile opportunities that HCI principles can support and build from. The article makes recommendations, forming a design-led HCI software 'blueprint'. Including guidelines on: part design, their interoperability, the design to production process, and embedding expertise and failure limitation within this process.

Keywords: HCI roadmap, User-designers, Digital Manufacturing, On-demand, Modularity.

Hypothesis: It was the researchers' hypothesis that due to the advances in four key areas (AM, CAD, AI and open design) it may be possible (in the near future) to develop an HCI system and retail service that allows the general public to custom design and have made functional products

with relative ease. Guided by a ‘design assistant’ the user would follow a series of steps to help define their requirements, take important real-world measurements and criteria, and help them select the nearest fit in terms of existing objects or parts from which to create their novel design. This design would then be tested for performance, durability, and optimized accordingly prior to being fabricated on-site. The hypothesis rationale is founded on; *1) the increase accuracy, affordability and usability of additive manufacture technologies - (machines, processes and materials); 2) the advances in usability and performance of CAD tools with features such as part libraries, FEA analysis, and other measures to improve speed and effectiveness of designers work; 3) the advances in AI and ML that offer the opportunity to embed or supplement a designers technical knowledge and 4) the open sharing and collaborative development of functional designs online*. Authors speculate this manufacturing approach benefits; resilience, circular economy and user-driven innovation.

1 Introduction

The order of this article; demonstrates a contextual design workshop, followed by a ‘design vision’ with state-of-the-art exemplars, combining contexts for a ‘HCI retail experience’, authors are aware it is unconventional.

3d printing materials and processes have seen significant development and investment [1], and technologies are now able to produce precision and high-performance parts, as evidenced in their use as critical functional components, for example in automated multi-material robot grippers, functional automotive parts, and medical devices. Computer Aided Design (CAD) tools are already excellent examples of systems with embedded expertise (snaps, guides, LCA, FEA, etc), however they often have a steep learning curve, requiring considerable time to master. Design technology is progressing toward more intelligent systems with development of algorithmic controlled generative design systems. Yet, these are nascent and still often require expert intervention. Insights demonstrate the system would need to result in ‘perfect first time’ use, where the results generated are desirable and safe to use, a critical criterion for functional products. Linking together design knowledge and specific product domain knowledge, as well as manufacturing capability and other input data to achieve this basic level of functionality. Platforms, close to ‘perfect first time’ can be seen in website building platforms, such as WIX *et al* [2], where users choose from predetermined features, guided by limited parameters and containing custom content all within a system that aims to guarantee a fully functional website. Mobile-based and lower cost scanning equipment, as well as AR/MR services offer the opportunity to take accurate real-world geometric data and measurements into CAD environments. The cycle industry was a primary industry to utilize; precision and adaptability of 3d printing, leading to a natural ‘research through design’ intervention. The cycle industry works to tight constraints including; stringent tolerances, human ergonomics, fit for purpose (lightweight road applications to rigorous off-road use), material and part optimization, durability, comfort, servicing requirements, environmental ingress, standardization, compliance and more. Rather than being a single product, bikes are essentially kits of parts, where off-the-shelf componentry works in chorus to rigorous tolerances. The industry is highly stratified and segmented; bikes are used across ranging environments, with large differences in the parts specification(s) aimed at professional vs amateur users. Keen cyclists often upgrade their bikes, changing parts to improve performance, comfort or aesthetics, suiting specific terrain or environmental conditions, and replace worn out or broken parts.

At the time of writing global supply chains, retail business and society in general has been challenged by Covid-19 and proved that localised production is viable. Covid-19 resulted in localised and global stock and material shortages. Amazon (the online retailer) has thrived [3], but the effect is to remove value from local economies and aggregate it off-shore. The disruption to global supply chains has resulted in shortages of mass-produced products – evident in the scarcity of bike parts. The response to the pandemic and the shortage of PPE across the world has seen rapid development of 3d printed alternatives (Prusa face shield) [4], which were designed openly and collaboratively, shared online and modified to create a multitude of versions to suit various material types and printers. This environmental ‘event’ has sparked powerful cultural, industrial and economic shifts that make on-demand digital fabrication in local retail not only possible, but viable, and necessary, in order to make supply chains more diverse and resilient.

This paper documents a workshop (repeated 4 times) exploring the challenges of what authors call *mass-configuration* within retail. As the technology, in the form of digital manufacturing and more specifically 3D printing, is becoming more accessible it brings with its opportunities for the general public, and by this we mean non-professional designers and makers, to create their own products. Scenarios are imagined where retail spaces offer the facilities that enable people to design and produce functional 3D printed artefacts. By functional artefacts we mean; products designed to serve a functional or technical purpose rather than being solely decretive or souvenir(s). We identify 3 overarching types of product creation scenarios:

1. *3D Print service;* where the retailer acts as service provider allowing customers to either print their own designs, ones that they have downloaded from the Internet or select from a range of products offered by the retailer. This type of product creation allows customers to make wholly custom objects for personal needs but does not offer a design framework for them to work within.
2. *Mass-customisation;* where the retailer offers customers a range of products that have been designed in such a way that the design is editable by the customer, prior to printing it out, in a limited way within known parameters, most probably with software tools. This type of product creation offers customers a design framework for them to work within but not the opportunity to make wholly custom objects for their own specific needs.
3. *Mass-configuration*; where the retailer offers customers the opportunity to modify and building upon a kit of virtual component parts and assemblies. Using software to modify them within known parameters as well as use them as building blocks for

new parts and opportunities for customers to create wholly new parts. This type of product creation offers customers a design framework for them to work within as well as the opportunity to make wholly custom objects for their own specific needs.

