

# Materials, machines, meanings. Possible design strategies to compensate three key shortages of distributed manufacturing

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## ABSTRACT

This contribution starts by observing the low presence of “indie made”, distributed and digital fabrication based products in the everyday life of most people. We assume that this low presence is a result of limitations regarding the available physical behaviors, achievable functionalities, and accessible market, all of which can be optimized to the extreme with mass manufacturing. The paper explores possible design strategies to compensate these three key shortages of indie manufacturing for everyday life, aiming at better materials, more advanced functional “machines”, as well as alternative ways of creating meaning. To broaden the available material qualities, the discussed strategy is developing (and designing with) microstructures to simulate various materials. To enter more functional product domains, or machines, the paper suggests facilitating the integration of mass-produced functional elements (e.g. electronics) into product “shells”, realizable with distributed manufacturing. Finally, to compensate for limited distribution and marketing resources, we discuss the strategy of leaving the design project open for user interventions, focusing on the conceptual development of meaningful personalizable design. Regarding this latter, the paper also describes a design method and canvas tool, while the suggestions on materials/machines raise awareness around issues and upcoming solutions, contributing to some parts of the canvas.

*Keywords:* Additive Manufacturing; Design Method; Electronics Prototyping; Microstructures; Personalization; Standardization.

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## INTRODUCTION

“Enabling indie designers and makers”, as the journal issue aims to, is a multifaceted challenge. Enabling might mean both reducing obstacles or increasing drivers of the practice of open and distributed designing and production. Considering digital fabrication as the major tool of indie making, it’s easy to recognize advantageous drivers such as the low barrier of initiating production, flexible manufacturing according to the demand, or the possibility of high geometric complexity or product personalization. On the other hand, obstacles of indie (digital) manufacturing include many limiting factors of the fabrication

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tools (speed, quality, materials, cost), as well as distribution logistics and consumer trust, just like regulation or intellectual property issues, all of which can undermine the financial sustainability of indie making.

So far, the ideology of democratized making helped the development of Open Design practices and Distributed Production platforms, and many consumers might be inclined to choose small makers rather than multinational corporations, supporting local fab labs rather than overseas mass production. This consumer sentiment can very well be an important marketing factor, similarly to the (often) higher perceived value of “authentic” artisanal products, even when there is no objective advantage in terms of product quality. Storytelling can elevate the products of low-tech artisans, high-tech makers, just like it does with global brands - but providing competitive core product values is essential for the long-term economic sustainability. Aiming at a mainstream distribution of distributed production, storytelling does not substitute significant functional, aesthetic or economic shortages: the indie maker should provide equal or higher value independently of the “indie” status. Compared to “conventional manufacturing”, the indie maker’s (digital) tools should meet similar qualitative standards, priced competitively while (ideally) providing otherwise unobtainable products.

This contribution is written from a product designer’s perspective, a professional figure which is mainly concerned with addressing user needs, creating meaningful experience, and defining the product’s material reality according to the available possibilities. Therefore, while organizational-regulatory-marketing issues might be tackled by today’s “multifunctional” designer, we will focus on issues strictly related to the design process of the product itself. We start from the assumption that designing for indie making (with digital fabrication) poses significantly different constraints compared to “conventional manufacturing” (term used here to mark anything from small batch artisanship to mass manufacturing injection molded plastic). To achieve valuable products, conventional manufacturing can use a rich array of materials (with specialized processes for each), and it can assemble many specialized parts (such as electronics) to achieve sophisticated functionalities – while a large company’s resources may also help to market more effectively, both through preliminary user research and though large-scale multi-channel product communication.

Hence, the paper elaborates on three challenges, identified by the keywords Materials, Machines and Meanings – roughly corresponding to the Vitruvian triad of the values *firmitas*, *utilitas*, and *venustas* (strength, utility and attractiveness), recognized for centuries, at least

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in architectural design. However, the impetus to elaborate on these comes from teaching experiences in the past four years, which explored “maker movement technologies” in different ways, most notably a semester around personalizable design, stemming from the idea that competing with the efficiency of mass manufacturing is possible with an effective use of the “anti-mass” nature of digital manufacturing. This semester was organized around a new canvas model, described in the section “5. Meanings”. Students were asked to identify mass manufactured products in their life, responding to a set of keywords that, according to the exhibition “Neo-prehistory: 100 verbs” and book (Branzi and Hara, 2016) represent the 20th century modern life and industrial production. Then, students needed to design new products in the very same categories, but making personalization an essential feature of the product. While the conceptual development was indeed helped by the canvas, the material reality of the finished prototypes suffered in many cases from the limited tactile qualities of 3D printing – albeit the point should have been exploring digital fabrication as a valid manufacturing alternative. Another difficulty was separating out and substituting functional components which needed to be sourced necessarily from mass manufacturing.

