Polycephalum: Aesthetic as a Measure of Ecological Intelligence

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Where did the 'polycephalum' story start? I have a background in drama, engineering and architecture and, in 2015, I cofounded ecoLogicStudio with Marco Poletto. The name of the practice refers to Gregory Bateson's definition of ecology: an interconnection of multiple systems.

In 2005, we started building our projects. In these projects, there was always an inherent interest and an implicit curiosity. The Light Wall Cirie (2009) in Turin, for example, was a housing project with seven units. A key feature of the project was the Light Wall House, a thick thermal wall system with spiralling perforations used to modulate the visual and thermal relationship between the user and the surrounding environment.

Other projects we did included the Carosello shopping mall extension, ROOFscape (2009), in Carugate, Italy, which was fitted with a large green roof perforated with double curved GRP cones to allow the shoppers to see the modulation of the sky and interact visually and thermally with the outdoors. We also worked on research projects with the Caracas Urban Think Tank (U-TT) in 2003—particularly, with the group that was dealing with the urban ecology in the *barrio* of La Vega, Caracas. There, we used a water flow simulation engine to try and understand how to harvest rainwater in the *barrio* while collecting and treating grey-water discharges in the landscape.

It soon became clear to us that these implicit interests needed a more in-depth investigation, one that we could not achieve purely within the practice model of the time. More or less, we consciously started dedicating more and more time to academic research and teaching. In 2008, we were invited to the Venice Architecture Biennale by Aaron Betsky and we proposed the project ecoMachines, which also became the title of our first design studio at the Architectural Association (AA) in London. The notion of ecoMachines provides a material and operational framework to deal with change and transformation, the two main defining qualities of our understanding of urban ecology. Moreover, it enables conceptual and material interaction between heterogeneous systems, such as social, infrastructural, architectural and environmental ones. ecoMachinic prototypes allow us to register and manipulate the unfolded processes in our daily life that define our city, our houses and our environments. ecoMachines turns us all into ecologists in the most operational sense of the term. The question, therefore, is: how do you transform architecture from something that deals with morphology, 'a cradle of static shapes', to an architecture that deals with morphogenesis? Morphogenesis is a dynamic process from which morphology emerges. It's the dynamic interplay of matter, information and energy.

In that time, we started building installations and devices to study architectural morphogenesis. We worked a lot with material processes inspired by biological morphogenesis, as in the installation FibrousRoom (2008) for the Garanti Gallery, Istanbul, where we learnt to work with fibrous, reinforced concrete without the need for a traditional rigid formwork. We also investigated the scale of landscape infrastructure and how to artificially manipulate processes such as sedimentation, erosion or mineral accretion. Our work was collected in the book *Systemic Architecture*[1] and, from then on, we tried to synthesise this research in further formed design projects.

One of the first was METAfolly (2012), the winning entry in a competition organised by Frédéric Migayrou and Marie-Ange Brayer for ArchiLab 9 at the FRAC in Orléans. METAfolly did not deal with a living biological organism that grows, but with self-organising, emerging material sound. The folly is produced with upcycled materials—mainly polypropylene plastic—and 300 piezoelectric buzzers that were taken from Christmas cards digitally interconnected. The morphology of METAfolly's external surface defines the tune and sound of the piezo buzzers which are activated by a weak electrical current traversing them. The flow of electricity is controlled by a set of six sensors and related microprocessors, located within the structural hubs, or legs, of the folly. The morphology of the folly is completely interrelated with its structural properties, but it also intersects with visitors and their movements in real-time. The information that make up this metainteraction evolves over time into a metaconversation between the user, the architecture and its inhabitants.

In terms of using material technology to produce the sound, we looked into living crickets and how the morphology of their body affects the wavelength of the sound they emit. We modulated the sounds in METAfolly through a morphological variation in the design of each tile forming the folly's skin.

[1] ecoLogicStudio, *Systemic Architecture: Operating Manual for the Self-organising City* (London: Routledge, 2012).

