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Growing materials for product design

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Abstract

The possibility to fabricate materials from living organisms offers appealing advantages for product design, such as higher sustainability and an interesting novel aesthetics. Several designers are now ‘growing’ their own materials. Despite the large interest shown, this emerging material practice is still scarcely understood in design literature. The aim of this paper is to shed light on what it means to design with growing organisms as collaborators, identifying the defining traits of this novel, designerly way of ‘doing materials’. To do so, we first compare this specific approach to the approaches of others working in the intersections of biology and design. In this way, we outline the boundaries of Growing Design, defining its unique characteristics. We then provide detailed descriptions of three classes of Growing Materials: fungal, bacterial and algal materials. For each class, we bring two examples of designers utilizing these materials for industrial design purposes. This helps to further explain what truly distinguishes Growing Materials from other conventional materials and to understand the challenges in working with them. Finally, this discussion enables us to set out a research agenda for Growing Design, supporting the development of these materials for industrial production.

Keywords

Alive Materials; Mycelium; Bacterial cellulose; Algae; Materials Experience

Over the last decade, designers have started fabricating new materials by utilizing the natural processes of growth and reproduction of living organisms such as fungi, bacteria and algae. Among others, the works of Suzanne Lee (BioCouture) and of Maurizio Montalti (Officina Corpuscoli) were pioneering in this new field at the intersection of design and biology. In the case of BioCouture, Suzanne Lee developed a collection of garments that were grown from bacteria by the fermentation of sugar and green tea (Lee, 2011). In his ongoing project, Maurizio Montalti explores strategies to employ mycelium (the ‘alive’ agent of fungi) for the production of novel materials and to explore alternative manufacturing techniques. Both designers achieved to develop a range of materials with different characteristics, from paper-like to leather-like, which offer promising technical properties and aesthetic qualities (Montalti, n.d.).

This approach to materials for product design originates from the advances in biotechnology, which were originally developed for the fabrication of biological tissues, such as skins and organs for medical purposes (Mironov, Trusk, Kasyanov, Little, Swaja, & Markwald, 2009). With the democratization of science and manufacturing technologies (Rognoli et al., 2015), biofabrication has become relatively accessible to non-experts. The fascinating opportunity to co-create with Nature, the diverse forms of expressions that can be achieved, and the possibility to reimagine the paradigms of production motivate the cross-fertilization of biology with art, architecture and design (Antonelli, 2012).

‘Growing Design’ (Montalti, n.d.; Ciuffi, 2013), which we define as the fabrication of materials and products from living organisms, can be considered as a type of “*DIY material practice”* (Rognoli, Bianchini, Maffei & Karana, 2015). ‘DIY materials’ are designed and created through individual or collective self-production practices, often by techniques and processes of the designer’s own invention (Rognoli et al., 2015). Through this lens, it is possible to identify other potential motivations that trigger the interest of designers towards Growing Design. These are: the opportunity of novel aesthetics, in contrast with the standardized model of perfection of industrial products; and the willingness of designers to have a self-controlled production process from the material development to the embodiment of a product (Rognoli et al., 2015).

All the reasons listed above have made the process of growing materials extremely appealing to designers. The amount of design exhibitions (e.g. Fungal Futures, NL: Montalti, 2016; This is Alive, FR: Collet, 2013), conferences (e.g. Biofabricate, NY: http://www.biofabricate.co/) and journals (e.g. Pavlovich, Hunsberger, & Atala, 2016; Mironov et al., 2009), as well as the establishment of online communities (e.g. Growing Materials, 2016) and bio-labs (e.g. Open WetLab at Waag Society, NL: Evers, 2016) are clear indications of the increasing amount of interest among design communities toward the production of materials from living organisms.

Despite the large interest, the phenomenon of Growing Design is still scarcely understood. The lack of a clear vocabulary and the confusion with other approaches that merge biology and design are evidences of this issue. In this paper, we aim to define what the practice of Growing Design is about, gaining more knowledge on what type of materials are grown for design purposes and how the process of fabricating them unfolds. We will first position Growing Design among other approaches that merge biology and design. This will give us a refined definition of the Growing Design practice. Furthermore, we will elucidate on three classes of materials derived from living organisms, namely fungal, bacterial and algal materials, to explain their unique opportunities for product design.