The article will describe the issues of Materials, Machines and Meanings in this order, zooming out from the tactile reality, towards higher level functionality and, finally, the significance of the products. For this highest level of Meanings, the article proposes a precise, step by step methodology. For Materials and Machines, suggestions cannot be as precise due to the work-in-progress nature of the related technological innovations. However, hopefully they will serve to highlight the issues and orient future research and development. Moreover, they can be informative for the effective compilation of two modules of the canvas (C1 and C4 respectively), which determine feasibility in the proposed framework.

## **1. CHALLENGES AND POSSIBLE DESIGN STRATEGIES – OVERVIEW**

This paper aims to explore possible design strategies to compensate three key shortages (materials, machines, meanings) of indie manufacturing for everyday life.

**Materials.** Regarding the necessary “material richness”, the challenge is to match conventional manufacturing’s ability to elaborate a wide range of materials. Designers can rely on (to mention a few) metals which are strong and mechanically resistant, plastics of various kinds which are cheap and easy to shape, natural materials which can provide particular aesthetic and tactile qualities (leather, wood, etc.). While much of these materials can be worked with fab lab equipment, there are serious limitations, and even when the same material is used, it tends to be of a lower quality: for example, reproducing an injection

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molded part with typical filament-based 3d printing will yield a rough layered look, while soft plastics (from living hinges to rubber sponges) are rather hard to imitate. A strategy could be developing ways that use existing fabrication equipment and materials, but structure them in a way that goes beyond the basic material properties, either by simulating the behavior of traditional materials or by inventing completely new material qualities.

**Machines.** Regarding the necessary “functional richness”, the challenge is to match conventional manufacturing’s ability to produce complex multi-part products, which provide the functionalities that are crucial for the comfort of the modern life. While the user is in contact with the “designed” shell of these products, what really matters is the electronical/mechanical content, which is in part sourced from a network of suppliers, in part engineered for the purpose, all which is brought together on a specialized assembly line. This model is hardly adaptable to the indie maker, at least in case of high-end product categories, which are in intense evolution on a ferocious marketplace. On the other hand, many appliances of the everyday environment are much less performance-critical, essentially unvaried for decades, and these seem to be ideal candidates to be fabricated by indie makers. A strategy could be to develop effective ways for integrating “product shells” (produced through distributed/digital fabrication) with electronical/mechanical components that are ever more readily available thanks to e-commerce.

**Meanings.** Regarding the issue of effective marketing, the challenge is a more subtle one: it involves not (only) how to sell, but also what, why and to whom. When responding to generic needs which require a simple, quick and cheap solution, mass production can be highly optimized, so that it produces thousands or millions of exact copies in perfect quality, which is obviously a capital-intensive operation, out of the reach of indie makers. Distributed manufacturing is a more competitive solution to respond highly variable user needs – those which can be satisfied with niche products, implying small batches and uncertain number of copies sold. Indie makers are particularly well-suited for on-demand production; in fact, mass customization is an increasing trend in conventional industries as well, but interventions in an assembly line are relatively limited. Therefore, a strategy could be to find product categories which can benefit from the significant personalization of the product shape, thus offering an otherwise unobtainable advantage. The conceptual design of personalizable products can be facilitated by understanding possible personalization principles.

## 2. MATERIALS: TOWARDS A RICHER SET OF PHYSICAL BEHAVIORS

The first of the three challenges we discuss is about material qualities. The everyday environment has a very wide variety of materials, shaped by various production processes, according any given object type's requirements and the equipment available to the manufacturer. Even the same molecules can be arranged into completely different forms to provide different functional, aesthetic and tactile characteristics: glass can be a flat window, a strong round bottle or a flexible fiber-optic cable; aluminum can be a deep drawn pot, a machined engine block, a light foam panel, or a malleable foil, just to mention a few. Industrial processes require careful fine-tuning to achieve optimal mechanical performance and surface finish and to ensure adherence to quality standards; such fine-tuning is time-consuming and expensive, but reasonable when thousands or millions of copies are made from the same object.