Figure 01. ecoLogicStudio, METAfolly, FRAC Centre, Orléans, France, 2012. A sonic environment which aims at establishing a playful dialogue with the user, enabling the development of a form of metalanguage based on material experience, patterns recognition and a real-time metaconversation

Activated by low-electricity information, the sound passes through the folly's fibrous structure to the piezo buzzer terminals. It's a fibrous system, but the fibres are not simply structural. They also carry energetic, biological and structural information along the same routes

The project triggered a series of important research questions: how are these energetic, informational and structural flows related, or spatially interrelated, in architecture? How can they be managed by its hubs, which are both nodes of stability and interaction? These questions stayed with us for a long time and informed several research projects later on. They also triggered additional questions about the nature of the unique times we are living. What's the relevance of designing such architectural metaconversations in times of fast-paced climate change and global health crises? When we use the definition 'climate change', what kind of change are we really talking about? Isn't the planet we inhabit inevitably changing all the time. Isn't change the only constant?

Timothy Morton once said:

> Why do we campaign to make our world 'cleaner' and less toxic, less harmful to sentient beings? Our philosophical adventure should, in some way, be quite the reverse. We should be finding ways to stick around with the sticky mess that we are, making things dirtier, identifying with ugliness.

This is not to glorify ugliness, but rather to say that we need to work from within. We cannot control the planet we inhabit nor can we reverse the impact we have had on it and stop change. Human infrastructures, the cities we have built, are out of our control. They have become a new natural system—the Urbansphere—and we are inextricably part of it. What we can do, however, is devise prototypes of interaction. Recently, I have been looking into the way mould organises and distributes resources through biological computation. I have also looked into how spiders can become part of our urban ecology, not just because of the incredible properties of the spider's silk, but because of the way they 'think' through their webs. The cognition of the spider doesn't reside completely in its body, but in the web itself. It 'thinks' through this spatial and material device; it 'eco-thinks'. Space is its way of thinking. It's an ecological instrument in spite of the spider itself.

At the large territorial scale, I have been studying glaciers, a striking example of the impact of climate change. All our glaciers can be mapped, but while we map them, change happens. They transform. How do we read and interact with them, eventually establishing positive dynamics and inducing positive changes rather than destructive ones?

One of my colleagues at the Bartlett School of Architecture in London, Professor Mario Carpo, published an article in which she speaks about the Mulino Bianco cookies, a type of Italian cookie, describing them as the pinnacle of postmodernism in Italy. They look like your grandma's homemade cookies and come in a soft package with a recipe on the side, but it's impossible to make them at home. In the article, Mario goes on describing the typical Italian preindustrial bakery.

> Bread and cookies [...] were made and baked daily on the premises [...]. The cookies themselves [...] had a different taste, shape and consistency every time, either by chance or by design [...]. My grandparents even had a theory to account for the changing quality of the cookies, which they related to the weather (humidity and temperature), to the time of the day and the day of the week (fluctuation in demand and supply), but mostly to the notorious irascible temperament of the said baker's wife'.[2]

In this sense, the cookie is a computer. The information input is human (the temperament of the baker's wife), economic (the fluctuation in demand and supply) and environmental or nonhuman (the humidity level and temperature). By indexing these inputs, the cookie generates

[2] Mario Carpo, 'Mulino Bianco or the Italian Invention of Postmodernism', *Log*, 34, 2015, pp. 133–38.

a morphological output which is always different as the combination of input parameters changes.

By analogy, can we invent an architecture able to read, process and transmit information, thus creating the conditions for a new social system to emerge? That is what we investigate in our most prolific series of projects to date, which started in 2006 with STEM before evolving into the H.O.R.T.U.S series and, finally, the recent PhotoSynthetica venture. STEMv1.0 (2006) deals with the integration of biological organisms, such as microalgae and bacteria, in architecture. In its most basic form, it is the stacking of a certain number of transparent containers. It takes a certain amount of shapes and containers inoculated with micro and macroalgae, in this case, from Victoria Park Pond in London.

