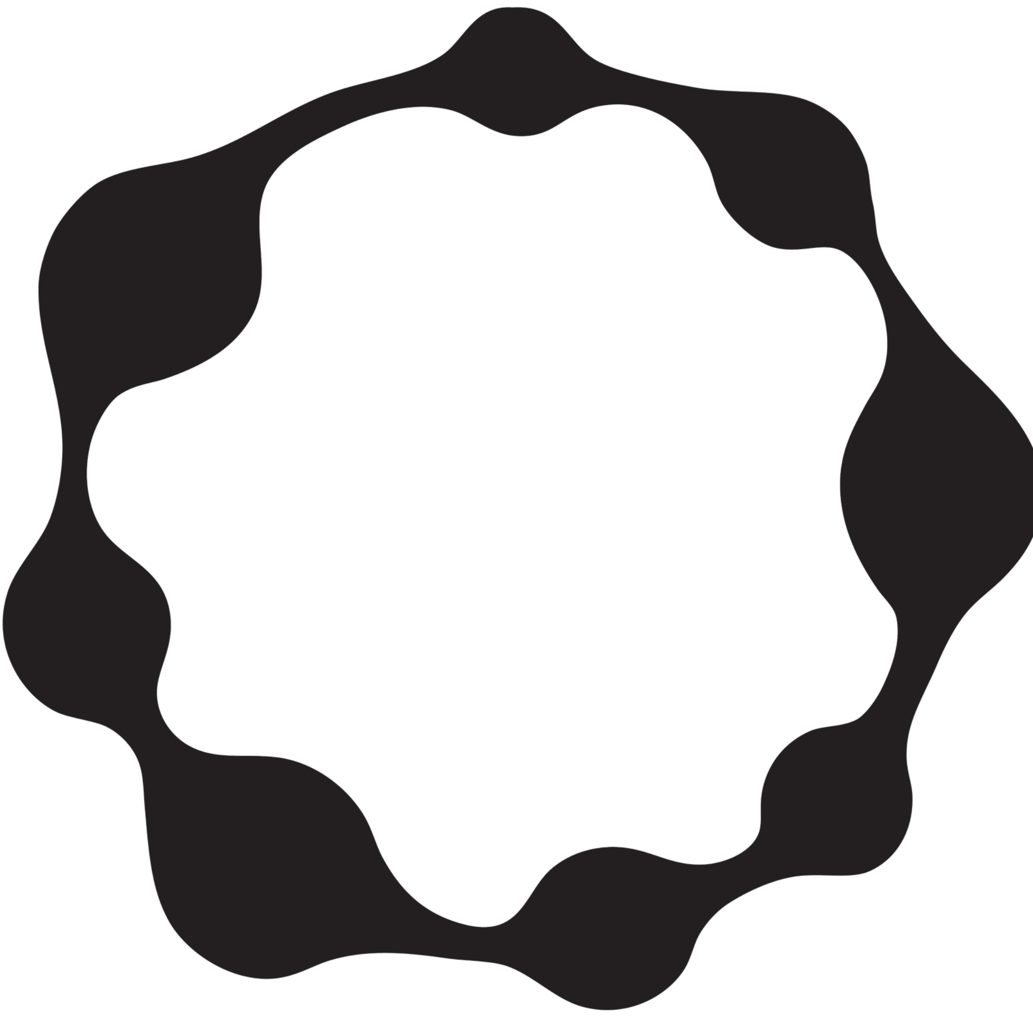
Evolving matter

The future of materials and design in the biofabrication era

Lorena Trebbi



D.I. FrancoAngeli
DESIGN INTERNATIONAL

The Design International series was launched in 2017 as a place for cultural exchange between the different design souls. Over the years, the series has consolidated its position as a point of reference for international research, outlining a continuously updated research map.
The Scientific Committee, consisting of experts in fashion, interiors, graphics, communication, product, service, social interaction, innovation and emotional design guarantees the level of the accepted texts. The Editorial Board, consisting of young experts in the different branches of design, supports the work of the scientific committee. After an initial evaluation by the two committees, the texts undergo international double revision.

Evolving matter

The future of materials and design in the biofabrication era

Lorena Trebbi

D.I. FrancoAngeli
DESIGN INTERNATIONAL

Book published with funding from the Department of Planning, Design, and Technology of Architecture of Sapienza University of Rome.

Cover image: Evolving Matter logo. Regenerative process of circular matter which goes through birth, growth, death and rebirth in an infinite cyclical loop

Isbn e-book: 9788835158738

To find out any information about books and journals published by FrancoAngeli, please join us on the World Wide Web at www.francoangeli.it

Index

Introduction	p.	7
Part I – Future perspectives		
1. Symbiosis: from parasitism to mutualism	»	11
1.1. Ecology and design: first steps	»	11
1.2. Focus shift: from product to material	»	12
1.3. New paradigms: re-thinking the system	»	14
2. Future materiality	»	16
2.1. Materials and design	»	16
2.2. A material revolution	»	20
2.3. Artificial nature, natural artifice	»	21
2.4. Born, grow, die, reborn	»	26
3. Future designers	»	35
3.1. The evolving role of designer	»	35
3.2. Bioneers and D.I.Y.: material labs and bio-makers	»	39
3.3. Design in lab	»	42
3.4. The design of nature: biodesign and ethics	»	45
3.5. Ethics and aesthetics	»	48
3.6. Designing *with* the world	»	53
4. Future factories	»	55
4.1. A new relationship with resources and processes	»	55
4.2. Waste streams	»	58
4.3. Living factories	»	60

Part II – Hands-on

5. How to design with nature	p.	67
5.1. Experience, action, reflection	»	67
5.2. Material experiments: methodology	»	70
6. Fermentation: design with living systems	»	75
6.1. Fermentation	»	75
6.2. Sensory exploration	»	78
6.3. Application scenario	»	120
6.4. Diffuse micro-factory: distributed production system	»	141
7. Microscope and Macroscope	»	150
7.1. Making is thinking	»	150
7.2. A cultural revolution	»	152
References	»	155
Acknowledgements	»	161

Introduction

The current environmental crisis, consequence of the broken relationship we established with the planet, prompts the question: what sort of future awaits us if we are able to escape extinction? Which materials, artifacts, resources and systems will populate the planet in fifty years?