When Biology Meets Design

Next to Growing Design, there are other approaches looking at the possibility to employ natural systems for design purposes. These approaches question the various roles that Nature can take in design, such as in rethinking the production of artifacts in a more efficient/sustainable way (e.g. biomimicry: Benyus, 1997; Cradle-to-Cradle: McDonough & Braungart, 2010). They are often grouped under the notion of BioDesign (Myers, 2012), which is described as "*the emerging and often radical approach to design that draws on biological tenets and even incorporates the use of living materials into structures, objects and tools*" (Myers, 2012, p.8). In a recent UK-based residency program named 'Synthetic Aesthetics', professionals of diverse backgrounds, such as design, art and biology, investigated the variety of approaches that designers can take to design Nature itself, with a special focus on the possibilities offered by synthetic biology (Ginsberg, Calvert, Schyfter, Elfick, & Endy, 2014). Yet, these approaches present nuanced differences in how actively (or passively) Nature is employed in the design process. For example, Carole Collet grouped 34 innovative projects under five categories based on their possible relationships with Nature: 1) Nature as a model (referring to designers as "The Plagiarists"); 2) Nature as co-worker in design process ("The New Artisans"); 3) Nature as reprogrammed and synthetic ("The BioHackers"); 4) Nature as hybridized with non-living technologies ("The New Alchemists"); 5) Nature as conceptualized and imagined in a provocative far future ("The Agents Provocateur") (Collet, 2013).

We position the notion of Growing Design under the second theme proposed by Collet, considering Nature as a co-worker in the material design process. The first category of the Collet's taxonomy, which refers to Nature-inspired design, uses Nature's principles to inspire ideas for new materials, forms and structures (Oxman, 2010), yet does not directly involve the use of biology, and, as such, of any living organisms. Accordingly, we identify four main material design practices at the intersection of biology and design: 1) Growing Design; 2) Augmented Biology; 3) Digital Biofabrication; 4) Biodesign fiction. Figure 1 depicts these practices and maps few related cases to this taxonomy. We retrieved these cases by screening two published books (Myers, 2012; Ginsberg et al., 2014), recent exhibitions (Collet, 2013; Montalti, 2016), online communities (Growing Materials, n.d.), design blogs (www.dezeen.com) and scientific publications (Bader et al. 2016; Oxman, 2015).