Indie making and distributed manufacturing, on the other hand, cannot afford much optimization for a single object or a small run produced – to compensate, it is possible to rely on digital fabrication's capacity to exactly repeat a construction process even in absence of a specialized production line. This basic assumption of distributed design might be disputable, as all the typical fab lab machines (laser cutter, CNC router/mill, FDM/SLA 3D printers) require some expertise to operate and the exact machine model and calibration can cause qualitative differences among fab labs. Putting these differences aside, it's easy to note that (compared to "conventional manufacturing"), fab labs have limited capacity to work with some of the most common industrial materials such as steel or glass, and these are likely to remain key shortages of distributed manufacturing. The lack of metals is particularly limiting; there are high-end SLS machines that achieve good quality metal printing, but these are large investments and expensive to operate, while promising mid-range FDM metal printers are still in their infancy, and still too complicated for small labs. On the other hand, there are many conventional materials which can be worked efficiently at a competitive quality even in fab labs, such as CNC routed/carved wood, laser cut leather or acrylic, among others, without a particular effort.

However, this contribution argues that design-led research is still very necessary around the most emblematic of the maker technologies, 3D printing, which has significant shortages compared to mainstream plastic production technologies. Most notably, injection molding can produce precise, light, thin, material-efficient objects; the mold can be shiny smooth or textured if necessary, plastic composition can be tuned for the specific application field; to achieve various degrees of soft and flexible objects, even air bubbles can be introduced (e.g.

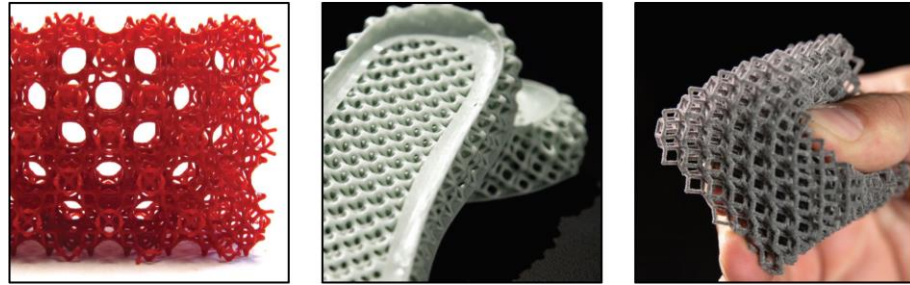
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EVA shoe midsoles). Can 3D printed plastic achieve a similar versatility? While there is an ever-wider variety of 3D printable plastics (both for resins and filaments), the number of options is limited (especially as fab labs cannot possibly keep a stock of every material and color).

Beyond the molecular composition, the mechanical properties of a 3d printed object can be fine-tuned with structure, similarly to foam-like materials, but with a (theoretically) higher degree of control, as the selective material deposition allows to modulate harder and softer areas within a single 3d printed volume. Some of the examples are in the footwear field, such as Adidas 4D-shoes, the New Balance's data-driven "generative" midsoles (using Carbon's stereolithography) or Nike's Flyprint which uses filament-based 3d printing for the upper part; all of which are limited-edition, premium products, that use 3D printing still in a limited role, rather than as a one-step manufacturing solution. Apart from the few existing commercial products, 3d printed (micro)structures were examined by academic research, especially in the scientific community of Visual Computing, as computation power and CAD tools are still significant barriers to designing microstructures.

An early example is the work of Bickel et al. (2010), who studied quantitatively the deformation of various foam-like materials in order to reproduce similar softness using a relatively simple, tubular subsurface pattern, optimized for printing in flexible photopolymers with the Objet's PolyJet technology (significantly limiting the geometric complexity of the pattern). Relying on the more capable stereolithography printing, Panetta et al. (2015) carried out a more in-depth study about the possible 3D cell patterns, focusing on truss-like structures, composed of wires of various thicknesses connected in various ways. Moreover, they studied a method for simulating the behavior of objects composed of numerous cells. Ion et al. (2016) make a step further and demonstrate that a multitude of cells can work together as machine, thus achieving functional mechanisms with a single block of 3d printed material. Beyond studying the mechanical behaviors with specialized tools, Ion recognizes that the diffusion of such cell-based material thinking is largely dependent on the design tools, i.e. software interfaces, so they propose an online editor ([jfrohnhofen.github.io/metamaterial-mechanisms](https://jfrohnhofen.github.io/metamaterial-mechanisms)) for constructing and simulating such mechanisms.

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**Figure 1.** 3D printed microstructure samples, from left to right: (a) lattice structure for stereolithography (SLA) printing, by Panetta et al. (2015). (b) lattice structures of the Carbon-SLA printed midsoles of the “Adidas 4D” shoes. (c) MultiJet Fusion printed flexible material sample by Hewlett Packard.