We have undertaken this research, as converging factors increase the prevalence of 1 and 2 and potential rise to scenarios resembling 3.

1.1 Affordable and capable production tools

The primary factor in these scenarios are the tools themselves; much has been written about the rise of Additive Manufacture (AM), commonly referred to as three-dimensional printing (3DP), and the opportunities that this range of technologies and associated materials offer [5, 6 & 7]. What once were sequestered in research labs and in high value manufacturing centres are now within reach of a mass market. The cost barrier that restricts who owns them is being eroded and the range of printers within the reach of small businesses has grown exponentially over the last few years with developments in printing technologies emerging on the market that offer increased accuracy, various material properties, an increase in the speed of production and an increase in the structural properties of the parts produced. As well as produce parts with a higher degree of accuracy and most significantly parts that are homogenously strong in all directions and comparable in strength with those made using injection moulding. A number of 2019 [8] [9] articles highlight examples of 3DP technology utilised to produce 'functional products' opposed to pure prototyping or 'demonstrator' projects. Notable are the UK manufacturer of bicycle components Reynolds, who are producing 3DP metal parts. Also, the Razor Maker project, a pilot collaboration producing custom 3DP razors.

1.2 Making as a movement

Another factor is 'information availability' in the public domain about 3D Printing and platforms for sharing 3D designs and encouraging making on the Internet. 3D Printing grew up alongside the Internet, and in tandem have been enabling disparate and interest specific networked communities to share what they are doing with one another with relative ease. A recent development for DIY and making enthusiasts, and an enabler of the nascent Maker Movement, are platforms such as Thingiverse *(www.thingiverse.com)* and Instructables *(www.instructables.com),* which act as repositories, guides and discussion boards for all manner of making projects. The Maker Movement can also be seen as manifest in the presence of open access maker spaces (*Techshop and Fab Labs*), magazines *(www.makezine.com),* making clubs (www.makerclub.org and www.diy.org) events *(www.makerfaire.com),* and successful start-up businesses (www.diydrones.com) and Local Motors *(www.localmotors.com)* that have their own active communities and collaborative development and content sharing platforms. Makerspaces and communities of makers, both physical and digital, foster openness and innovation as core to their philosophy and can avoid influence of mainstream innovation practice [10] [11]. This arrangement of the social and technical leading to 'information availability' is key to possibilities of new forms of production.

1.3 Design Tools & 3D printing

In most cases to make 3D printed objects a 3D CAD (computer aided design) file will need to be generated. Mastery of CAD tools was once solely the preserve of professional designers, architects and engineers. More recently new CAD tools aimed squarely at the non-professional/novice markets (3dtin, Tinker CAD, Blokify) as well as more sophisticated free tools (Fusion 360, SketchUp, Blender, Sculptris) is abundant. Major CAD software developers such as; Autodesk Inc, and Dassault Systems have released free to use CAD tools aimed specifically at a young and novice sector that is enamoured by the potential of making things with digital fabrication tools. Autodesk released the 123D suite of tools, for desktop and tablet use, specifically created for ‘people who want to make things themselves’ [12]. Design tools targeted at children and the wider general public speak of a potential near future where there is a greater proficiency of the general public with 3D design software. One tool of note is Design Spark 3D *(www.designspark.com)* which is made available for free by Allied Electronics and RS Components and which allows users to import 3D CAD versions of parts both companies supply online. This allows users to create designs based on real parts without the need to measure or model them themselves, as well as automatically creating a bill of parts needed to realise their design. Some other CAD packages are also equipped libraries containing 3D models of standard parts such as nuts, bolts and bearings that users can customise to create non-standard parts.

Where the elements in these repositories are accurate and relate to parts in the real world, they can be considered *smart content*; as they are well-designed functional objects that were specifically created for others to utilise and be confident in their accuracy. Such objects that are simple parts but hard to model can act as a springboard for novice designers. Where parts imported from RS Components *(www.rs-components.com)* into Design Spark are the work of professional designers, the Open Structures project *(www.openstructures.net)* is an online repository of parts, where all parts conform to a geometrical grid that builds ‘a kind of collaborative Meccano to which everyone can contribute parts, components and assemblies’ [13]. 3D Hubs *(www.3dhubs.com)* online platform connects people in needed of a 3D printing service with a community of over 20,000 globally distributed 3D printer owners. Major software providers [14] are beginning to offer algorithmically controlled generative design systems as part of their professional suite of products [15]. Generative design creates multiple alternative design solutions in response to set boundary conditions, for example material type or performance criteria. Coupled with the geometric freedoms of 3DP, generative design offers relatively unconstrained outcomes. These systems still require expert input to understand and define goals and boundaries. Yet a future can be imagined where intelligent systems can intervene where now an expert is required.