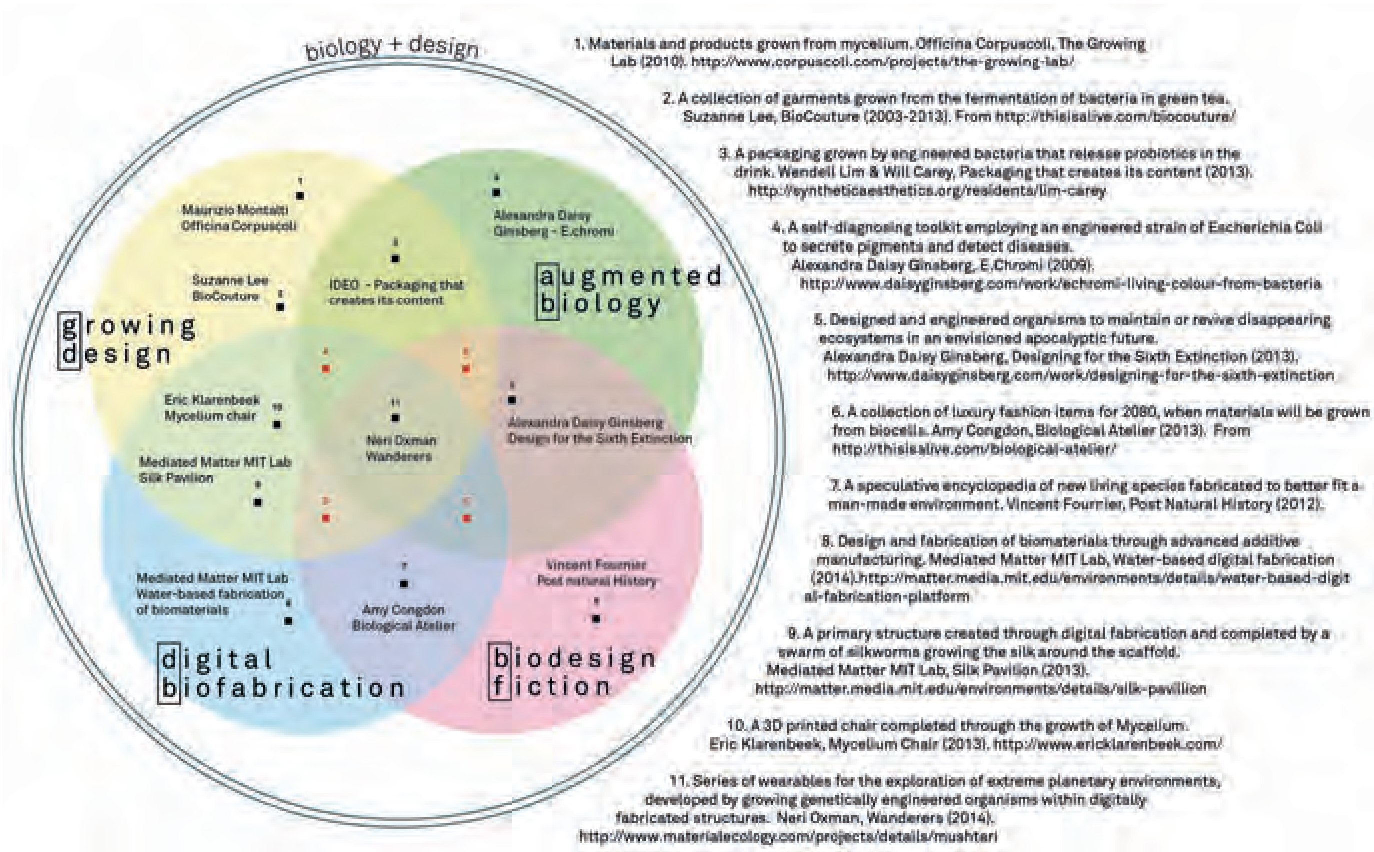

Fig 1. Mapping the four approaches using biology for design purposes.

Under ‘Augmented Biology’, we group cases that explore the potential of re-engineered cells for contemporary societal challenges, such as famine, disease and energy shortage (Collins, 2012; Agapakis, 2013). Specifically, designers working with this approach employ synthetic biology, i.e. the manipulation of living organisms using engineering principles like ‘standardization’. Synthetic biologists aspire to redesign Nature to achieve faster, repeatable and more predictable results (Ginsberg et al., 2014). To do so, they seek to alter the organisms’ genetics, either through genetic programming or other forms of mutagenesis. With Augmented Biology, Growing Design shares the ability to descend at the micro scale, to control the material’s variables and achieve the intended qualities. However, Growing Designers do not directly engage in the re-design of Nature, as they only employ existing genomes and seek to adopt Nature’s strategies of production, instead of redesigning them through engineering principles.

Designers working with Digital Biofabrication stretch the possibilities of what design can do with synthetic biology even more, by adopting computational tools and advanced technologies. In this approach, Nature is hacked through digital fabrication to breed new “ecologies of materials” (Oxman, 2015). By combining additive manufacturing, digital technologies, and mathematical modelling tools, these designers achieve a ‘digitally-inspired’ Nature, in contrast to the conventional notion of Nature-inspired design (Benyus, 1997; Oxman, 2010). In Digital Biofabrication, computational tools are used not only as fabrication means, but also to model how the living organism will behave. It does not necessarily involve the alteration of the natural genomes, as in the case of Augmented Biology. Nonetheless, its use of computational tools and advanced technologies, and its focus on Nature as object of design process differentiates Digital Biofabrication from Growing Design, which is rooted instead in making, crafting and tangible practices.

When designers who work with biology envision a far, provocative future, they adopt the perspective of BioDesign Fiction. Generally, BioDesign Fiction generates highly conceptual visions of our interactions with living, natural ecosystems in the far future. This approach is grounded in Speculative Design (Dunne & Raby, 2013; Sterling, 2005). The practice of Growing Design is rooted instead in the analysis of the present manufacturing paradigms, working toward the development of new ways to sustain our existence.

So far, we have described a neat separation between the approaches coupling design and biology. However, many recent examples combine a number of them, as, for example, the case of the 3D-printed *Mycelium chair* by Eric Klarenbeek (2016). In this case, the designer used additive manufacturing to print a scaffold on which the mycelium can grow. This example couples advanced technologies with a growing organism, thus falling under the intersection of the Growing Design and Digital Biofabrication approaches (Figure 1). Cases with such nuanced identity are very common, combining multiple perspectives to reach the intended design purpose. Using this taxonomy, we can even speculate on possible future cases, as identified in Figure 1 (in red) by points (A), (B), (C), and (D). For example, at the intersection of Growing Design, Augmented Biology and Digital Biofabrication, we anticipate the fabrication of materials by growing genetically modified organisms, whose behavior is tailored by the designer through a computational algorithm. Similarly, at the intersection of Growing Design, Augmented Biology and BioDesign Fiction (B), we envision that the future plants could be genetically programmed to produce "superfoods" along with materials for man-made artifacts – similar to what was already conceptualized by Carole Collet in the project *BioLace* (Collet, 2013).

The presented taxonomy has helped us to reflect upon the distinct characteristics of Growing Design as follows:

1. Designers cooperate with Nature to achieve specific design purposes
2. The materials employed in Growing Design are grown from living organisms
3. Designers do not alter the genetic structure of the living organisms
4. Designers actively engage in growing the materials (DIY)
5. The fabrication process is rooted in crafting and making
6. The material is envisioned to be used in products today or in a probable future

This list identifies few traits that manifestly characterize the practice of fabricating materials for products from living organisms. Having detailed these qualities, we now seek to understand what are the unique opportunities that Growing Materials offer to product design. In the next section, we will describe three classes of materials fabricated from living organisms, providing illustrative cases for each material class.