**Figure 2.** 3D printed microstructures for filament-style extrusion, samples, from left to right: (a) Nike Flyknit shoe upper, obtained by the FDM printing on the flat printing bed. (b) clay extrusion printing with the direct control of g-code, by Ronald Rael and Virginia San Fratello (c) experimental soft plastic structures specially developed for FDM 3D printing, by the author.

The issue of software tools is an important one for designing with microstructures; as Vidimce et al. (2013) or Li et al. (2018) argue, the now mainstream explicit modelling of NURBS or mesh surfaces is not very suitable for additive manufacturing. Implicit modelling allows the efficient modelling and simulation of internal structures using “field-driven design”, leveraging the modern GPUs, transforming the mathematical representation of the substance into Additive Manufacturing files without converting the microstructures into mesh. A powerful example is the proprietary nTopology Platform, while a simpler, free and open-source implementation is ImplicitCAD(.org).

The above approaches to internal microstructures are best realized with relatively expensive 3D printing solutions, such as the resin-based SLA or powder-based SLS/MJF, because they are composed of extremely fine details, which should seamlessly change in thickness and thus flexibility. Printing these structures on the most typical filament-based (FDM) 3D printers is highly impractical due to the fixed nozzle width, inefficient interruptions and potential layer adhesion issues. FDM-specific infill can be considered as a microstructure, but its objective is mostly to spare material and printing time and to support the object during the print time. The infills produced by common slicer software (Cura, Simplify3D, Slic3r) help to keep the object rigid when using hard filaments, or squishy when using flexible

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filaments, but such behavior is hardly controllable and strongly anisotropic (different along the layers). IceSL, a more niche slicer (employing implicit modelling) offers also variable infill density with a variety of foam-like structures, as well as an interface for “painting” material properties on the object surface. The CrossFill project (Kuipers, Wu and Wang, 2019) is another research effort to optimize variable density infills for FDM printing, which they call functionally graded materials, using a space-filling surface that can be sliced into a continuous toolpath with no intersections.

All of the above examples of flexible microstructures have a somewhat abstract approach, starting from ideal geometries which should be materialized with an infinitely high-resolution printer. While resin and powder-based machines might be precise enough for this approach, filament-based microstructures are not particularly mature yet. It is suggested that further effort in this field should start specifically from the close observation of filament-based printing: relatively strong and flexible filament is laid out horizontally, while vertical structures are stacked and therefore both more fragile and stiffer; moreover, a limited number of steps can be achieved due to the fixed nozzle width. These issues raise the question of more precise machine control. The designers’ typical approach is focusing on the definition of the desired surface, choosing material, then letting the slicer to control the exact machine movements.

There is, however, an increasing awareness of the potential of custom g-code definition. 3D printed clay is good example; its large scale and slow speed probably helped to reflect on the process, and designers started to think in terms of machine movement, going beyond the paradigm of surface approximation and achieving interesting and unusual aesthetic languages (e.g. Ronald Rael and Virginia San Fratello, or the studio Co-De-It). Beyond beauty, this approach might help to develop a wider range of internal microstructures for plastics, as well as new tactile qualities by modulating the surface of 3D printed objects. Consequently, these new physical and sensorial characteristics could be part of the fab labs’ and indie makers’ strategy to offer alternatives to the rich variety of materials qualities in conventional manufacturing.

### **3. MACHINES: TOWARDS A RICHER SET OF ACHIEVABLE FUNCTIONALITIES**

The second discussed challenge is about the electronic and mechanic components which are essential for many products. While in the previous section we focused on the gap between traditional material qualities and those of digital manufacturing, here we tackle with the functional components which cannot be substituted in the “typical” indie maker’s laboratory.



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These components are necessary to many of the most valuable consumer products that enable the contemporary lifestyle, from simple manual utensils to household appliances and consumer electronics. Take an example as simple as scissors: while mechanically easy to reproduce, scissors require a cutting edge that must be strong and manufactured to tight tolerances, but this could be only a few percent to the total mass of the object. More complex electro-mechanical objects (from a coffee maker to an inkjet printer) also tend to be largely “dumb matter”, plastic or metal shell which covers and keeps in place a few key components which must be done in more precious materials and with very precise processes. However, these products are manufactured, transported, stored and sold as a whole, implying a lot of potentially futile effort and waste, especially taking into account that consumer products are often notoriously hard to service. More high-tech products (such as computers or smartphones) come in tighter package, so a higher percentage of the product’s volume (and matter) is essential to the correct functionality; in these cases a high degree of optimization is necessary, the development is fast and involves thousands of people, so independent and open distributed manufacturing does not seem to be realistic. But even if some product categories remain the privilege of well-capitalized enterprises, there are many other products with numerous functionally equivalent options, which differ mostly in styling and minor features, while sharing the same core components.