Biofabrication is offering us an opportunity to radically change the way we interact with the Earth ecosystem, and designers are urged to take action and play their part. The dynamic exchange between design and science has proved particularly fruitful, leading us to understand the functioning of Nature – of which we are an integral part and not something separated from – and learn how to adapt to the cyclical nature of its metabolism rather than try to stand against it, by replacing the idea of progress with the one of evolution – adaptive and variable according to context.

The designer – which always acted as mediator between research and society – is now aware of playing a crucial role. The impact design has on everyday life behaviours, determines on the large scale our collective behaviour as society and designers must exercise such ability consciously as opposed to what has been done so far, characterising design as an activity not anymore in service of the market but rather in service of the planet. We should grasp the technological opportunities provided by biofabrication, in order to re-think the world we inhabit starting from matter and processes through which we shape it. We should not just search for circular materials, nor focus on individual and partial points of views. We need to shift our scope of *refl-action* from micro to macro, expanding such technological revolution to the cultural sphere and pushing our material culture towards radical and systemic changes.

The book is meant to offer an overview of the revolutions that biotechnological innovations have been triggering over the last decades from the perspective of materials, designers and industry, providing at the same time a comprehensive and holistic approach to biofabrication and material design through which moving beyond the paradigms of industrial revolution and radically redesign our production-distribution-consumption systems in a perspective based on collaboration and symbiosis with other life forms and circularity of local metabolic flows.

Part I
Future perspectives

The future is not a predefined destination, a separate space or time

The future is a multiplicity of ideas, critiques and potentialities that are embedded in the narratives, objects and practices of our daily lives

In this sense, multiple, often conflicting, futures are always already here as part of a continuously unfolding present and past

M. G. Kjaersgaard, J. Halse, R. C. Smith, K. T. Vangkilde, T. Binder & T. Otto

1. Symbiosis: from parasitism to mutualism

1.1. Ecology and design: first steps

Within the design culture, the first environmental considerations were made by Victor Papanek who highlighted the huge social and environmental impact of design, and then its moral and social responsibilities. He stated that "the designer is powerful enough to put murder on a mass production basis" (Papanek, 1971)[1]. The design of each single product indeed, has consequences on a wide scale, which go from the environmental ones related to life-cycle, resources and disposal, up to the social ones such as determining the working conditions of the people who are going to produce that product.

History teaches us that designers, engineers and producers have often employed harmful or toxic materials in architecture and design projects with no concern of their effects, spreading them globally. That's what happened with asbestos for construction purposes, lead for printing inks or pencils, and is still happening today with the employment of plastics for disposable products, which are accumulating, breaking apart and contaminating soil and waters worldwide. In practice, however, the disruptive approach proposed by Papanek was not actually applied in the design practices. The first steps in that direction were made with green design but were focused on the single product rather than on the overall design approach. Green design tried to decrease the environmental impact through punctual

[1] The design of a product determines several aspects which go far beyond the scope of its use such as the way it is produced and therefore the kind of factory, where this factory is located (with consequences on the urban environment), where and how the factory workers live (with consequences on housing and society). But its influence is not limited to the production stage, affecting through the objects that we use our behaviour and our interaction with the environment, hence the great social and moral responsibilities of designers.

interventions on the individual features of each single artefact. It was followed by the reuse-reduce-recycle paradigm, aimed at reducing the amount of material used, facilitating the disassembly and reusing elements of discarded products to make new ones, as well as at employing recycled or recyclable materials. Later, in the second half of the 90s, such approach was broadened to address the entire product life cycle, from resource extraction to product disposal. Therefore, with a life-cycle approach green design evolved into ecodesign, supported by life-cycle assessment (LCA) methods which allowed the quantification of environmental impacts from a technical perspective, but still with limited attention to the human-related aspects. Between late 1990s and early 2000s design researchers started to look at nature as a source of inspiration to address sustainability, with a greater focus on processes and productive systems rather than on single products. It is the case of biomimicry (Benyus, 1997), through which transfer the efficiency of nature's solutions to the human-made world, looking at nature as a model and ecological standard to which to refer.

Starting from this concept, the Cradle-to-Cradle approach (Braungart & Mc Donough, 2002), puts the focus on the flows of material and resources, suggesting a regenerative approach for the industrial model as opposed to the exhaustive one that we developed so far. In each of these approaches, all the social aspects related to the use of products are completely disregarded, despite the user-product relationship can influence many aspects such as energy consumption or durability. Therefore, new approaches emerged, as the emotionally durable design, to overcome the psychological obsolescence and allow the user to create an emotional bond with the product; or the design for sustainable behaviour, in order to intervene on the way users interact with the product through affordances and constraints. And yet, also in these cases the intervention was limited to the dimensional scale of product innovation, a necessary but not sufficient condition to introduce radical and far-reaching changes, offering once again "symptomatic" solutions unable to tackle the deeper roots of the problem. From the late 90s then, designers started to move towards wider approaches taking into account the interconnection among environmental, social and economic systems, as in the case of product service systems (Thackara, 2005; Ceschin & Gaziulusoy, 2016), and design for social innovation (Manzini, 2015).

1.2. Focus shift: from product to material

With the evolution of the idea of sustainability in the design culture, we witnessed a shift from punctual interventions on single products to a systemic approach, through which look at interconnections, and conceive each product as part of a system, node in a network of interactions (Myers, 2012; Antonelli, 2008). Acting just on the social impact of design, as well as on products' life-cycle, proved to be ineffective in facing the complexity of today's global issues, as long as there is no intervention on the actual matter with which we design, and so on the nutrients flow among the open systems constituting our planet.