Growing Materials from Living Organisms

Although organisms like chitin or protocells can be used in Growing Design (Alper, 1992), in this section we focus solely on ***mycelium (fungal materials), bacteria and algae***, as these three groups of organisms are used relatively more by designers.

Fungal Materials

With the term 'Fungal materials' we define materials derived from *mycelium*. 'Mycelium' is a network of interwoven, thread-like hyphae that constitute the vegetative part of mushrooms (Kavanagh, 2011). Fungal materials are grown by two alternative methods: either exploiting the abilities of mycelium to interlock other substances within its network, forming a bulk material (mycelium-based composites), or harvesting a liquid culture of mycelium (pure mycelium). For mycelium-based composites, the substrates used can span from agricultural waste to sawdust, to orange peels or any organic element that can provide nutrients to the mycelium. The choice of the substrate has a significant impact on the final material, as it influences both the technical properties and the *experiential qualities of the material* (Karana, 2009; Giaccardi & Karana, 2015).

Pure mycelium materials are instead fabricated from a liquid culture, in which the mycelium is provided with the right nutrients (the 'minimal medium') necessary for its growth, and maintained in static or machine-shaken containers. The resulting substance forms thin, leather-like sheets of material, which can vary in properties, depending on the nutrients provided. For example, different colors and translucency effects can be obtained adding chemicals (e.g. glycerol or ethanol) to the liquid culture (Blauwhoff, 2016).

In order to obtain appropriate results and prevent infections by other organisms, the fabrication of fungal materials requires the sterilization of the growing environment, including the substrate on which mycelium should grow. The process always starts with a growth of mycelium on a base-plate. From this, it is possible to inoculate the substrate in the case of mycelium-based composites, or to initiate a static or agitated culture. Depending on the intended results, the growing process can last two to three weeks. To ensure the growth of mycelium, it is necessary to create a controlled environment, in which the temperature and moisture are maintained stable. Depending on the strain of fungi, these conditions can vary from 25-30°C in temperature and 60-65% in humidity. At the end of this process, the mycelium can be killed by drying the material at 60°C, or left in 'hibernated' state, preserving the possibility of future growth.

Manufacturing of products starting from mycelium-based materials is possible through different techniques, including conventional processes as CNC cutting, milling, laser-cutting, etc. Other unique opportunities are offered by the materials' features: for example, as mycelium-based materials can grow into the shape of the container used to fabricate them, molds of the same shape of the final product can be used as growing environment. Below, we present two cases illustrating how fungal materials are used in design.

The Factory of the Future – By Emma van der Leest, Zoe Agasi and Loeke Molenaar

Fig 2. "The Factory of the Future" – a concept of sustainable packaging made from a mycelium-based composite, developed for the circular-economy-based farm 'Uit Je Eigen Stad'.

This project was commissioned to three graduates of the Willem de Kooning Academy by the company Uit Je Eigen Stad, a city farm in Rotterdam focused on circular food production (van der Leest, Agasi, Molenaar, n.d.). The project aimed at the development of sustainable packaging for the company, to replace the conventional plastic packaging. The designers developed a concept based on a waste stream of the farm, which occurred during the cultivation of Shiitake mushrooms and vegetables. The designers re-used the hemp mats that was previously employed to harvest vegetables and were no longer useful. Nevertheless, these hemp mats could still provide sufficient nutrients to be qualified as a substrate to grow the Shiitake mushrooms. Furthermore, designers envisioned that the hemp mats, after being reused for the cultivation of Shiitake, could be recycled once more as substrate to start the fabrication of mycelium-based composites, which eventually enabled them to create a more sustainable packaging for the farm's production of vegetables (Figure 2). The material developed is fully compostable, with good thermal insulation properties. It is also highly water repellent. In this particular case, the designers intentionally designed a process to tie the company's loose ends and improve the sustainability of the food production system.

MycoTEX – By Aniela Hoitink (Fungal Futures)

The project has been developed as part of the NWO-funded project 'Mycelium Design', in which several artists and designers experimented with mycelium (Montalti, 2016). One of the designers, Aniela Hoitink, used pure mycelium to make textile-like materials for garments (Figure 3). The dress concept is fabricated by forming different modules of the dress from pure mycelium directly on the body, a solution that yields for easy repairs and adjustments and is showing a new production process for manufacturing clothing.

Fig 3. "MycoTEX" – development of pure mycelium as textile for garments.