Could distributed manufacturing have a role in realizing the common objects which make possible the modern comforts? This is a similar question to the one posed by the Open Source Ecology initiative, which aims to make available the blueprints and know-how for all the basic machinery that allows productive activities; a similar approach lowered the barrier to 3D printing starting from the RepRap project. Would this be possible also for common household machines? This does not necessarily mean starting from zero which, as Thomas Thwaites (2011) demonstrated with his Toaster Project, is a hopelessly complex job even in the case of a ten-dollar worth appliance; it is far easier to rely on a local network of makers, like Andrea De Chirico did with his Super Local hairdryer project (reproduced in three cities). When an object requires more advanced components, such as microchips, these are necessarily produced in specialized factories, concentrated rather than distributed. Fortunately, contemporary e-commerce platforms enable the rapid sourcing of countless components, even at convenient bulk prices if necessary, opening new perspectives for indie makers.

As Dominic Muren (2010) suggests, electronics can be perceived as an organism, divided in skin, skeleton and guts (what he calls SSG framework), in a way that would allow to separate

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the desired technical characteristics from to the desired ergonomic configuration or aesthetics. This approach could enable the distributed manufacturing of more complex products; supposing project files and instructions coming from an original designer, the client's local fab lab would "only" fabricate the product casing and assemble it with existing, standard components. Still, tracing down and shipping all components from different vendors is a significant effort, especially if some parts are substituted by newer versions.

Adopting a "kit-design" approach could be a possible strategy to mitigate this issue: the centralized collection, compact packaging and on-demand shipping of "mission critical" parts would still bring much of distributed manufacturing's advantages in terms of empowering local economics, avoiding overproduction, and maybe even making available now-expensive niche products to more people (e.g. medical devices for rare conditions). The separate sales of core functionality and "designed shell" is practiced also in mainstream industry, often for customization purposes, from wrist watches to cars accessories. Compact and powerful consumer electronics can even be incorporated in other objects for enriching the user experience, such as virtual reality visors which use a smartphone (Google cardboard), or the Nintendo Labo cardboard kit to extend Nintendo Switch consoles and its detachable controllers (Joy-Con), to be converted in Toy-Cons.

Electronics kits are available for many purposes also in the maker community, especially for beginners, and the kit-based strategy contributed to the success of another emblematic maker technology, Arduino, and its even more user-friendly alternatives such as littleBits, TinyCircuits or makeBlock – even though these are not intended to assemble a predefined end product. Arduino in its many forms (and its derivatives) have lowered the barriers to integrating electronics into products of distributed manufacturing; even if it started out as an electronics prototyping platform, by now there are many compact and cheap alternatives which can be computationally sufficient and economically convenient enough to be integrated in end-use products. On the other hand, prototyping and manufacturing custom printed circuit boards (PCB) is getting ever more feasible even in small labs thanks to compact desktop devices such as BotFactory and Voltera, which can print traces on custom substrates, apply solder and even place tiny chips.

Kit-based products and open manufacturing should have a positive effect also on sustainability: as of today, servicing most electronic products require highly specific skills, so often it is more convenient to buy a new product. By contrast and by definition, the distributed manufacturing of consumer electronics would be more open, and just as open source encourages clear, robust, well-documented software products and reusable software

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components, open design for distributed production should encourage better constructions and design for disassembly, promoting circular economy and reducing e-waste. Security, however, should be an important concern. Today we are used to every appliance in commerce being complaint to standards, otherwise manufacturers would face severe consequences. As Phillips et al. (2016) argue, the proliferation Open Design pose a risk to the “trustworthiness” of the current material culture, therefore some form of standardization should be re-introduced even into on-demand manufacturing.