When I first showed this project to Brett Steele, the former director of the AA, he looked at it and said, 'It looks like pixelated nature!' That definition is, in my mind, still the most successful synthesis of the core motives of the project at the time. We didn't know much about algae at the time, but were trying to correlate the photosynthetic potential of the algae and their density patterns to fields in the surrounding environment that could be digitally simulated. Solar radiation, CO_2 emissions and concentrations of pollutants in the air which, previously, could be digitally simulated are now visualised materially for the effect that these have on the patterns of algae growth.

When we talk about cyanobacteria and microalgae, like the ones blooming in the Baltic Sea or in London's canals network, we feel we are somehow outside of the realm of architecture. However, today, architects and planners rely on a 'sanitised' vision of the world's ecosystems. This notion may be one of the most enduring aspects we have inherited from modernity. If bacteriological control was at the origin of most sanitation efforts, modern architecture and urban design turned it into a style. In other words, modernity embedded sanitation into an aesthetic value system and contemporary green and smart city paradigms are, from this perspective, the direct consequence of that value system's evolution.

Most urban systems today are nonlinear and composed of billions of interlocking feedback loops. Waste, decay, digestion and dissolution are some of their most intense processes and a critical part of their circularity. These processes often constitute the dark side of urban ecology, a side confined to restricted zones and erased from the consciousness of most urban dwellers. It becomes apparent, therefore, how critical it is to address the necessary drive to a sustainable urban future by challenging its underpinning aesthetic value system.

Reassessing the dark side of urban ecology means opening up to a new aesthetic of nature as a consequence of architecture, projecting the architectural discourse into the realm of microorganisms.

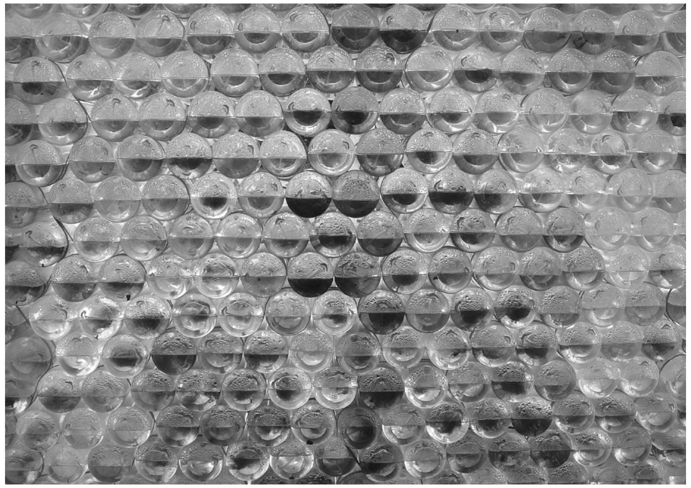

Figure 02. ecoLogicStudio, STEMv1.0, London Architecture Biennale in Broadway Market at the SevenSeven Gallery, London, United Kingdom, 2006. A 'living' screen system able to engage with sun light and to generate oxygen via photosynthesis

Bacteria and fungi, for example, are creatures endowed with exceptional properties that make them capable of turning waste and pollution into nutrient and raw material. These scalar and material domains unveil the missing links to redefine the contemporary urban metabolism.

On the other hand, biologists and scientists are telling us that some of these bioproducts, some of these bacteria, have exceptional properties that allow us to remetabolise the waste that our cities have been producing. Can we look at these products and try to understand how they could be remetabolised by working with materials such as bioplastic? Of course, if you work with bioplastic, it will not be durable like petroleum-based plastic. If we look at the issue of plastic, for instance, we can find several kinds on the market which all have different time spans before they disintegrate. Petroleum-based plastics, therefore, are not dead; they are biological. They too come from trees, but the metabolic cycle from the original tree and back again takes an incredibly long time to complete naturally. It will be interesting to overcome the 'petroleum-based plastic is bad and bioplastic is good' ideology and look, rather, at the time span of each plastic's life cycle.