Bacterial Materials

Several design projects investigated the use of bacteria in the fabrication of materials for product design. When provided with the correct nutrients and growing environment, some species of bacteria produce a layer of cellulose, which differs in its properties from the cellulose derived from plants. Specifically, the compound derived from bacteria is almost pure cellulose and contains no lignin, which makes it flexible and consequently, easier to mold and process than plant cellulose (Iguchi, Yamanaka & Budhiono, 2000). The formation of cellulose is triggered by the symbiotic culture of bacteria with yeasts. The bacteria, when placed in the nutrient medium, produce subfibrils and subsequently microfibrils, forming a thick layer of cellulose floating on the medium surface (Iguchi, Yamanaka & Budhiono, 2000). The *Acetobacter Xylinum* is the most widely used strain of bacteria for applied studies such as in product design, although several other species are known for their abilities to produce cellulose (Huang, Zhu, Yang, Nie, Chen & Sun, 2014; Ng & Wang, 2016)

The process of growing bacterial cellulose starts from the fermentation of bacteria in an acidic nutrient medium (pH=3), containing either glucose, fructose or glycerol (Iguchi, Yamanaka, Budhiono 2000). The growing process, similar to that of pure mycelium, can be activated in static or agitated (i.e. machine-shaken) conditions. In product design, bacterial cellulose is normally harvested in static conditions in tanks or containers that can allow the fabrication of large sheets of material (Lee, 2011). The growing process requires a sterile environment to prevent the formation of by-products such as moulds and/or to spoil the culture with other strains of bacteria. To ensure the formation of cellulose, the optimal conditions are a temperature of 28-30°C and scarce direct sunlight. After two-three weeks, a layer of material forms on the surface of the solution. The growing process can then be prolonged in order to achieve a thicker material, or stopped by collecting the cellulose sheet and washing it with water and soap. At this stage, the material is dense with water and needs to be dried on a flat surface or on a three-dimensional mold. During the drying process, the cellulose will release the excess water and decrease in thickness, acquiring its true experiential and technical properties such as color, thickness and surface appearance. Depending on the type of nutrients the medium provides and the strain of organism used, the type of material derived can vary significantly. It can be fabricated as thin paper-like layers with a soft and matte surface, or as thicker, leather like materials.

Different techniques can be used to process the bacterial cellulose and manufacture products with it. Along with conventional shaping technologies, such as laser-cutting, sewing and blow-molding, other possibilities are prompted by inducing shape formation during the fabrication process or during the drying phase by using 3D shapes. For example, some design cases investigated the possibility of growing bacterial cellulose directly into shapes (see the project Xylinum Cones, Hülsen, n.d.) or by rotating a 3D shape mold into the fabrication tank (Ng & Wang, 2016). Moreover, the growing abilities of the organism can be employed to make self-assembling materials, which bind together during fabrication and growth processes.

Xylinum project – By Jannis Hülsen and Stefan Schwabe

In the project Xylinum, Jannis Hülsen and Stefan Schwabe explored the use of the Acetobacter Xylinum to grow everyday products with different production techniques (Hülsen, n.d.). They experimented with few techniques to produce bacterial cellulose directly in three-dimensional shapes, ranging from basic conic shapes to the complex form of a stool (Figure 4). Their intention was to combine the cooperation with microorganisms and the reproducibility of objects, finding a balance between industrial precision and organic formation (Rognoli et al., 2015).

Fig 4. "Xylinum project" – growing bacterials cellulose directly in 3D complex shapes.

Invisible Resources – By Zuzana Gombosova

In the project 'Invisible Resources', Zuzana Gombosova explored the diverse roles that bacteria could take as 'white biotechnologists' such as acting as assemblers, generators or catalysts of growth (Figure 5, left). Beyond this categorization, Zuzana experimented with different techniques and nutrients to grow bacterial cellulose. She developed a collection of furniture to demonstrate the material's qualities (Figure 5, right). The products are not fully functional because of the material's high degradability. Yet, the ability of bacterial cellulose to constantly transform and change properties over time is interpreted by the designer as a way to question our sense of value for materials embedded in everyday products (Gombosova, n.d.).

Fig 5. “Invisible Resources” – research on the potential of bacteria as collaborators of manufacturing process (left). One element of the furniture collection “Made by Invisible resources” (right)

Algal Materials

With the term ‘algae’, we identify a large group of photosynthetic organisms that are not singularly classified into one biological domain. The majority of algal species are eukaryotic organisms, thus belonging to the same biological domain of fungi, plants and animals (Brodie & Lewis, 2007). However, some organisms that belong to the domain of Bacteria are generally included in the group of algae, e.g. cyanobacteria – the so-called ‘blue-green algae’. The use of algae for the production of artifacts, materials, chemicals and fuels has been investigated for centuries. Algae offer a promising and almost inexhaustible resource to sustainaible alternative production systems, because of their diversity (more than 50000 species identified), and their exceptional growth rate (Jensen, 1993). Some species contain up to 70% of cellulose, and almost zero lignin, characteristics that make algal materials easier to process and more sustainable than other bio-based materials. Moreover, algae are extremely tolerant organisms, adaptive to various environmental conditions, allowing their growth practically anywhere. Algae can be processed to extract biofuels, electricity, cellulose, alginates (useful as binding agent) and other materials with many potential applications (Wijffels, Kruse & Hellingwerf, 2013).