**Figure 3. Electronic circuits in 3D printing, from left to right: (a) Voxel8’s experimental technology, printing conductive metallic traces over FDM printed plastic; (b) Voxel8’s demo object, a complex electro-mechanical system (mini-drone) featuring directly printed electric cabling and standard components; (c) NanoDimension’s demo object, a body thermometer demonstrating the possibility of printing fine, highly detailed objects with integrated electronic traces in UV-curable resin, on an inkjet-style printer.**

Another frontier is integrating circuits directly in the products’ structural elements, possibly in the same 3D printing process. Perez and Williams (2013) reviewed various ways of printing circuits directly on 3D printed objects (either FDM, SLA or SLS) using conductive filaments or inks through Inkjet or Aerosol Jet; an approach which can lead to simpler, lighter and therefore more resistant assemblies, potentially substituting fragile printed circuits. The development of these research threads is confirmed by a more recent review of Lu, Lan and Liu (2018), but challenges remain open regarding lower conductivity, risk of delamination or microelectronics integration. As of today, commercial machines for this purpose (such as the resin-based NanoDimension DragonFLY printer) are geared towards prototyping rather than manufacturing, due to the complexity, cost and size of such systems. Voxel8’s filament-based machine was a promising as well, but it is now discontinued. Nonetheless, there are continuous attempts to lower the barriers to 3D printed manufacturing with integrated electronics, and inventing use cases with a designer’s perspective might help the development of the field. Internet of Things and wearable electronics applications could, in particular, benefit from this approach, as these require the electronics to be embedded in objects that are small, thin or even flexible. 3D printed electronics allow the intelligence to be distributed across the “body” of the object, and this is

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a fundamentally new opportunity on which designers should reflect, as electronic products can go beyond simplistic machines and become much more like complex, sensing organisms.

#### **4. MEANINGS: TOWARDS A BETTER FIT TO USER NEEDS AND DESIRES**

The third discussed challenge is about the value of artefacts in the lives of their users. While the previous two sections responded to physical issues with distributed/digital manufacturing (especially 3D printing, as the most emblematic of the “fab lab technologies”), here we tackle with the issue of “what to do” with ever more complete possibilities of distributed production. As already mentioned, distributed production is hardly a reasonable choice when consumers want millions of the exact same product, as mass manufacturing (and consumption) allows to concentrate and channel resources into the most efficient possible production and distribution. Distributed production is, therefore, reasonable for manufacturing smaller batches and it is most interesting for the on-demand fabrication of custom-made products.

Beyond the technological optimization, producing many copies allows more research effort in order to understand the targeted market; on the other hand, large brands can afford to use marketing to bend consumer perceptions through comprehensive campaigns. In comparison, indie makers can hardly afford either in-depth quali-quantitative market research or substantial campaigns (albeit the social web helps in this regard too). Hence, indie design has a disadvantage in terms of information and control over how desirable the product is. Personalization, therefore, is a possible strategy to mitigate this disadvantage and, as this paper argues, a way to create new meanings, more engaged consumers, and the better emotional durability of the material culture which, in turn, should contribute to environmental sustainability (Chapman, 2005).

Designing for product personalization is a rather different challenge than designing a mass manufactured product: user divergences should not be smoothed out, but considered as resource to be valorized. As De Mul (2011) expresses, “the designer [...] should become a metadesigner who designs a multidimensional design space that provides a user-friendly interface, enabling the user to become a co-designer, even when this user has no designer experience or no time to gain such experience through trial and error.” In this way, the designers are freed up from the responsibility of choosing a single design that may or may not work, but they must foresee a multitude of possible products. Moreover, the design effort must include not only the product itself, but also a process which guides the user towards a desirable outcome, keeping in mind that “with too much structure the outcomes are

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controlled by the hidden hand of the designer”. On the other hand, “too little support and many potential creative contributions are lost because starting from a blank page is difficult, even for experienced designers.” (Cruickshank, 2016). Even with a careful balance, designers must be aware that possessing personalized products is not a universal desire: psychologist Barry Schwartz (2004) highlights the paradox of choice, an anxiety caused by excessive options that represent a burden for the consumer, who can even end up less gratified with the purchase. Therefore, design for personalized (and distributed) production seems to require the same set of ingredients which are considered fundamental also for mass customization: a well-defined Solution Space, and an intuitive Choice Navigation process, as well as a robust manufacturing solution (Salvador, de Holan and Piller, 2009).

Having recognized the difficulty of deciding what and how to personalize, this contribution proposes a novel design method and a relative design tool, which guides the designer from the choice of a product typology to the definition of the concept and detailing all the main factors that would influence the major strategic choices. The proposed method is based on the observation that there are some tendencies among already existing personalizable products, which were gathered from online design press (e.g. Core77, Designboom, Notcot) as well as a specialized website (configurator-database.com) which currently lists 1360 product personalization websites. The research from these sources focused products that have personalizable three-dimensional shape; merely modularity-based or graphical personalization was mostly ignored (neither requiring nor valorizing digital fabrication). Analyzing these case studies led to identifying six main types of motivations that can justify the usually higher price and effort needed. These six motivations are divided among mechanical motivations, including (1) physiology/ergonomics; (2) environment/objects; (3) function/performance and cognitive motivations, including (4) aesthetic/emotional; (5) social/cultural; (6) narrative/experience. Beyond the dominant motivation for personalization, often there are additional reasons, and the unique mixture and intensity of these factors constitute a profile of personalization that can be represented by a radar diagram.