1.4 Mass-customisation

Defined by Tseng & Jiao [16], Mass-customisation is "producing goods and services to meet individual customer's needs with near mass production efficiency". It is on one hand an offering of products to a mass market that have been designed specifically to allow for customer involvement to modify product designs, either formally or aesthetically within set variables that still allow single variants to be made together at high volume, and on the other a mechanism for manufacturers to offer wider choice. Mass customisation can therefore be thought of as having the capability to match both mass manufacture in terms of scale and efficiency, and custom manufacture in terms of suitability to the individual needs and wants [17]. In thinking about tailor's shops, it is evident that allowing people to make individual decisions from a framework or set of options is not a new phenomenon in product creation. What is a new phenomenon is the use of flexible fabrication tools and systems coupled with simple to use interfaces that allow the general public to customise prior to purchase mass produced goods that previously would have been standardised. Products as varied as footwear *(www.nike.com/nikeid)*, 'all over print t-shirts', dolls *(www.makie.me)* and blended whiskey *(www.whiskyblender.com)* are now being offered as customisable products. Manufacturing and design unite custom fabrication of goods to high streets.

1.5 Why Bikes?

Bikes are used for many purposes, varying greatly in their design accommodating multitudes of sports, contexts, and users. There are many bespoke niches and have needs that are yet to be met. Lead users involved in these niches are people that are at the leading edge of their discipline or personal hobby, 'positioned to benefit significantly by obtaining a solution to their needs' [18]. Bikes are a familiar territory for self-improvement and as they are an assembly of parts often from a wide range of manufacturers, open to modification and customisation. There is currently a wealth of evidence online of people designing and making personal bike related items on Instructables *(www.instructables.com)*, Thingiverse *(www.thingiverse.com)*, as well as bike specific websites such as bikehacks *(www.bikehacks.com)*. Bikes are durable with Red bull changing advertising strategies to support 'extreme sports' operating at the edge of what is possible. During the current time, cycles are turned to as sustainable transport that is individual. Leading brands, i.e., 'Shimano' [19] produce group sets and assemblies that work across countless engineering and design visions for tolerances and inter-operability, set by industry and monopolising it. Finally, the equitable nature of the product is; rented [20], owned [21], a healthy transportation option [22], open to repair [23] and continually used throughout world wars and in times of hardship [24].

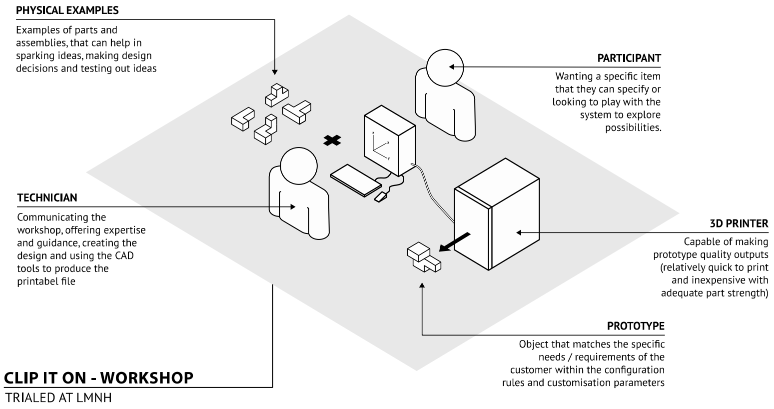

Fig. 1. Workshop's 'design vision' and then the operational functions of an optimal HCI system.

2 Method (Contextual Design Frame)

In order to trial the scenario of mass-configuration as a viable method to enable people to create their own products, either by building from the work of others or by creating a wholly new product; a workshop called *Clip-It-On* was run four times over two days. It was imagined that for this type of product creation the people who would participate would have specific interests and specific needs, people Von Hippel calls "lead users" [25]. The *Clip-It-On* workshops were run at *Look Mum No Hands* (LMNH), a bike themed café, repair workshop and accessories retailer, during the London Design Festival. As '*Clip-It-On*' suggests the co-design workshops focussed on clips that enable items; lights, cameras, phones, tools and anything else, to be mounted on to the frame of any bike. Although bike mounting attachments are currently available for sale, the purpose of the workshops was to explore the potential of creating custom solutions for individuals to explore, create and "imagine their ideal products" [26]. The 'uniqueness' of the product was derived from the item to be 'clipped on' to the bike, and then the design by which this was achieved. The workshop focused on the creation of something new that linked a standard component (bike mount) to a yet unimagined item, for example a banana. LMNH was chosen as a test venue as it has a large community following among cycle enthusiasts, drawing in specific interest and user groups (that might be) motivated to create their own products, as well as being located on a main cycle route within London, thereby enabling testing in "the richness of the real world in which the applications are placed" [27]. The LMNH café was large enough for researchers to establish a design and 3D print area.