Such partial approaches are simply aimed at damage control, while the fundamental goal – in order to expand the equilibrium condition of natural ecosystems to human production systems – is to manage to give back the nutrients subtracted from the environmental system into a usable form. For this reason, the attention of designers has shifted from design for sustainability to sustainable materials, thus highlighting the centrality of the materials we use. Designers indeed have the opportunity to change processes behind products, and resources used to fabricate them, addressing the issue at greater length. To face environmental issues superficially, without fully understanding the effects of our choices, can be worse than doing nothing (Braungart & McDonough, 2002). A recycled material for instance, is not automatically "good" from the environmental point of view: recycling is often sub-cycling – just think of plastics, paper, and some metals – and it requires high impact chemical processes, as well as the employment of harmful contaminants. Therefore, designers started to research bio-based materials as an alternative to fossil-based ones, drawing the attention on biopolymers. Biopolymers or bioplastics, are materials derived from renewable biological sources such as plants, bacteria and algae. Unlike traditional plastics, they can be degraded by microorganisms present in the soil without any release of pollutants. These materials are not something new, but no-one gave them much attention in the first place since oil and its derivatives were cheaper and easily available. Only during the 1970s, with the oil crisis, people started to deepen the research on alternatives sources for polymer production. The first bioplastic was the Parkesine, trade name for a plastic made from cellulose, created in 1862 by the British chemist Alexander Parkes. In 1897 in Germany the Galalite was invented, a material made from casein, the milk protein, and treated with formaldehyde. In 1912 Cellophane was invented and patented, a transparent sheet made from cellulose and treated with chemicals and plasticisers to make it waterproof. In 1926, from his work with the bacterium Bacillus megaterium, the French researcher Maurice Lemoigne discovered polyhydroxybutyrate (PHB), the first bioplastic made by bacteria. Even Henry Ford experimented with bio-based materials: in 1941 realised the "soybean car", made of tubular steel and panels of a composite material made from soybeans, hemp, flax and ramie. However, the outbreak of World War II suspended all automobiles production, including the soybean car experiment. Between 1950s and 1960s experiments on bacterial biopolymers were revived for the production on the industrial scale of Polyhydroxyalkanoates (PHA) and PHB. In the 1980s, after the oil crisis of the previous decade, the first bioplastic companies were set up, and in the 1990s the first biopolymers from plant sources were developed, extracting starches from agricultural crops, as in the case of polylactic acid (PLA). For several years therefore, organic raw matter has been employed as a new resource, though often manufactured with chemical processes and additives which turned it into something different. Contamination and nutrients' waste however, is an even greater problem than the amount of waste produced. Mixing together "technical" and organic materials means that none of them could be retrieved at the products' end of life, giving rise to the so-called "monstrous hybrids" (Braungart & McDonough, 2002). In this way we keep on consuming the available resources in a linear way, according to the take-make-dispose paradigm. On the contrary, the natural world operates through circular loops based on the equivalence "waste equals food" (Braungart & McDonough, 2002), using rather than consuming the resources available.

Moreover, the impact of the overall material life-cycle has to be properly taken into consideration. Bioplastics production for example, often resulted in greater amounts of pollutants, due to the fertilisers and pesticides used for crops and the chemical processing required for their transformation. Hence in recent years, designers started to look at new sources for the production of biopolymers, replacing plants with algae: abundant, available worldwide, fast-growing, requiring way much less land and water than terrestrial plants.

1.3. New paradigms: re-thinking the system

The many approaches described in the previous chapters have as common point the tendency to isolate one of the many aspects of the same issue, facing them as something separate from each other – technical aspects related to environmental impact, social aspects related to consumption behaviours, procedural aspects related to production systems. This is no longer enough, and we need to introduce structural changes in our production and consumption systems, abandoning end-of-pipe and damage limitation solutions in favour of a systemic and holistic approach.

Usually, any kind of material innovation makes its way in our human-made world according to two stages: in the first place it spreads through imitation of materials currently in use, modifying the existing system as little as possible; subsequently instead, the whole system is redefined in the light of the aforesaid innovation (Manzini, 1986). That's what is happening with bio-based and living materials, which today are paving the way for a whole industrial revolution. Designers are returning to nature to source materials, not as throwback to a non-technological era, but recoding and decoding their structures to push their properties toward augmented applications and aesthetics (Lipps, 2019).

The majority of industrial materials and methods are damaging, although unintentionally. The global linear industrial system exerts an "intergenerational remote tyranny" on future generations, through the effects of actions we implement today, and operating within the same exact system which is cause of the problem, according to the eco-efficiency concept, is limited to just slow it down (Braungart & McDonough, 2002). Damage control, as for example turning factories' fumes wither or labelling a material as "more sustainable", can be extremely dangerous since it makes the negative consequences less visible and then more acceptable. As stated in a famous Einstein's quote we need a brand-new way of thinking in order to solve problems caused by the old way of thinking.

Symbiosis with Earth as our habitat is what allowed humanity to evolve. In biology Symbiosis is defined as a close relationship between two species in which at least one species benefits. There are different kind of symbiosis: Mutualism is a symbiotic relationship in which both species benefit; Commensalism is a relationship in which one species benefits while the other species is not affected; and Parasitism is a kind of symbiosis in which one species (the parasite) benefits while the other species (the host) is harmed. Currently our relationship with the planet is a parasitic one and shifting to a mutualistic symbiosis entails a radical change of perspective, impossible to achieve through incremental changes. For a long time, humans have embraced the dog-eat-dog culture, according to which only the strongest, the biggest, the most efficient and even the meanest survive, a culture based on the idea of competition and dominion. Such cultural framework over the centuries has declined in different ideologies and social phenomena such as racism, colonialism, capitalism, patriarchy and last but not least speciesism, which represent only the variety of forms that the same core values can take – the common denominator is always the same: command and crush otherness. In nature however, the one who survives and thrives is who is able to adapt rather than who prevails over the other. Adaptation entails a relationship of interdependence between living beings, energy and materials of the place they inhabit (Braungart & McDonough, 2002). Interdependence, opposed to independence, is a systemic concept resulting from the permeability between open systems and the environment (Minati, 1998). Therefore, in order to pursue a new mutualistic relationship between us humans and the planet, we have to learn how to operate within the context in harmony with it, and not despite nor against it.

2. Future materiality

2.1. Materials and design

The Design Process has always been the result of the interaction between ideas and matter (Manizni, 1991), intentions and choices of designers, and the functioning of the systems they are part of. Schön[1], defines Design as a "reflective conversation with the materials of a situation" (1992). Any artefact produced by humankind then, can be seen as the materialisation of what Manzini defines "thinkable-possible" (1986), intersection between what can be imagined – and it's therefore related to the cultural sphere – and what is made possible by the techno-scientific development.