The Computational Concept Canvas is a design tool that was developed to help applying the observed principles of personalization to any chosen product typology. The tool (and relative design method) aims to guide the designer’s thinking towards product concepts to which personalization is essential – a very different challenge compared to designing serial products, and a challenge not yet facilitated by any specific tools. New design tools often aim at promoting a novel approach to design according to the discipline’s evolution (e.g.

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Hanington & Martin, 2012 or Kuma, 2012). The most important inspiration was the widely used Business Model Canvas (Osterwalder and Pigneur, 2010), which helps developing and evaluating entrepreneurial ideas through a well-defined structure that reminds to consider the key factors for developing a profitable product or service.

The work on the Computational Concept Canvas revolves around the evaluation of the chosen product typology according to the six mentioned principles that could make personalization desirable for a variety of users. Before and after this, there are analytical steps and concept detailing through a variety of techniques, stimulating the designer to consider a series of important factors that might underpin the success of a personalizable product, helping to follow the progress and to identify roadblocks. The Canvas is composed of 15 fields which are grouped in three modules, to be completed more or less sequentially: even if fields within a module are not compiled in strict order, the designers should fill in at least a hypothesis of them before moving on the next module.

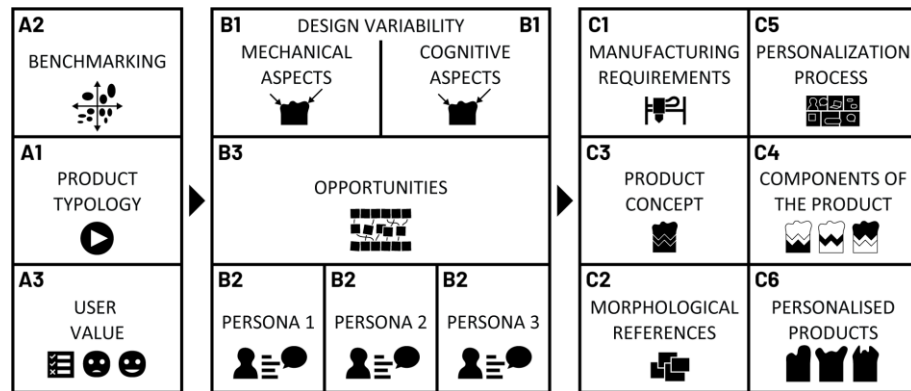
The module A is focused on defining the Product typology through 3 fields: A1 is for deciding the adequate scope of the design activity; A2 for analyzing existing products within the chosen product typology (benchmarking); A3 for clarifying the possible user values through jobs-pains-gains analysis.

Module B is the key part of the work, which helps to define the Personalization principle to follow. This starts by B1 evaluating the relevance of the previously mentioned six personalization principles; then B2 constructing personas that represent potential users and their personalization need; and finally B3 identifying design opportunities between the previous elements of the module.



**Figure 4. Computational Concept Canvas, completed. Different colour post-its show the three main blocks of the canvas, better explained on the next page. Note that also various smaller versions have been elaborated, as explained later.**

Malakucz, V. (2020). Materials, machines, meanings. Possible design strategies to compensate three key shortages of distributed manufacturing. *Strategic Design Research Journal*, volume 13, number 01, January – April 2020. 06-23. Doi: 10.4013/sdrj.2020.131.02



**Figure 5. The general structure of the canvas. Several formats of the canvas are available (from 150 cm wide, as above, to A4-optimized) at [computationalbydesign.com](http://computationalbydesign.com), along with a detailed guide booklet.**

Module C. gives space for the detailed concept definition through a loosely connected set of fields. C1 starts by analyzing manufacturing requirements and identifying manufacturing options – the previous section “3. Materials: towards a richer set of physical behaviors” is relevant mostly to this part of the canvas, as the described strategies might help to 3D print products that otherwise wouldn’t be considered for this production technology. C2 is for collecting morphological references (moodboard); C3 for crystallizing the product concept based on previous opportunities; C4 for identifying variable and invariable elements of the design – the previous section “4. Machines: towards a richer set of achievable functionalities” is relevant mostly to this part of the canvas, especially useful to clarify if and how to integrate advanced functionalities in the product. C5 for defining the personalization process through storyboarding; and, finally C6 gives place for hypothesizing possible outcomes of the personalization based on the personas.