3 Workshop Setup / Parameters

Over 2 days, open recruitment led to an ‘inhouse set-up’ in existing business with 20 self-selecting participants. The scenario envisioned is one where users build their ideas using a repository of pre-designed parts; six components were developed to form a ‘kit of parts’ that had changeable dimensions to connect / fit various items by using parametised dimensions to a range of bike frame sizes. Parts were designed by looking at existing plastic bike accessories and then generating and physically testing designs optimised to the capabilities of the UP Printer (build orientation, printing resolution and material properties) as well as testing how they connect to each other to give various assembly options. 3D CAD software (Dassault Systems SolidWorks) was used to design parts, which allowed for them to be modified or adapted during the workshop. Each part had a preferred build orientation that corresponded to its optimum structural strength although the parts were not designed to meet any recognised safety standard. Not all elements of the kit of parts needed to be 3D printed. In order to connect parts and secure the assemblies to bike frames or items to assemblies, 30mm M6 stainless steel bolts, sprung washers and M6 stainless steel wingnuts were used. Due to the exploratory nature of the workshops, all parts made, needed to be seen as ‘prototypes’ rather than ‘finished products’, which would be the case with the imagined scenario. Two PP3DP UP Printers *(www.pp3dp.com)* were chosen to fabricate parts as they are ready to use out of the box, while being very small and easy to transport, and capable of producing objects with a reasonable level of resolution. The UP is a low-cost desktop FDM (Fused Deposition Modelling) printer that uses reels of ABS (Acrylonitrile Butadiene Styrene) plastic filament to produce parts. ABS is a common thermoplastic that is used in many consumer products, as it has properties of “toughness and impact resistance, while being lightweight” [28].

3.1 The Consultation Process

The four workshop sessions were identically conducted. Four researchers acting as design technicians staffed the consultation. The technician’s role was to help draw out, embody and realise the participant’s ideas. In effect, mediating between the participant’s ideas and the capabilities and constraints of the kit of parts, printer and design software, and taking on the role of the imagined ‘embedded expertise’. The consultation space in LMNH consisted of a large table for participants and technicians to sit at, 4 laptops with Dassualt Systems SolidWorks, 2 UP 3D printers and a collective resource of digital cameras, sketchbooks, pens, pencils and measuring tools. The workshop followed a participatory design approach [29] where participants “engaged in a proposed design scenario, and developed design solutions with the technicians”. Empathetic or co-design “get[s] people personally, emotionally engaged so they can reflect on a process” [30]. Co-design gathers “information about the contexts of people’s interactions” comprehending applications, its practice provides “tools that create a fluency” [31]. This is in itself a form of engagement and Participatory Design (PD) involving users in “evaluative research: testing existing products or prototypes” [32]. The difference “between human-centred and user-centred design is huge as they don’t address the same audience". "Human-centred design relates to people, user-centred design relates to consumers" [33]. The use of 'CAD operators' (i.e., design technicians) builds on Sinclair's practice [34] of exploring design territories in collaboration with technical mediators to provide software for users to explore ideas. Previous work on participatory design highlighted the need for "lay users to access to a technical third party to help translate their concepts into tangible, viable outcomes" [35].

Participants were briefed to ensure they understood the aims of the workshop, technological capabilities (3D printing), and the limitations of the workshop, namely that objects fabricated as a result of the workshop were 'prototypes', not finished products. Participants were also given a printed resource itemising the parts dimensions, their build direction, and a brief overview of the process. This also served as a reference and template for the technician and participant to draw on during the consultation. A number of copies of each part were printed, and available to hand on the table so participants could see and touch finished examples. The consultation process started by discussing the participant's object, how and where it might be attached to their bike. Participants were shown the range of clips, and discussed with the technicians, their or modifications. Once a brief/idea had been agreed, sketches and measurements taken, the technicians used CAD to alter and create new parts. The participants were consulted throughout this process, and the CAD models served as 'virtual prototypes' with which to discuss any required design changes. By building on the kit of parts, participants could be taken through 'small steps' of the design process, and so not be overwhelmed by the task of designing on their own and from scratch [36].

4 Results

Results are curated into; appropriate, tangible and diverse exemplars. Artefacts, motivations and participant needs created the LMNH workshop. *Pump mount* (Fig. 2) - This participant wanted to replace a lost component of an existing product. The bike pump they owned came with a mounting bracket that was subsequently damaged, and the producer doesn't sell replacement parts. 3D printing was of significant interest. *Banana Holder* (Fig. 3)– The participant wanted to mount something to hold a banana so that they could have an energy boost during long rides. The participant acknowledged the playfulness of the idea but was keen to engage in a workshop that combined design, 3D printing and cycling. *Light clip* - Similar to the Pump Mount - the free nature of the workshop was a key aspect for this participant, both in attendance and getting a free product. They wanted a clip to mount a light to their handlebars replacing a lost item.

Fig. 2. Pump mount, components from kit of parts.

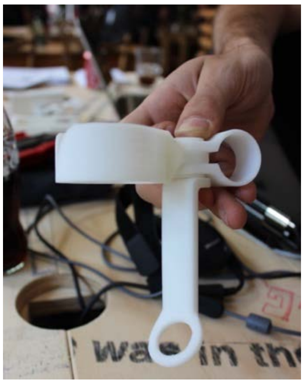

Fig. 3. Banana Holder

Fig. 4. Seat mounted opener.

Fig .5. Water bottle rack, custom built for hand-built bike.