Design has always been a discipline based on a hands-on approach, nonetheless at some point it turned away from materiality, creating a separation between mind and hand. The digital revolution and the consequent digitalisation process that hit our society in the last century, was indeed accompanied by the idea of dematerialisation of the outside world, reduced to surfaces that convey messages. In practice, however, despite the forecast of a virtual immaterial world, our reality is characterised by an increasingly hulking and constantly expanding materiality, which rapidly turns into piles of waste (Maldonado, 2003). At the same time, we are immersed within the material world and also part of it. We live in a multi-sensory reality, made of things that we can touch, smell, see, hear and taste. Materials represent the building blocks of such reality, basic elements each equipped with a specific set of sensory attributes that interact with light, air and people around it (Schifferstein & Wastiels, 2014).

[1] Donald Schön was a philosopher and professor in urban planning at MIT who introduced the concept of reflective practice in 1983, distinguishing between two kinds of reflection: reflection in action (thinking while acting) and reflection on action (retrospective contemplation of the action).

The post-digital era then, has been characterised by a return to matter, to physicality of objects, tactility and craft, "returning design to his haptic origins" (Gerritzen & Lovink, 2019). What is left as positive legacy of such transition is that with design thinking design expands its range, looking not only to products but also to processes and systems, becoming a "way to work, live and think" (Gerritzen & Lovink, 2019), a way to produce and consume, and a way to determine the kind of relationship we establish with the outside world. Through design we can explore materiality other than materials, looking at them for their social significance as meaningful and implicated in social acts, able to deeply affect human thought and behaviour, enabling and empowering people's lives as well as constraining them (Tilley, 2007). Materials then, are not a blank slate or tabula rasa, available to be freely and passively shaped, but they have a specific identity, an "hidden character" (Ashby, 2014), and act as collaborators (Rosner, 2012) in the design process, according to this character. Over the years, materials have shifted from being given entities upstream of the project, to being themselves something to be designed, generating innovation and changing the way we think and produce objects (Doveil, 1991). The evolving relationship between materials and design, gave rise to a dynamic process of socio-technological innovation (Lucibello, 2018), where science, design research and new craft are blended together.

2.1.1. Hyper-selection and material libraries

Originally the designer was an expert of materials and production techniques, and materials were something to select from a pre-existing palette. The knowledge of designers was then built through the experiential approach of learning-by-doing, not a passive education based on superficial factual knowledge, but an active elaboration of ideas which locates in the experience the starting point for knowledge building (Dewey, 1938). The Bauhaus school was structured around this approach, placing the laboratories at the very core of the teaching activities, juxtaposing the study of materials and processes alongside the study of shape. Experimentation on materials for design is rooted in particular in the textile design laboratory by Annie Albers, and her research on the organoleptic and expressive qualities of textiles, which represent the first attempt to build a new matter, beyond chemistry and controlled by the designer (Branzi, 2004).

Subsequently, the acceleration undergone by the techno-scientific innovation, resulted in the proliferation of new materials. Besides traditional materials such as wood, metal and plastic, the material world expanded into a universe made of many subcategories constantly and rapidly updating, developing new hybrid materials, and determining a condition of hyper-choice (Lucibello, 2009). The hyper-choice, though, implied the rise of a knowledge gap with regard to materials, since the amount of information became so huge that couldn't be adequately handled by designers. Abstract knowledge of materials then became the only way, turning the design process into an activity that is mostly carried out sitting behind a computer or at a drawing table. In an effort to shorten this knowledge gap, in 1997 G. Beylerian founded Material ConneXion in New York, the first material library, a physical and virtual place where materials' samples and information relating thereto are collected. In the following years, many other material libraries popped-up all over the world, becoming an essential tool for designers, acting as material archives as well as consultancy services. These databases connect the companies who produce and manufacture materials with designers who apply and use them. In this way, it is possible to acquire a lot of information with no need to reach each company individually, creating a network among different fields of production.

The materials in the availability of the libraries are categorised following different criteria, involving technical and performance features as well as sensory and perceptual ones, but also ecological requirements. However, any categorisation is always incomplete, since with the multiplication of possibilities and materials becomes more and more difficult to divide them into rigid categories. One way or another categories overlap, material families no longer exist and an objective and universally valid classification criterion is impossible to determine.

Material libraries have therefore become a quick and widespread means of communication of information about materials, helping designers in the acquisition of knowledge about the latest material innovations. Increased knowledge however, doesn't mean facilitating the selection of the right material for the project. This tool provides fundamental information which would otherwise be unreachable, but this is not enough to completely replace the experiential dimension. Compared with the past indeed, there is a loss of the ability to manage materials and processes, and to be their "inventor" or manufacturer (Lefteri, 2009). Above all, this tendency underlined a design approach where the project is something abstract, untied from the material it is made of, which, in turn, is something selected from a range of options because more appropriate, performative or economically viable. Data of designers, though, come in the form of senses (Lee & Bongaerts, 2019), we experience a multisensory reality where the overall perception is not a mere sum of each sensory stimulation, but is given by the interaction among them. In the attempt to translate the perception of a material into a list of characteristics – which becomes alongside pictures the only form of interaction – we lose the overall view and miss the opportunity to grasp all the intangible aspects related to meanings and emotions, which originate from sensory interaction.

2.1.2. Materials as input of invention

In the last few years are emerging new approaches to materials and design, both in teaching and in the design practice, with a shift from mere selection to direct experimentation (Trebbi, 2018). Materials become input of the creative process, with a transition from selecting materials for the project to designing with materials, overturning the traditional and linear design process based on problem solving – which starts from a need to transform it into a product (Lucibello & Trebbi, 2018). The experiential approach instead, starts from the observation of materials, their physical exploration, tinkering and manipulation, in order to kick-start the creative process and begin the experimentation. This allows to carry on a sensory and perceptual investigation, through which integrating the technical-productive features together with the aesthetic-perceptual ones, vehicle of sensory and immaterial aspects which significantly contribute to the overall quality of the product. The centrality of the material as design input is the basis of the Design with Materials approach (Lucibello, 2018), as well as of the Material Driven Design approach (Karana, et al., 2015), which considers the material not only for what it is, but also for what it does, what expresses, what elicits to us, and what makes us do, thus designing in the light of the so called Material Experience (Karana, et al., 2014).