While aiming to create useful knowledge across many industries, so far CCC was tested mostly with young designers, with participants of a start-up acceleration program and, most consistently, with product design students – future practitioners who should be most interested in developing useful skills for upcoming industrial and social tendencies. Detailed discussion of these experiences is beyond the scope of this paper due to space constraints, but in general, the canvas has fulfilled its main function of guiding the discussion in the desired direction. However, it’s worth noting that students still found it difficult to change their approach from developing a single solution (that respond specific problems) to wide solutions spaces (that respond variable requirements). Of course, the ‘Computational Concept Canvas’ provides a framework only for the first steps of a design project. While the technology to use for the parametric modelling can vary according to the business model suggested by the concept, Grasshopper for Rhinoceros 3D offer a powerful but an easy to use

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solution, ideal especially for education purposes. Using also the ShapeDiver platform, today one product designer together with one web designer can easily put a personalizable product on the worldwide marketplace.

On a more general process level, the practical implementation of a personalizable product implies significant differences compared to a serial product: a permanent feedback loop is introduced into the process of design-production-distribution. Conventionally, a unique geometry is mass manufactured, resulting in a serial product which is distributed on a uni-directional channel. On the other hand, personalizable products come from a variable geometry that is continuously modified through an experience-based, bidirectional Channel of distribution. This renewed process is strongly connected to the Canvas, which helps the strategic choices in three key areas: First of all, it's important decide the ideal parametric design tool, which can range from the very familiar solid parametric to more abstract visual programming (Grasshopper), until the fairly challenging direct scripting (e.g. Processing, three.js), and the chosen tool determines also the possible extension of the solution space. Then, another key decision is about choice navigation: the way of personalization and distribution, either online or offline, from conventional retail to digital artisan shops. Finally, distributed manufacturing can happen with different relations to digital manufacturing resources, which can range from generic equipment through external services to investment-heavy specialized equipment within the organization.

## 5. CONCLUSIONS

The paper has identified three areas in which distributed (digital) manufacturing has important shortages and outlined a possible strategy of development for each, based on the recent technological evolution and academic research related to each topic. The paper is geared towards the general vision of progressively substituting mass manufactured products with on-demand, locally fabricated ones; it was also considered that such a systemic industrial transformation is necessarily a slow one. The three chosen topics were represented by the keywords Materials, Machines, Meanings, a set of complementary issues, with varying amount of prior research already carried out, resulting in suggestions of varying levels of specificity.

Regarding the shortage of 3D printable Material qualities, there is already a significant amount of research and industrial practice which, however, focuses on the use of high-end machines for high-performance applications. Since filament-based printing is far simpler (thus more accessible and widespread), the suggested strategy is valorizing it though



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microstructures, in order to develop a richer set of mechanical, tactile and aesthetic qualities. This is an ongoing research effort also by the author.

Regarding the Machine topic, the difficulty is in the distributed reproduction of functionally complex objects. Here, a logical separation is suggested between dumb product shell and smart components, which can lead to a hybrid design/production strategy, with much of the product produced locally and assembled with standard components, limiting centralized production and distribution to the few key parts of the product which require special machines and knowledge to reproduce. Among the three topics, this one has the least specific prior research, but it is a planned topic for the author's future research.

Regarding the issue of Meanings, the paper observes that the distributed production cannot "push" its values as forcefully as mass production (and marketing) does. Instead, a better strategy seems to be establishing a more interactive relation with the users, catering to their individual needs and desires - in essence, offering personalizable products. Having developed a doctoral research in the topic, the author proposes a new design method and tool for the more effective ideation of meaningfully personalizable products, based on a set of personalization principles derived from case studies.

Materials, Machines, Meanings is by no means a complete list of issues, but with the (ever) limited resources, issues cannot be resolved all at once. Nonetheless, understanding that there is progress in various areas helps to paint a positive picture on the perspectives of distributed production, even beyond the "ideologically" driven vision behind movements such as Fab City.

The evolution of open and distributed design and distribution naturally implies an evolution of the professional figure of the designer. The changes might be multifaceted: on one hand, designers need to talk the language of ever more technological fields, from generative modelling to circuit design, beyond of course the production technologies themselves. On the other hand, designers need to be ever more flexible in their workflow, assuming different disciplinary roles or swiftly collaborating with experts, across the table or across the globe, potentially changing the nature of their creativity.

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