Algal materials, including biofuels and natural pigments, can be derived either from micro- or macro-algae. In the case of micro-algae, the production starts from harvesting the micro-organisms, but for macro-algae, materials are produced by first drying the algae and then processing them with various techniques. For example, designers have developed techniques to extract algal sub-components from dried algae, such as gelatinous substances, pigments or other alginates. The use of macro-algae, being a process of re-purposing rather than that of growth of an organism, seems to slightly differ from what we defined as Growing Design. However, we argue that designers still actively cooperate with algae, because they re-configure the biological components of the organism to fabricate new materials. Doing so, designers need to develop an in-depth understanding of the biology of the organism employed, without which they would not be able to fabricate new materials. Furthermore, we suggest that the diverse biology of algae still presents a whole set of unexplored opportunities to Growing Designers. Microalgae, for example, have a large potential for the production of cellulose-based materials, along with other interesting abilities such as the generation of electricity (Hannon, Gimpel, Tran, Rasala, & Mayfield, 2010). Yet, the lack of an effective indoor system of harvesting algae limits their potential use in biotechnology and in product design. Since several researchers are addressing this topic (Talukder, Das & Wu, 2014), it is possible to speculate that in the near future, designers will be able to exploit the full potential of algae for Growing Design.

Similar to the other materials fabricated by Growing Designers, algal materials are also highly influenced in their properties by the strain of organism employed and by the fabrication process adopted. Depending on these variables, it is possible to achieve almost any typology of materials, from foam and bio-cement to inks and textiles. Hence, the potential of algae lies in this vast range of possibilities they entail, as much as for the high quality of the materials produced.

De Algarum Natura – By Officina Corpuscoli

In this project, Maurizio Montalti (Officina Corpuscoli, already mentioned in this paper for his work on fungal materials) engaged in the fabrication of materials from seaweed, triggered by its vast accumulation in marine environments (Montalti, 2015). In collaboration with the company Huiberts/Danvos BV, he developed fully biodegradable materials, whose properties range from hard to flexible and from translucent to opaque (Figure 6). The intention behind the project was to make effective use of seaweed waste produced by the company, which uses algae as fertilizer for their production chain. In order to utilize the waste stream, the designer developed a technique to extract agar-agar and carrageenan components of algae that are used to fabricate the material. These components are then recombined with the fibrous leftovers of the company's production cycle to form 2D flat materials, that can then be processed to form 3D shapes.

Fig 6. "De Algarum Natura" – a palette of materials derived from seaweed.

Agar plasticity – By AMAM group

The group of Japanese designers are conducting a research project to use agar to replace synthetic plastics (Araki, Maetani & Muraoka, 2015). Agar is extensively sold by the Japanese food industry in the form of blocks, whose light, feathery qualities inspired the designers to investigate its potential as packaging material. They developed three techniques to fabricate materials from agar using either pure agar powder or recombining it with red algae fibres. By experimenting with different concentrations of agar and algae, designers were able to obtain several types of materials having varying hardness and thickness. Figure 7 shows the fully biodegradable materials achieved by the AMAM studio, ranging from a clay-like composite to cushioned packaging for plant pots and wine bottles. The AMAM group is now establishing industrial partnerships in order to find support to develop the materials further.

Fig 7. “Agar Plasticity” – development of a set of materials grown from algae, ranging from foam-like to cement-like materials.

Discussion

The descriptions of the various cases of Growing Design identify few shared characteristics of the materials grown from living organisms. A clear advantage that these materials bring is higher **sustainability**. Mycelium, bacteria and algae are almost inexhaustible organisms, as they are widely distributed around the world and are fully renewable. Being fully compostable and biodegradable, they can be sustainable alternatives for disposable products. Another advantage is the **efficiency** of the production methods. Growing Materials are produced from the growth and reproduction of living organisms, which occur at impressive rates. The efficiency of this system becomes apparent if we compare it with our conventional system of producing artefacts from raw matters which took centuries, if not ages, to form. With the current rate of deforestation worldwide, even wood fails to qualify as renewable resource. Organisms such as mycelium, algae, and bacteria are instead easily reproducible and are abundantly formed in terrestrial and marine ecosystems, thus promising a far more sustainaible source of materials. In Figure 8 we present a timeline that highlights the striking differences in the production of fungal, bacterial and algal materials when compared to wood and fossil-based plastics.