Knitting wool spool holder - This participant wanted to use the workshop for technical experimentation; the justification behind the creation met no other needs other than for the individual to learn about 3D printing. The ‘wool holder’ was a bespoke object, fulfilling a very niche function and not (knowingly) in manufacture. *Ketchup Horn* - Two participants wanted to modify a bike horn, so it fired ketchup at inconsiderate/dangerous drivers, as London’s roads are noisy, a standard horn has limited effect. *Seat mounted bottle opener* (Fig. 4) - This participant cycles to meet friends for picnics in the summer, forgetting their bottle opener and wanted to mount it onto her bike, drawn to the workshop to find out more about 3D printing. *Water bottle rack for a Penny Farthing* (Fig. 5) - This participant races Penny Farthings. She brought her bike to the workshop and described how she wanted to attach a water bottle, as her bike didn’t have bottle cage mounts built into the frame (as modern bikes do). As she did not want to drill into the frame her solution was a clamp that held a bottle cage onto the frame. Penny Farthing racing is a niche sport and she couldn’t find suppliers of this kind of product. She was also interested in 3D printing and the workshop in general. *Flag Clip* - This participant had recently been involved in an informal bike race and wanted to attach a small flag to their bike, showing their allegiance to charitable causes. They also thought it might ‘look cool’ to have it on their bike as a permanent feature. The participant brought a range of ideas as to how it might work as they worked as a professional designer; for example, they originally imagined the flag would be attached to the handlebars, but through consultation changed the location to under the seat.

5 Workshop Transferable Insights

In creating a facsimile of the scenario imagined there were a number of limiting factors. They were free to attend and the artefacts produced were offered at no cost and this perhaps meant that participants saw little or no risk in their involvement. It used entry point 3D printers, which are not best suited to commercial product quality, technical artefacts. It used designers to drive industry standard design software and contribute their expertise, instead of the participants driving the process and software themselves; and so, participants did not test any software or face the challenge of designing on their own. However, these factors should not be taken as negative, merely conditional; the workshops and wider research yielded a number of insights that would inform the requisite tools and resources needed to enable lay users to create technical products on-site and on-demand using 3D printing technology. Workshop findings have been grouped, addressing questions set out in the introduction.

5.1 Translating participant's ideas

Participants had no prior knowledge of the kit of parts, and so their ideas were quickly categorised into those that the kit could service and those that the kit could not. This task was undertaken, in the most part, by the technicians. To enable users to take on more of the design work it would be beneficial for them to be well informed as to the kit and its capabilities. In running the workshop, it was clear the technicians performed a number of roles in consultation with participants. To mediate the consultation using software these roles will need to be taken in to account:

1. Explaining the workshop process.
2. Identify elements of the kit that could be used and then explore modifications or additions that would deliver a solution in collaboration with the participant.
3. Explore solutions outside of the kit of parts, using their expertise to suggest and convey ideas to participants as well as stimulating participant led solutions.
4. Modify parts from the kit by altering dimensions or adding features.
5. Creating new parts that interact with parts from the kit.
6. Creating new parts or assemblies not linked to existing parts from the kit.
7. Communication of limitations of 3D printing within CAD, explaining decision making about form, part thickness, or surface finish, etc.

As the Participants were only asked to bring a ‘thing and their bike’, none came with preconceived designs, and as such all-design work was conducted with the technicians. There was a varying degree of engagement in the design process between participants and technicians: Some used drawing and dialogue to co-design solutions that were then realised in CAD by the technicians; others played more of a passive role where they explained their need and let the technician deliver them a solution, in which case CAD software was used to explain the final design. Analogue measuring and sketch tools aided exploration and communication for both the technicians and participants.

5.2 Effectiveness of approach

It took time for participants to examine the parts and information supplied in the workshop in order to understand what was possible. Having the kit of parts 3D printed and physically for the participants to build tactile assemblies positively affected the design process and dialogue. It allowed solutions to be reached, and in some cases tested very quickly. Having more examples of assemblies, choices of materials, possible finishes, and off-the shelf components, would be beneficial. The kit, as it was used in the workshop, served as a useful base to build on; however, as a number of participants wanted solutions that did not utilise it, a more comprehensive toolkit would have been useful in order to limit the need to create entirely new parts. Technicians needed to rely heavily on their expertise as industrial designers to create solutions beyond the kit, and it was notable that solutions that used the kit required less time and effort than and those that deviated from it. The capability of the kit of parts was taken for granted by participants, and there was a general assumption that each part or assembly of parts would function effectively. This was of positive benefit as designs could progress quickly, but this also meant that participants did not scrutinise the parts in order to see if there was a better alternative, or if an improvement could be made. All elements of the kit must be rigorously designed to perform to a high standard, as users will expect this and use them accordingly. Constraints such as build orientation, material strength, maximum part size, and optimisation of build were solely within the technicians' remit; on occasion some of this information needed to be imparted to the participant to validate the technician's design outcome. Technicians made suggestions regarding the best mounting point for each item on the bike, whether additional features or a simpler design, would be preferable. For the most part, participants were not focussed on the constraints of the material or the 3D printing process, rather their interest was what could be achieved with it. When technicians explained the need for designs to be a certain way for strength or durability, the participants were happy to rely on their judgement.

6 Discussion (Updated Technologies)

There is a difficult line between; parametric, AI, fully Open Design and limiting participants capabilities. Open Design (OD) is a "catchall term for various on-and offline design and making activities, describ[ing] a design process that allows for (is open to) the participation of anybody (novice or professional) in collaborative development[s] of something" [37]. OD democratizes access to construction information in a post-industrial world, presenting opportunities for communities to sustainably respond to bespoke needs. EU 'right to repair' laws are transforming industry approaches, as "manufacturers [will] have to provide spare parts for 10 years" [38]. OD, unsettles hierarchies, manufacture, stimulating agency and responsibility "providing people the means to rip, mix and burn physical objects" [39]. Open Design cannot always be deployed as it relies on embedded knowledge. Authors re-reviewed the state of the art and the unification of three areas that have advanced since the LMNH workshop.