In this sense, we can embed a new form of intelligence and a new value system to the byproducts of urbanisation in the city. From this perspective, the work of my practice promotes a new urban aesthetic centred around a novel appreciation for the microscale of bacteria as well as around other forms of nonhuman intelligence. Within ecoLogicStudio's body of work, these are 'culturalised', thus entering the realm of architecture and, alongside humans, biocitizenship. We could argue, in fact, that fungi, microorganisms, intelligent machines and all other communication devices are becoming biocitizens

alongside human beings in that they are organisms we interact with to create a collective intelligence.

In the case of Microbial Cellulose [Metabolizing Urban Waste] (2015–16), a project done at the Urban Morphogenesis Lab, B-Pro, we were looking at the curing process of made-in-the-lab bioplastic samples and the corrugation that emerges over time on the surface of the bioplastic, exploring how it becomes part of the structure of the bioplastic, but also an aesthetical material property of the time.

For this research, we were working in Liwa, a beautiful oasis in the north part of Saudi Arabia on the border of the Rub' al Khali Desert, one of the deserts richer in petrol between Saudi Arabia and Abu Dhabi. There is a scarcity of water there and the water table is salty, so the water is reused four times. By the fourth time, it becomes so saturated with these bacteria that it cannot be used anymore, even to wash. We brought some of these bacteria to the University College London (UCL) and discovered research in the biochemical department that uses these bacteria at a certain temperature to synthesise calcified bones for biocementation.

Nonhuman Architecture

To us, reassessing the dark side of urban ecology brings up a necessity of opening up a new aesthetic of nature and, as a consequence, of architecture. This new aesthetic connects the architectural discourse to the realm of microorganisms, such as bacteria, fungi—creatures endowed with an exceptional ability to turn waste and pollution into nutrients—and raw material. These scalar and material domains unveil the missing links that help us to redefine the contemporary urban metabolism across scales.

EcoLogicStudio's biodigital architecture promotes a new urban aesthetic centred on a novel appreciation of the bacterial microscale, as well as other forms of nonhuman intelligence. Within ecoLogicStudio's body of work, the cultivation of these organisms becomes an act of 'culturalisation' as their direct foray into the realm of architecture. A notable example of 'culturalisation' by design is ecoLogicStudio's H.O.R.T.U.S. series, which began in 2012 and is currently still ongoing. H.O.R.T.U.S. is the Latin term for 'garden'. Here, it stands for 'Hydro Organism Responsive To Urban Stimuli'. It refers to a series of photosynthetic sculptures and urban structures that create artificial habitats for cyanobacteria integrated into a built form. Within H.O.R.T.U.S., cyanobacteria are deployed not only as photosynthetic machines but they also absorb emissions from building systems. H.O.R.T.U.S constitutes a new active layer that is part of both urban and natural metabolic cycles, thus reconnecting the so-called green and dark sides of ecology.

Figure 03. Urban Morphogenesis Lab, B-Pro Group, Bartlett School of Architecture, Microbial Cellulose [Metabolizing Urban Waste], London, United Kingdom, 2015–16

The latest instance of this concept is a biodigital piece titled H.O.R.T.U.S. XL Astaxanthin.g. It was first presented at the Centre Pompidou in Paris in 2019 as a part of *La Fabrique du Vivant* exhibition. This specific installation is inspired by studies conducted by the authors on the collective behaviour of coral colonies and their morphogenesis. Individual coral polyps host microalgae called zooxanthellae within their tissues. As the algae photosynthesises, it provides a metabolic flow of energy to the polyps, which, in turn, build their exoskeleton of calcium carbonate. More exposure to sunlight results in more rapid growth, creating a positive feedback loop that enables the characteristic convoluted morphology of many known coral species to emerge.

H.O.R.T.U.S. XL Astaxanthin.g deploys an algorithm to simulate a growth of a three-dimensional substratum inspired by coral morphogenesis. The result is a set of digital meshes that are subsequently analysed. Two of them are selected as inner and outer layers of the 3D-printed substratum for the sculpture and each vertex of the mesh represents a virtual version of coral polyp. The substratum is further developed into a 3D-printable structure. As in the case of corals, this structure is developed to support the proliferation of colonies of cyanobacteria that will inhabit its individual cells, called biopixels. Each cell occupies the interstitial space between inner and outer layer and these two layers are then translated into a porous field of contour lines indexical of incoming solar radiation.