The involvement and interaction with the material plays a significant role in the cognitive process, and the manual activity represents a tool through which "logically thinking through senses" (Nimkurlat, 2010), understand and learn through experience, and deepen the relationship between material, shape and process through a practical investigation. Such cognitive process is what the psychologist Edward de Bono defines lateral thinking (1967): the perceptual part of thinking which allows us to organise the external world into pieces that we can then "process". The human brain indeed, works by learning and then "locking" subconscious behaviour and thought patterns, in order to let the conscious brain focus on something else. This can result in getting stuck between certain boundaries or perspectives that we can bypass through creativity, looking at the same issue from a different and unusual angle. The experiential knowledge of the material then, allows the designer to overcome the gap between theory and practice, understand and interact with production processes, experiment with perceptual features and imagine new applications. Through material exploration, opposed to analytical knowledge, invention can arise. An example is the "Up" seats family produced since 1969, developed by Gaetano Pesce exploiting the distinctive features of polyurethane. The inspiration arose right through the observation of the qualities of a shower sponge that, like the polyurethane seats packed in vacuum bags, could be compressed and then return to its original volume when released (Martin, 2017).

Starting from the material exploration, the experiential approach goes up to the design of materials themselves (Lucibello, 2018), with DIY (Do It Yourself) and self-production practices implemented by designers. Such practices highlight the importance of the contribution provided by emotions – generated within the material's creation process – in inspiring the design process, unlike what happens when the material is selected from a pre-existing palette (Rognoli, Ayala Garcia & Parisi, 2016). The experiential approach allows designers to investigate through practice, gaining a transformational knowledge rather than a merely documentational one (Ingold, 2013; Groth et al., 2019). Design then, does not simply intervene in the final stages of the project, but can step in from the very early stages and act on processes, resource management, lifecycle, as well as on the semantic and emotional side of products.

2.2. A material revolution

Today, with biofabrication, we are witnessing a new material revolution which is paving the way for the next industrial revolution. The matter we relate to as designers becomes alive, marking a radical turning point for the objects populating our world as well as the way we produce and consume them.

Biofabrication – literally fabricating with biology – is a technology that found application in the first place in the field of regenerative medicine and tissue engineering with the goal of growing replacement parts for the human body. It is usually defined as the production of complex biologic products from raw materials such as living cells, matrices, biomaterials, and molecules. In the first place, it started as bioassembly, automated assembly of cells containing building blocks. Thereafter, this rapidly evolving technology has been influenced by the development of 3D printing technologies, giving rise to bioprinting, which allows direct cell deposition in organotypic architecture. Examples of application in the biomedical field are the fabrication of myocardial tissue through alginate extrusion-based bioprinting, as well as skin biofabrication through jetting-based bioprinting of collagen (Seol et al., 2014). Another important application in the biomedical field is tissue engineering from plants. Andrew Pelling from University of Ottawa, has grown human ears from apples: through removing plant cells from leaves, it is possible to obtain a cellulose structure which acts as a scaffold for the growth of human cells, creating apple slices shaped as human ears. Following the same process, a multidisciplinary research team from Worcester Polytechnic Institute, used spinach leaves to rebuild heart muscle tissue, with the leaf branches acting as blood vessels.

Biofabrication is today expanding and evolving, giving rise to new researches involving different fields and disciplines, from synthetic biology to food sciences, from fashion to product design. The tissue engineering techniques of regenerative medicine have indeed found new applications. One of the most disruptive examples is the production of lab-grown cultured meat, obtained by harvesting muscle cells from living animals and multiplying them in order to create tissues. In this way, besides the relevant ethical aspects, is possible to drastically reduce the space used, emissions and environmental impact of industrial livestock farming, which is today responsible for 7.1 Gigatonnes of CO_2-equiv per year, representing 14.5 percent of all anthropogenic GHG emissions (FAO, 2013).

In 2015, the design researcher Amy Congdon with her speculative project "Biological Atelier" showed how tissue engineering could be used to grow biological textiles for the fashion industry, using textiles as a scaffold for cell growth. Not long thereafter, in 2017, Modern Meadow – a US company led by the British fashion designer Suzanne Lee – launched Zoa, the first ever lab-grown leather. Yeasts are genetically engineered to produce collagen instead of alcohol during fermentation. In this way, the team harnesses living organisms to manufacture new materials, which, freed from the animal form, can assume any shape or thickness. Biofabrication then, has today transcended the boundaries of the biomedical field, and is seeping into the world of materials with the potential of affecting many aspects of our everyday life, marking the birth of Biodesign.

2.3. Artificial nature, natural artifice

The relationship between science, nature and design is an ancient phenomenon constantly evolving, rooted way back in the past as of the Vitruvian search for harmony. The more the comprehension of the surrounding world grows, thanks to advances in science, the more the solutions of the artificial world get closer to the ones of the natural world. Talking about the techno-scientific evolution of humanity, which is reflected in the materials we use, Ezio Manzini pinpoints three main stages (1986): suffered complexity materials, such as the first materials used, like stone, wood and the first metals; controlled complexity materials, made available through the development of processes able to produce homogeneous and isotropic materials equipped with specific properties; and finally managed complexity materials, where the manipulation goes deep into the structure of matter, and anisotropies and impurities can be produced in order to get specific performances. Looking at the evolution of materials, as well as at the relationship between humans and matter, we can see a tendency to develop and imagine increasingly complex materials, characterised by behaviours more than performances, and by a high amount of data, so materials increasingly similar to biological organisms (Langella, 2003).