6.1 Digital manufacture & production in retail spaces

Over the past 2 years retail 'bricks-and-mortar' revenue has dropped by 14% with an online increase of 20%. With world leading brands producing augmented reality stores [40], live streaming instore experiences and even 'digital clothes' representing avatars (with billions in revenue) interactivity is transforming our current HCI and retail models. Netlooks *(www.netlooks.fr/)* is a collaboration of instore and digital ensuring that their glasses are personally fitted and adapted instore, based on sizing requirements and machine learning. Pixsweet.com a leading brand combining traditional toolmaking and 3d printing to manufacture 'Ice Pops' to any physical form and flavor. Whilst these projects are ‘gimmicks’ the foundations are based on function. Ellis Brigham, the world leading UK ski brand has a unique custom boot fit system ‘Surefit’ that builds onsite manufacture, deep staff expertise and personal taste to customize and adapt your sports equipment [41]. Adidas’s *‘Knit for you’* is restraining the parameters of what it can make, but is getting a retail proven system stating “we need opportunities to be collaborators in experimenting with new ways to craft how our future works, and what it looks like” [42]. All of the retail exemplars; using off-the-shelf parts i.e. (assembly not making), not fully ‘durable’ or standards defined outputs and they do not interoperate within other constraints, highlighting the uniqueness of *Mass-configuration* research.

6.2 AI ‘Decision making’

AI is becoming a viable technology being considered for critical industry such as healthcare, where decision support systems are being considered for many specialisms and for many conditions. The application to manufacturing is less mature yet there is perceived benefit especially for additive manufacturing. Intelligent systems can automate some of the pre-process ‘heavy lifting’ making design decisions and ‘repairing’ parts prior to manufacture [43]. This type of decision support comes after a design is produced and retains knowledge sets concerning specific manufacturing processes. On the design side, generative design [44] adopts intelligent algorithms to ‘create’ digital artifacts within set parameters. CAD software such as Autodesk Dreamcatcher embed AI into the design system to automate geometric decision making [45]. It is plausible FEA analysis will follow, generating more efficient; parts, mechanisms informing artefacts design(s), i.e., ‘torsional stiffness’ is embedded into F1 race car design, but can (over time) review dynamic stresses & strains on dynamic components [46].

6.3 AR / VR: experiences

AR and VR experiences are crossing a large divide, lowering high level experiences. Wieg water rides, specialise in providing VR experiences within ‘water parks’, both on water slides and snorkelling [47]. These truly compelling experiences partner the ‘physical with the digital’ leading to new opportunities, i.e., ‘try digital products’ before you make them and or buy them. The real estate industry (pre-covid) devised VR home viewings for properties and spaces (saving carbon impact, visiting locations without travelling). Could professionals get a view of ‘racing courses’ before the race and change/tailor parts. Mobile experiences (come on leaps and bounds) of how your smart phone can customise your personal experience, based on what it knows about you [48]. For example, when you are physically measured for clothing, can this data be used to determine your ‘bike frame size’ and or position to ensure optimum performance without injury over time? Invent Medical maps your size and scale (working of body and live anthropometrics), i.e., guaranteeing fit from different brands. Breezm, have revolutionized the ‘eye ware’ retail so there is perfect ‘fit’, without requiring overstocking in their outlets. Evidence of ‘scanning’ for fit is even entering the equine sector ensuring better hoof care for animals, with the limiting factor being the quality of scanning technologies, that will only improve in time. The final exemplar ‘Maker Mask’, is a custom

Cloud service that fits a person's exact physical (face) size and complies to countless medical and functional standards. These rigorous standards are one of the last barriers uniting the retail / functional opportunities for 3D printing and the authors context. The Maker Mask, is not only a standard approach, but it is re-skilling participants;

> "Enabling communities to create necessary goods locally and quickly will lessen the spread of disease, protect more people, reduce burdens on medical facilities/DoD/governments, and give Americans something to be part of the solution to this pandemic, while building and training capability for the future" [49].

6.4 Unifying Enablers

The advancement of digital retail spaces, no doubt will advance into more and more digital spaces, due to covid-19 and producing more financially resilient models. For example, Fujitsu's "personal checkout" [50], is already transforming payment, personalization and the opportunity for more feedback between users and retailers. As input systems advance, 3dprinting resolution and more complex materials become mainstream, it is plausible that this type of work will lead manufacture (within certain domains) where consumer-led customizations in turn lead industry. For example, the Lego Builder platform has had "over 13,000 projects have been submitted to the LEGO Ideas platform" [51], where avid fans can create digital Lego, get crowd supporters and see their concepts translated into products and revenue.