Figure 04. Urban Morphogenesis Lab, B-Pro Group, Bartlett School of Architecture, XenoDerma, *La Fabrique du Vivant* exhibition, Centre Pompidou, Paris, France, 2019

The curvilinear profiles provide partial enclosure to the cells while enabling light penetration, and oxygen and CO_2 exchange.

The final digital model of the substratum for the living sculpture is then prepared for 3D printing in Polyethylene Terephthalate (PETG) on a Wasp 3D-printing machine and processed with Cura software. The layering process is algorithmically controlled to match the curvilinear profiles of the outer layers with the actual tool paths of the 3D-printing nozzle. This workflow allows high fidelity transition of digital models into the lines of deposited material.

Each layer is 400 microns thick with triangular infill units of forty-six millimetres. It is printed in 105 hexagonal blocks of 18.5 centimetres on each side, producing an overall substratum that is tall enough to enclose a human adult and that reaches 317 centimetres in its tallest point. Photosynthetic cyanobacteria cultures are then inoculated on a biogel medium into the individual triangular cells, or biopixels, forming the units of biological intelligence of the system. Powered by photosynthesis, their metabolisms convert radiation into actual oxygen and biomass. The density-value of each biopixel is digitally computed in order to optimally arrange the photosynthetic organisms along surfaces of progressively higher incoming radiation. Among the oldest organisms on Earth, the cyanobacteria's unique biological intelligence is now gathered and organised by means of the latest innovation in 3D printing.

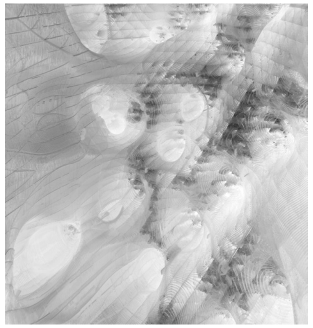

Figure 05, 06. ecoLogicStudio, H.O.R.T.U.S, Architectural Association (AA), London, United Kingdom, 2012. The project proposes an experimental engagement that illustrates the potential applicability to the master-planning of large regional landscapes and the retrofitting of industrial and rural architectural types

The scales of architectural detailing and the urban microbiome become compatible for the first time in history, conjuring a new form of biodigital architecture. Noticeably, this enables multiple interactions in buildings that can now be activated by the intelligence of microalgae colonies. The microorganisms grow faster in the biodigital environments that the authors have designed than in the wild because, in these artificial habitats, they are very closely connected with human life. Man-made emissions, like heat and carbon dioxide, for instance, stimulate biomass growth. The biomass, in turn, can be used as a source of energy or food, creating a bioarchitectural symbiosis.

The Photo.Synth.Etica Venture

The architectural dimension of biosymbioses has been recently explored in a new instantiation of our research, unveiled in November 2019 at the Mori Art Museum in Tokyo. Suspended at the fifty-third floor of the Mori Tower with the backdrop of Tokyo's urban sprawl, the sculpture materialises its urban dimension as a new prototype of living architecture, the PhotoSynthetica Tower (2019). Explored through a series of associated speculative images, the project unfolds the

architectural implications of H.O.R.T.U.S as the embodiment of Tokyo's evolution into a future powerhouse of biodigital culture and technology.

At the city scale, it appears as a complex synthetic organism in which bacteria, autonomous farming machines and other forms of animal intelligence become biocitizens. Alongside humans, they all contribute to the new formation of Tokyo's own synthetic urban landscape. Additionally, the intricate morphology of PhotoSynthetica Tower and its sheer scale promote a significant microclimatic effect. The prevailing winds generate enough draft and turbulence to force both the natural seeds and air-polluting particles through its porous skin. Each module of this skin is then activated locally to evolve into a unique function.