The very fact that the materials are grown – i.e. **grow-ability** of the material– opens up new possibilities for design. For example, such materials can be grown directly into a shape, symbiotically producing the material and the product together. Other cases demonstrate that their grow-ability can be used to skip binding processes of different parts, by triggering growth of the organism such as to join the edges seamlessly (Lee, 2011). Connected to this characteristic is another important dimension of Growing Materials: the **time** necessary for the organisms to fabricate the matter. They grow over time, and when the growing process is completed (i.e. when the product is ready), they still continue to change and **adapt** over time. Conventionally, designers are used to interact with materials as a means to craft their ideas, making them tangible (Manzini, 1986). They tinker with material and reflect upon the outcome of their experiments in a learning-by-doing cycle. Instead, Growing Design involves a delay in time of few weeks, temporally separating the moment of crafting from the evaluation of the outcome.

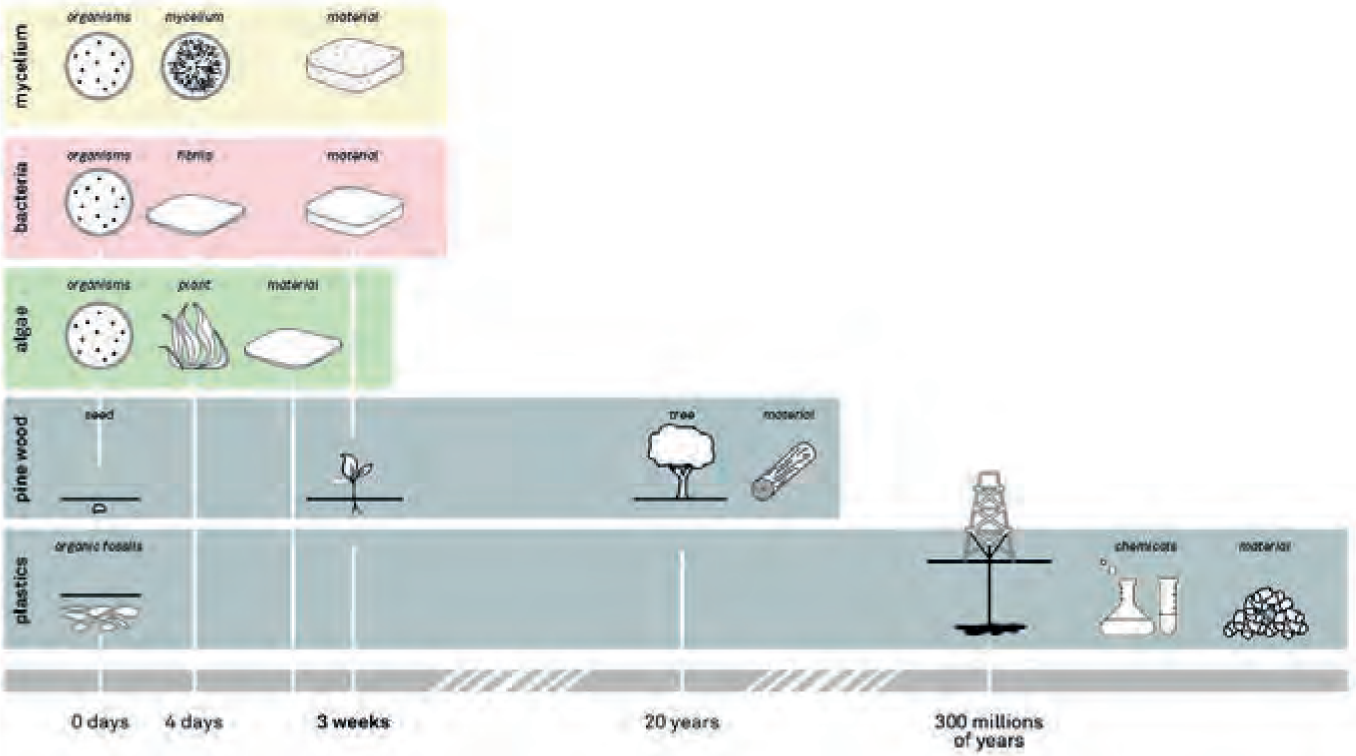

Fig 8. Comparing the timescale of industrial manufacturing with Growing Materials (top three) and more conventional materials used in product design.

Besides time, Growing Design also radically changes the **scale** at which designers work with materials. While designers typically relate to materials at the scale of millimeters, in this emerging practice they descend to the microscopic scale, entering a domain traditionally assigned to material scientists (Miodownik, 2007). This offers Growing Designers the possibility to control the material composition, fine-tuning its qualities through the variables of their fabricating process. The cases provided in the paper enable us to outline the variables shared by Growing Materials (Figure 9). These are the variables that Growing Designers can manipulate to achieve their intended results of the controlled fabrication process. Being concerned not only with the technical performances of an artifact, but rather with its social significance, designers can use these elements to consider how people will receive the material, and achieve their goal in terms of experiential qualities (Karana, Barati, Rognoli & Zeeuw Van Der Laan, 2015).