The boundary which for long time separated Nature and Artifice, is actually a cultural construct. This boundary today is dissolving with the growing awareness that we are nature. It is no longer "humans versus nature", but "humanity as integral part of nature with each mutually affecting the other" (Mc Quaid, 2019). Going back in time, we can find this concept since ancient Greek philosophy with Plotinus, which stated that "all is One", and the universe in its countless multiplicities always carries in itself the whole. Therefore today, we have to make an effort to always recognise "the whole in the part" (Minati, 1998). It is indeed impossible to still look at humans as something outside of nature, when the 95% of birds and mammals on the planet are humans or livestock exploited to feed or clothe them; half of the world's habitable land is used for agriculture, the 77% of which is used for livestock and only the 23% for crops; and microplastics are invading waters worldwide reaching even the most remote places[2] (Ritchie & Roser, 2018). Agriculture itself is one of the first forms of design of nature. The work of the artist Sam Van Aken "Tree of 40 fruit", realised using grafting techniques to combine different fruit trees, represents a form of "augmented nature" (Lipps, 2019) where we can no longer distinguish between natural and artificial.

The world we inhabit must be seen as a whole, or rather as a complex system that can acquire features which don't belong to its individual parts but emerge from the interaction among them. This novel perspective is affecting many fields of knowledge and is based on the core concepts of evolution and complexity (Langella, 2003). It has its background in the scientific

[2] Microplastics are everywhere, in the sea, on glaciers and in human faeces. Recently, they have been found even in the human placenta. Moreover, it has been found that plastic micro particles can travel even through air and be transported across the globe. Recent studies have reported the finding of microplastics on Pyrenees, notoriously wild and uncontaminated areas. The particles were transported there through atmospheric phenomena and could have been travelled for 100 km.

thought of the twentieth century, starting from the work of the biologist Ludwig von Bertalanffy, father of the Systems theory (1937), which undermined the basis of sure and certain science, opening the doors to the topic of complexity. In 1963, with his Chaos theory, the mathematician Edward Lorenz identified in chaos the status of dynamic systems, a new kind of order characterised by unpredictability, but that can still be determined. All is then in relation with everything, and the modification of a single factor can bring unpredictable transformations to any other element.

2.3.1. Learning from nature

The natural world has gone through 3.8 billion years of research and development, with failures and successes, in the search for the most effective and convenient solutions. Looking at nature as a source of knowledge and inspiration, is an ancient phenomenon. In the beginning it assumed a decorative, symbolic and semantic function, as happened with Art Nouveau between the nineteenth and twentieth century. In the late 1950s the term "Bionics" was coined to describe the research of formal and geometric principles of nature for their technological transfer to human-made systems. In the following decades, Biomimicry has pushed further this relationship between nature and the human-made world, looking at nature not only as morphological reference, but as a source of new methodologies and logical principles (Langella, 2003), seeking "the logic of formation rather that the description of forms" (Legg, 2017).

In 1997, Janine Benyus deepened and disseminated this concept in her book "Biomimicry: Innovation Inspired by Nature". Nature becomes a model, source of inspiration for designs and processes; a measure, ecological standard and evaluation criterion; and a mentor, something we can learn from. Following these principles, we can act at three different levels: on products, processes, and finally systems. The 3D-printing technology represents an example of biomimicry. Nature indeed, creates biological structures through additive "manufacturing", as in the case of spider webs or silkworm's cocoons. The same goes for auxetic materials which, since having a negative Poisson ratio, expand perpendicular to the solicitation when subjected to traction, getting thicker instead of thinner. This property can be found in tendons, cat skins, mussel shells and so on, and enables high energy absorption as well as fracture resistance. The project Water Reaction by Chao Chen, starts from the study of pine cones and their ability to open and close reacting with water. This property has been transferred to an architectural laminated skin which stays open in good weather conditions, letting air and light flow inside, and closes when in contact with water preventing the rain from penetrating. The same principle has been implemented in HygroSkin Meteorosensitive Pavilion, by Achim Menges, Oliver David Krieg and Steffen Reichert, a climate-responsive architectural skin which opens and closes autonomously in response to weather changes.

Another example is the structural colouration found in butterflies' wings, peacock's feathers, bugs' exoskeleton and also Flavobacteriia. This kind of colour isn't determined by pigments but by the micro-structure of the surface which reflects light according to different angles, often resulting in iridescence. The fashion and textile designer Donna Sgrò realised in 2009 the first structurally coloured dress using Morphotex fibres, which mimic the colour of Morpho butterflies. Techno Naturology by Elaine Ng Yan Ling is a project which explores the potential of natural sensing systems like wood combined with shape memory alloy and polymers. Her collection includes responsive textiles and architectural surfaces which react to different external stimuli such as temperature, moisture or movement. Cilllia, by the Tangible Media Group of MIT Media Labs, is a 3D-printed micro-structure which mimics hair at different resolutions. In nature hair has many functions – from the more technical as insulation, adhesion or locomotion, to the more perceptual such as sensing, tactility and aesthetic – which can now be transferred to 3D-printed artefacts. With biomimicry designers work to decode nature's principles and laws. With the growing understanding they are moving from imitating to stimulating nature (Lipps, 2019), as in Alexandra Daisy Ginsberg's Resurrecting the Sublime. With this project the designer recreates the smell of extinct flowers using biotechnologies and working with stored DNA specimens, in order to learn which smell molecules the flowers may have produced when alive.

2.3.2. Collaborating with nature

In the last decade biodesign went beyond imitation of nature interacting with her as a co-worker (Collet, 2017), designing together with nature and often designing nature herself. Today, in the Anthropocene era, everything is designed, but on the flip side everything can be re-designed (Ryan, 2014). The human footprint on the planet has deeply upset the balances among ecosystems. Now we have the potential of building new ones, regenerating and remediating through what Paola Antonelli defines "restorative design", as highlighted by the XXII Milan Triennale "Broken Nature" (2019).

Restorative design can act to reconstruct biodiversity, as with the

Totomoxtle project by the Mexican designer Fernando Laposse. Using the colourful native corn husks to realise a new veneer material, he pushes for the preservation of local crops and the craft traditions related. Biodiversity preservation means also to design for other species. An example is the Monarch Sanctuary by Terraform ONE, the concept for a new commercial building in New York City. The aim is to establish a coexistence between humans, plants and butterflies, integrating monarch habitats in different parts of the building, making it a large-scale Lepidoptera terrarium. In this way it will be possible to provide a habitat for wild monarchs and increase their population through colonies, at the same time raising awareness about the decline in their population and biodiversity loss. Similarly, Bioreceptive Concrete Panels by Beckett, Cruz and Ruiz, want to encourage the growth and thrive of life, creating the enabling conditions for nature to spread. These concrete panels are designed to accommodate and support mosses, lichens and algae, organisms which absorb air pollution through photosynthesis.