6.5 Perceived functions & requirements

The proposed system (researched) needs to include the following;

- *Intelligent Leverage Points;* choosing when and how to inform decision making and or make suggestions, based on users' parameters.
- *Measure & Tolerances;* digital measuring equipment connected to the 'system', either scanning or measure, translating back into CAD.
- *Translation;* of ideas and mechanical detailing from the user to the screen.
- *Efficiencies;* material, production time & substitutions on appropriate existing parts, for example bolts or more durable hardware.
- *Contextually Durable;* through predictive FEA, outputs can leverage generative design processes based on activity; road bike, commuting or downhill.
- *Pre-flight Checks;* leveraging AR/VR people should be able to 'digitally' check the fit of the part, ensuring failure reductions and material sustainability.
- *Digital Standards;* checking parts and assemblies to high industrial standards through digital inputs to safeguard compliance of retailers, i.e., 'fit for purpose'.

6.6 Design mediated by a kit of parts

The kit of parts served as a useful base to build on, however, as some participants wanted solutions that did not utilise it (e.g., mounting under seat), it should be refined and expanded through the use of workshops, such as *Clip-It-On*, to draw out insights and needs. The kit is seen to be the work of professional designers, where each part and the interconnectivity between parts have undergone much consideration. A vital aspect of the workshop and indeed overall scenario, was the focus on an interest / user group as a customer base. Understanding the untapped or underserved needs of a particular group is vital if the kit is to provide an effective platform to build on. However, if users are allowed to create new parts for the kit, as might be the case if the kit is open for all to expand upon, a rulebook or guidelines should be created to set the conditions for successful parts. By combining mass manufactured parts with those of the CAD repository, it is possible to limit the need for the 3D printer to be capable of printing multiple materials that possess various mechanical properties. As is the case with Design Spark, repositories used in retail could use proprietary non-printed parts that need to be purchased from the retailer. Parts could be functional (electrical or mechanical) components or convey brand identity. Various 3D printers and materials or processes, alongside other digital fabrication tools (such as laser cutters and CNC routers) could be used to fabricate parts as can be seen in the Open Structures project *(www.openstructures.net)*. However, this will undoubtedly make engaging with the kit much more complex users and so might need sophisticated design software in order to overcome the complexity. Suites of these digital tools are currently seen in maker spaces (Tech Shop and Fab Labs) and would-be ideal test beds for further research. The kit of parts needs to be physical as well as digital. The real benefit of the on-site aspect of the scenario is the ability for users to play with physical parts, this helps them imagine and test out ideas. Much can be achieved with digital tools, but physical interaction is a fundamental element in comprehending functionalities and imagining new possibilities.

6.7 Design mediated by software tools

The ideal scenario for the provision of point-of-sale design and fabrication is that consumers should be able to design for themselves. The consultation process revealed that in order to replace the role of the technician, their expertise and capability should be embedded into software tools. The design software would also be the primary means for users to understand the kit of parts and would need to not overly complicated for novice users, while also being sufficiently functional. The software would need to:

1. *Quick guides*; Enabling users in understanding the design and 3D print process / capabilities.
2. *Part selection;* making and informing interconnect decisions.
3. *Exemplars;* demonstrate possible assemblies (providing users to comment).
4. *Off-the-shelf parts;* Illustrate how to incorporate mass produced or non-printed parts into assemblies.
5. *Help users;* to choose attachment locations on to their chosen bike.
6. *Enable*; users to alter parts within functional parameters.
7. *Provide guidance;* informing the functional needs of products (such as load, stress, flexibility fit tolerance, ergonomics, etc) and deliver analytical tools (such as FEA) to virtually test parts and certify them to required standards.

8. Preparing CAD parts for 3D print; taking into account build orientation for optimum strength and part nesting.

Although not explored in the workshop, it may be useful to import 3D models of standard bike dimensions/manufactured parts, i.e., handlebars etc. Elements or whole bike assemblies could be imported into CAD software, to virtually mount parts. Other elements such as lights and smart phones could be imported aiding designers. This should be applied broadly to items that would aid designing for any instance of scenario(s). Implementing the software, could be a CAD software plug-in to existing applications, or a stand-alone design tool. Alternatively, operating similarly to Wordpress *(www.wordpress.com),* where the capability to create tailored tools and customisable kits of parts, allowing for multiple retail applications. Enabling brands to engage with custom on-site and on-demand manufacture at a relatively low entry point, with the added benefit of building upon a system that could be familiar to customers. The CAD tools can be, cloud-based CAD allowing users to generate ideas anywhere and allowing stores to operate as; interaction, demonstration centres, fabrication and pick-up points.

6.8 Potential issues

In a scenario where authorship of a design is the result of collaboration, issues arise surrounding ownership and liability. Creative Commons *(www.creativecommons.org)* licensing allows for authorship to be attributed to the contributors of design project(s), while allowing for digital design content to be openly appropriated. This means users of on-site design and fabrication, as it is imagined, would forgo exclusive rights to their contribution/design while still being acknowledged for it. If the work of each customer was not be added to an archive for use by others they could retain some exclusivity, as is the case with some mass customisation (*Nike ID* and Makielab). In a scenario where the customer's designs can be shared, credit or financial reward can be paid to the author when it is used by others; a system of this kind is outlined in Jaron Lanier's book *Who Owns the Future*. In this case a design evolves over time and be the work of many individuals, with a system keeping track of the chain of contributions and ascribe authorship and reward proportionally. The cost of 3D printed artefacts are usually calculated based on 'material volume' in their construction *(www.shapeways.com),* and so costs could be calculated during the design process as parts are imported and modified. If the design is built upon the work of another user, payments can be factored into costs. Parts could be optimised for budget solutions based on material cost; however, this may result in products, vulnerable to failure. It is important to note that it was impossible to guarantee the effective functionality of anything designed and made during the workshop.