As we have seen from the cases presented, Growing Designers do not usually focus on the development of *one* material– but rather of *a palette* of materials. Growing Designers are somehow redefining the concept of ‘natural’, as they are able to control the matter and achieve variants of natural materials. For this reason, we argue that Growing Design changes the way we relate to Nature. Moreover, designers who grow materials set up the fabrication process and then let the living organisms take the role of creators/makers. The organisms collaborate as active and sentient agents of the creative process, offering their intelligence and productive abilities. At the same time, the growth of these organisms is guided and driven by humans, who provide a specific environment for it. This symbiotic relationship identifies the **collaborative process** in which designers and Nature mutually benefit from each other. Growing Designers forge the conditions for the invention of new matter, which would not exist otherwise. Take the example of mycelium-based composites: mycelium would certainly grow into sawdust, forming mushrooms or decomposing waste, but it would not transform itself into a bulk material that has no ecological purpose – rather than man-made ones. In Growing Design, Nature is triggered by the human intervention for the production of man-designed, yet ‘natural’, materials.

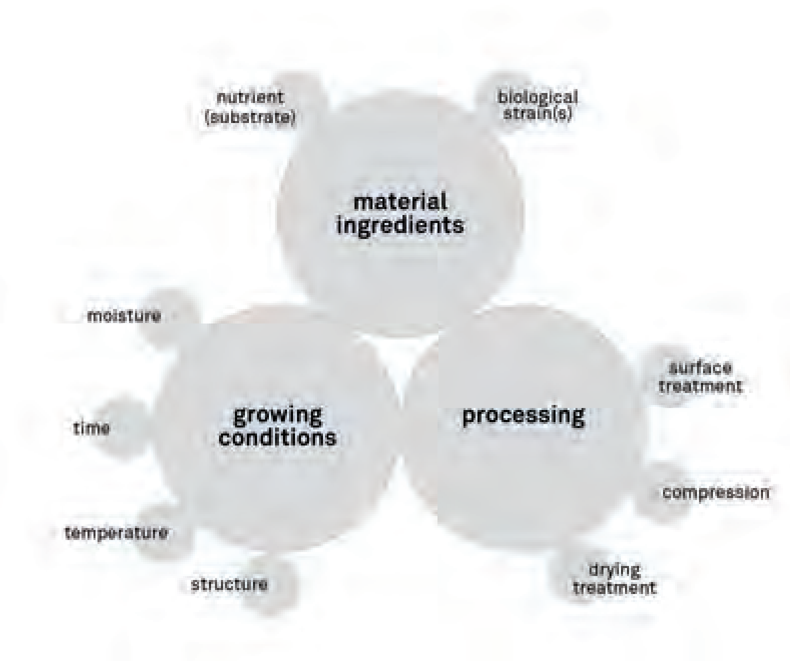

Fig 9. The variables designers can manipulate in Growing Design, to affect the final result in material qualities (adapted from Blauwhoff, 2016).

Conclusions

This paper contributes to a fundamental definition of an emerging material design practice: Growing Design, which involves fabricating materials from living organisms. We positioned this practice among other related approaches at the intersection of biology and design. Through this taxonomy, we identified six traits that manifestly characterize this emerging material practice, such as its roots in crafting and Do-it-yourself practices. Furthermore, expanding on the three classes of Growing Materials derived from fungi, bacteria and algae and presenting two design examples for each, we achieved an understanding of how these materials are fabricated. The subsequent discussion elucidates the unique opportunities of Growing Materials, such as the possibility to grow them directly into a shape (the grow-ability) and their growing time. In the near future, this emerging material practice will be confronted with challenges such as upscaling the fabrication methods to meet the requirements of industrial manufacturing. We see the necessity to understand the materials grown from microorganisms in a more systematic manner, both from the technical and the experiential perspective. As these materials are very novel to product design, there is limited knowledge on their technical properties and mechanical performances. Likewise, how people receive these materials hasn't been explored to date. Failing to explore the experiential properties of Growing Materials could engender a connotation with unfavorable aesthetic and cognitive associations (Karana, 2009). Instead, we see the potential in Growing Materials not just in acting as a surrogate to others (Rognoli et al., 2015), but also to be identified by their own, unique characteristics that can be expressed and embedded in appropriate designs. In this sense, understanding the growing materials from a technical and experiential perspective can be a true asset to the future development of Growing Design. In the upcoming project 'Mycelium-based materials for product design' (STW-project nr. 14572), we will be targeting this research agenda and the further development of mycelium-based materials for product design.

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