Interacting symbiotically with other species, microorganisms and life forms, can result in mutual benefits such as climate control and lowering of emissions and energy used to heat and cool buildings. Another example of designing with and for life, is the bioprinting of coral structures which, mimicking the optical properties of corals, are able to grow microalgae reproducing the symbiotic relationship they have in the oceans. This project is the result of a collaboration between Cambridge University and University of California San Diego and uses printed corals as incubators for algae cells, which can in this way grow at much higher rates if compared to standard growing mediums.

Design is one of the human activities more loaded with consequences, shaping behaviours that affect any aspect of life (Antonelli, 2019). Starting as an activity in service of the market, it moved gradually to a human-centred approach, in the pursuit of the progress of society rather than technology. However, human-centred or user-centred design reflects a totally anthropocentric perspective which today appears obsolete. If it is able to shift from an egocentric to an allocentric mindset, moving humans from the centre to the edges (Caffo, 2017), design can become a repair tool instead of a tool for destruction.

We need to implement interspecies collaborations, connect and empathise; shifting our attention from short-term individual interests, to a collective, systemic and long-term approach (Wilson, 1999). This of course doesn't mean that design is the ultimate panacea, the solution to every problem. Means instead that we can reframe our priorities and choose the future we want for ourselves and the planet (Mc Quaid, 2019). We should ask ourselves which idea of "better future" we are chasing, and who would benefit from it. If we learn to look wider, long-range and long-term, we can easily understand that what is better for humans is what is better for other species and nature as a whole. In order to establish an equilibrium condition between the many terrestrial ecosystems, we have to design for a harmonious development, substituting the linear concept of growth with the rhizomatic concept of evolution. Within the system theory, the concept of harmonious development is related to harmony among all growth processes, assuming as a necessary condition that none of them has constantly zero nor negative value (Minati, 1998). In this blend between biosphere and technosphere the materials, resources, processes and technologies that we are facing belong to the natural world and are subject to its laws. The matter of the project becomes alive, and as designers we have to learn to interact with it in a new unprecedented way.

2.4. Born, grow, die, reborn

Despite the numerous theories which have been highlighting the interconnection between ecology and design for many years now, within the design practice such issues have been neglected for long, remaining good intentions never applied and well away from reality. Therefore, decades of environmental crisis have followed, which led to new awareness – starting with the concept of limit and development in a limited world – and gave rise to countless novel environmental issues to face. It is the case of plastics and micro-plastic pollution, fossil-based disposable products, planned obsolescence and electronic waste, synthetic dyes and the release of harmful chemicals in the environment as well as on our body, just to mention some. This gave birth to a new chapter of design history, as well as to a new generation of designers who is reinventing its practice with disruptive and radical approaches and who, through the focus on materials and processes and the embrace of the "different states of temporality" of materials (Agapakis et al., 2020), is paving the way for a future characterised by alternative systems of production-consumption.

Once discarded the idea that the world is a mine at our disposal from which freely extract resources to the bitter end, we can turn our gaze elsewhere, towards new materials and resources in the pursuit of an "alternative abundance" (Franklin & Till, 2019): looking at waste from current production processes as valuable resource, exploring new kinds of farming with algae cultivation, and acting collaborations with microorganisms to grow organic materials and dyes. The principle is to understand and adapt to the functioning of the natural world we are part of and therefore implement circular and cyclical processes in order to establish symbiotic relationships between social and environmental systems. Eliminating the idea of waste according to nature's law "waste equals food" (Braungart & McDonough, 2002), means to ensure that materials at the end of their lifecycle do not represent anymore something troubling which has to be disposed of, but they can instead be directly returned to the ecosystem as new resource. The time dimension becomes then a predominant element and materials are designed according to their life-cycle, taking into account the "internal clock" of matter (Langella, 2003). We need to understand the "timing" of the planetary ecosystem and adapt to its velocity and cycle duration. With biofabrication substances are transformed into new matter, which relatively rapidly transforms again into something else with biodegradation. Non-biodegradable materials however, die and transform anyway, but in a much longer timeframe and often releasing harmful pollutants into the environment. Looking at the future of materials, we can thus observe two main tendencies very often intertwined with each other: the reconsideration of what was once waste as valuable raw material, and the collaboration with microorganisms in order to grow matter that can be harvested, or to be used as living system as a whole. The most disruptive feature is that such "future" materials are not eternal, flawless, static or unchanging but alive: they are born, grow and die as any other organism on the planet including us humans, in a continuous cycle that is repeated again and again.

2.4.1. Waste

Within the current industrial system there is a huge amount of waste generated through the various stages of each production process. Starting from agriculture, where usually only the most precious part of the plant is used while the rest becomes biomass which is fermented or chemically treated to produce fuels and electricity, burned to produce thermal energy, or used as food source for livestock farming. Even the following stages of food processing produce many kinds of organic waste such as peels, shells, fibres or wastewater.

The designer Tamara Orjola, with her project "Forest Pine Wool", researched the potential use of waste from wood processing. Usually indeed in the wood industry billions of pine needles go unused, while with different manufacturing techniques such as crushing, soaking, steaming, carding, binding and pressing, they can be transformed into paper and textiles, extracting at the same time essential oils and dyes. "Cornspan" is a material developed by Apilada Vorachart starting from his research on the atmospheric haze effect in Chiang Mai province, Thailand, caused by the burning of agricultural corn husks and cobs after the harvest. The designer uses corn husk fibres to manufacture panels for sound and thermal insulation that can be used in local construction. Also waste from the zootechnical sector can be turned into a valuable material: Merdacotta by Locatelli and Cipelletti is a material made from cow dung, processed to create a clay composite used to produce tiles, pots and tableware, giving new life to a material amongst the poorest. The manufacturing industry produces a wide range of waste streams besides organic waste, including offcuts of leather and textiles, glass and clay scraps, stone dust, etc. Sophie Rowley experimented with different kinds of common waste within her project “Material Illusions”, turning them into objects and furniture with entirely new aesthetics. An example is the reuse of denim offcuts layered into rigid elements in a way that recalls the natural processes of earth stratification and erosion. With a similar process, leather industry leftovers are used by Barbora Veselá to create a pattern based on rock formations on the surface of her “Geology of Shoes” footwear. Jorge Penadès instead, mixes together shredded leather and natural bone glue to create furniture with marble-like patterns.