A significant hurdle to overcome if this type of practice is to become commonplace. Technical products need to function in situations where they are subject to load, stress and environmental factors. If products are created through a part software and part user / customer collaboration, complications arise if that part fails. Responsibility must be taken by the service provider to mitigate any failure where possible, limiting risk where it is possible to predict and eliminate. Likewise, the service user must take responsibility when they deviate from any advised parameters. The challenge lies in attributing responsibility to aspects of the design artefact when legally required. 3D printing of functional artefacts in a retail environment would need to conform to industry standards by possibly using the model applied to ‘mass-customisation’ in order to limit technical or structural failure, as can be seen in MakieLab dolls. To ensure product safety standards, the software would embed restrictions on what lay users should and should not be able to edit. For the purposes of traceability digital 3D parts could be encoded with information, detailing location of manufacture, designer, material and printer used. Coded stamps or integrated markings into the 3D printed parts could offer quality control, provenance, or identify where liabilities lie in the case of accident or failure. Encoding a 3D printed product with this type of information might alter its value, if ever resold etc. The pitfalls outside of HCI territories and designers are;

- *Part accuracy;* if files are used in unspecified 3D printer.
- *Material failure,* temporal environments and miss use i.e., in different temperatures, hydrology’s, etc ware and failure will behave differently.
- *FEA limitations;* potential legal challenges, i.e., Terms and conditions of how ‘output miss-use’ as the products will remain between ‘prototype and product’.
- *Intellectual Property;* how would it work if parts undergo development with 5+ users building on each other’s work.
- *Interoperability,* how would the ownership model of the part work? Would you be able to edit it, own it or only use it in that system?

6.9 Potential opportunities

- *Collaborative branding*; working through ‘part sharing’, partnering corporates and local makers, comprehending conditions and requirements.
- *Enabling cottage industries;* of bespoke needs and knowledge, supported by a digital economy, creating new commerce and legacy.
- *Complete stock control;* traceability ‘code’ embedded in part without being financially tied to a physical stock room.
- *Sustainable practice;* as parts is not ‘over produced’ and can be updated according to new EU law (right to repair).
- *Revisiting;* ‘crowd’ Intellectual Property that does not hinder progress but protects stakeholders’ interests.
- *Digital experience(s);* (within bike context) going for ‘VR ride’ with custom components to perform for that location, trying before you fabricate.

6.10 Conclusion

It is more than credible that 3D printing and other digital manufacturing will be used in retail environments to make functional products. It is also credible that these products will be custom made, or customisable and delivered using digital manufacturing. Challenges also lie in how the process is managed to ensure quality outcomes, that allow for the creative authorship of the customer, that meet the needs of the customer, require the least effort or training from the customer, carry guarantees of use and can be attained at affordable costs. Customers will need some education prior to creating their custom product but this needs to be delivered with minimum of effort on their part. The workshops showed that while some customers were willing to spend time observing or participating with something they deemed interesting, others were more time limited and wanted information delivered quickly and concisely. Efficiencies can be delivered through the use of parametised CAD models, guided CAD tools and a comprehensive kit of parts, both printable and off the shelf. By combining a repository of parts with an intuitive CAD system it is possible for the novice to quickly understand the potential of building their ideas upon the expertise and work of others. Embedding design expertise into parts is an effective means to cater to novices, but what has been embedded needs to be understandable. The CAD system needs to be capable without being complex by automating all functions that are relevant to all products and guiding users through a step-by-step process. Analytical software should be used that virtually tests the product for use in certain conditions and under certain loads, and so certify it for a period of time and stipulate limits of use. Showing users exemplar designs that are formed from assemblies of parts would be effective as users can directly appropriate as well as understand the system of parts in use. It is important to note that the main focus of the scenario is to enable individual solutions rather than to invent new products, so many known factors can be in-built. Future retail environments may well have displays that showcase assembly options, libraries of parts, material choices and idea provoking images or text to inspire customers in choosing options or formulating ideas.

Bike culture was a good fit for this activity, and retail spaces that are tailored to cultural or hobby communities such as LMNH offer a knowledgeable target audience that have an understanding of their equipment as well as latent needs. This can be transferred to other groups i.e., extreme sports, robotics or prosthetics as well as more generally in homeware, footwear, toys and electronic devices. Furniture manufacturers *Unto This Last* and makers could use ‘kits of parts’ coupled with CAD to offer flexible products beyond the constraints of mass customisation or parametrised CAD, while still being tied to manufacturing capabilities. It is not proposed that this type of product offering will become the prevailing one, ousting mass produced goods sellers on the high street; however due to advances in software tools and fabrication technology the cost to implement it and the functional attributes of the printed artefacts are no longer prohibitive. Opportunities are seen for a provider of tailored systems for brands wanting to offer the imagined scenario; delivering a custom created kit of parts, CAD tools and design interface and manufacturing tools and material as well as support service. Beyond commercial space(s), Fab Labs could develop ‘smart content’ libraries, shared as common resources, with parts clustered by themes, with brands collaborations.

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