Waste however, shouldn’t be intended just as the leftovers resulting from industrial processes, but also as what we produce in the everyday life within the urban environment, both on the wide scale of the city and on the small scale of household waste. The “RE-source” research project, by Ester van de Wiel, Joost Adriaanse, David Hamers and Ginette Verstraete, maps out flows of residual urban materials in the city of Rotterdam, NL, in order to develop strategies that show how design interventions in public spaces can reframe residual materials into resources which can be used again and again. The same principle is at the base of the “REFLOW” project, focused on development of constructive metabolic processes for material flows to implement circular economy city models, involving different pilot cities in urban and periurban environments across Europe. The “Precious Plastic” project by Dave Hakkens is a combination of people, machines, platforms and knowledge aimed at creating an alternative global recycling system. Through collection points citizens and local businesses can gather plastic waste, which is then transformed into new products using different machines. The project is open-source and can be implemented everywhere through starter kits, in order to create a worldwide network to connect all the local realities in a global community. The centrality of people and the social side of environmental issues is at the core of “ReMade in Sanità”, a project which combines technology, social innovation and ecology. Founded in Sanità district in the city of Naples, IT, defined a suburb in the hearth of the town, it wants to offer an alternative waste management model through virtuous small recycling plants able to turn urban plastic waste and metals derived from e-waste into new products, increasing at the same time people’s sensitivity on such issues. Moving on a smaller scale, in 2011 Philips presented the "Microbial Home": a set of tools and furniture elements through which turning the home into a biological machine able to convert waste into power, provide lighting and preserve food in unconventional ways, creating a cyclical ecosystem comprising different domestic areas and activities.

A material with a great potential for new applications is human hair, an abundant and renewable resource that has always been seen as waste. Studio Swine created "Hair Highway", a collection of accessories – combs, decorative boxes, furniture – made infusing hair into natural resin. Tomas Vailly, within his graduation project "the Metabolic Factory" turned human hair into a new leather-like biomaterial melting it with sodium sulphite and glycerine. With the project "The colour of Hair" instead, Fabio Hendry and Martijn Rigters used hair to develop an innovative printing technique which turns it into an ink to be used on a variety of metals. Since 2021 Green Salon Collective is operating in Ireland and UK to provide a collection and recycling service for hairdressers' salons, recycling and reusing hairs besides traditional materials as metal and plastic packaging or aluminium foils. Even dust can become a valuable material as illustrated by Agùsta Sveinsdottir who turned it into a jewellery collection, or Matilda Beckman who mixed dust from vacuum cleaner bags and wood glue and made it into a table and chair. In the last few years, the Graviky Labs of MIT have been working on "Air Ink", an ink obtained from air pollution generated by burning fossil fuels. They developed a device able to capture air pollution and turn the captured particulate matter into a safe, water-based ink for different applications and writing tools.

In addition to the examples mentioned, we can find many projects which give a second-life to pollutants such as oceans' plastics. Adidas and Parley for example, partnered to retrieve plastic waste from shorelines and turn it into a thread woven to create running shoes. This kind of initiative is essential to raise awareness on the topic in this historic moment, however it seems to be inadequate as a long-term strategy when the plastic waste is used to make products which will rapidly turn into new plastic waste, polluting our environment again and again in a never-ending process.

2.4.2. Growing

With the spread of biofabrication designers turned their attention to living matter, acting new forms of interaction and collaboration with microorganisms as a source for materials production. They started to create the conditions to foster and harness their natural growth and reproduction processes in order to “harvest” their fruits in the form of materials and products. This kind of production system represents an inexhaustible source of circular materials, since the growth conditions of many microorganisms can be easily replicated in different areas and climatic conditions around the globe. Micro and macro algae for instance, are one of the most renewable organisms on the planet, they can be grown worldwide and can often thrive also in the adverse conditions brought by climate change and sea acidification. Moreover, they are beneficial for the environment, fostering the life of many marine species, essential to life on earth for oxygen production, and have always proven extremely versatile to us humans, finding application in many fields from food to medicine, and today also in the world of materials.

There are a variety of substances extracted from algae, one of the most known is probably spirulina which is widely used in food related products but also represents a good source for natural dyes production because of its blue-green colour. Agar agar, also used in food products as a gelling agent, is derived from different kinds of red algae, and it’s made of two components: the linear polysaccharide agarose and a heterogeneous mixture of smaller molecules called agaropectin. Its gel-forming property make it suitable for the production of biopolymers and to be used as a binder in the production of bio-based composites. Ari Jónsson with “The Agari Project” realized a water bottle made up of agar agar which starts to decompose as soon as it’s emptied from its content while keeping water fresh when full.

Another wonder substance is Alginate, a polysaccharide abundant in the cell walls of brown algae which forms a viscous gum when hydrated, and if used in combination with calcium chloride as curing agent a shrinking reaction occurs, which turns it into a waterproof biopolymer. The water resistance opens a window of new opportunities for its application, as shown by the edible water bottle (or rather bubble) “Ooho”, a sphere made of a thin alginate membrane filled with water.

Besides algae derivatives, seaweed – or macro-algae – can be also used in their entirety as vegetable fibre source or as textile-like material. Some examples are Kelp, which has a high growth rate and grows in underwater forests, or Posidonia oceanica, also known as Neptune grass, an endemic species of the Mediterranean Sea. From its foliage are originated balls of fibrous material called Aegagropila, and both the foliage and the felt-like balls are used for material production. The designer Julia Lohmann established the “Department of Seaweed”, an interdisciplinary community exploring the marine plant’s potential as a design material. Her “Oki Naganode” is a large-scale installation made of Japanese Naga seaweed, treated