Some components of the system are designed as photobioreactors. These are custom-printed bioplastic containers that focus sunlight to feed living microalgal cultures and release luminescent shades at night. Unfiltered urban air is pulled in and through the bottom of each module. As a consequence, the air bubbles naturally rise up through the liquid medium within each photobioreactor, thus coming into direct contact with the voracious microbes. CO_2 molecules and air pollutants are captured and stored by the algae and grow into new biomass. Freshly photosynthesised oxygen is released at the other end of the module and naturally channelled into the vast inner lobby of the tower. Here, a clean urban microclimate is synthesised and air circulation is supported within a shared public space.

Other components become receptive to seeds and wild plants, thus forming emerging artificial habitats. These biotopes remain open to wildlife, including insects and migrating birds. The biomass that grows on the active areas of the tower is made available to the occupants of the building itself, supplying a plethora of emerging activities that define the programmatic mix of the building and its occupational pattern for both human and nonhuman inhabitants. Additionally, biodigital research units, gardening centres, wildlife observation terraces, self-sufficient dwelling and a potentially infinite variety of other programmatic combinations are supported by the continuous catalytic action of the tower, which constantly remetabolises anthropic pollution and biotic contamination into local circular economies of raw materials, data and energy.

In order to promote the evolution of this concept, the authors have recently launched the PhotoSynthetica venture, a transdisciplinary design-innovation project. In the last two years, the venture has built a series of large-scale, 1:1 demonstrators of photosynthetic building membranes, sometimes referred to as photosynthetic urban curtains. The first demonstrator was unveiled in November 2018 in Dublin, Ireland. At thirty-two-metres-long and seven-metres-high, the membrane was designed specifically for the Climate-KIC, the European

Union's most prominent climate innovation initiative, and aimed at accelerating the adoption of nature-based solutions to tackle the global climate crisis.

Conceived as an 'urban curtain', PhotoSynthetica captures CO_2 from the atmosphere and stores it in real-time at a rate of approximately one kilo of CO_2 per day—equivalent to that of twenty large trees. Composed of sixteen modules two metres wide and seven metres tall, this unique curtain prototype envelopes the first and second floors of the main façade of the Printworks building at Dublin Castle. Each module functions as a photobioreactor, a digitally designed and fabricated bioplastic container that utilises daylight to feed the living microalgal cultures.

The main purpose of this installation in terms of its performance is to test the process of filtration, as described above in the PhotoSynthetica Tower. Here, the urban air enters through the bottom of each of the curtain modules. Similarly, the CO_2 molecules and air pollutants are captured and stored by the algae and grow into new biomass that can be harvested and used in production of raw materials, such as varied bioplastic products. Because the curtains were manufactured with a double layer of PolyAir biobased plastic sheets, the main building material of the photo-bioreactor itself is produced out of bioplastic. To culminate the process, freshly photosynthesised oxygen is released at the top of each façade unit of PhotoSynthetica, out into the urban microclimate. Because of their serpentine shape, the modules optimise the carbon sequestration process and the full curtain pattern is reminiscent of a large trading data chart that embodies Climate-KIC's commitment to promote new models with a potential of solving the global climate crisis.

Designwise, the PhotoSynthetica system integrates three layers of functionality: (i) wetware, the selection and management of the microalgae cultures, (ii) software, the digital management system that uses sensors to optimise performance in real time (it also provides long-term projections and predictions of the system's carbon capturing and air cleaning capabilities) and (iii) hardware, the artificial habitat for cultivation of living cultures, or photobioreactor. The project combines digital design and fabrication technologies to optimise aesthetic qualities and environmental performances into an architecturally integrated system.

There are significant economic, social, environmental and health benefits in the actualisation of PhotoSynthetica as a large-scale building façade. This project embodies multigenerational, long-term benefits of adopting a carbon-absorbing technology and is ten times more efficient at carbon sequestration than any other green technology based on conventional planting methods.

Figure 07. ecoLogicStudio, H.O.R.T.U.S., Expo 2017 Astana. An installation that aims to reload the notion of biospheric garden as Hydro Organisms Responsive To Urban Stimuli (H.O.R.T.U.S), the project was built for but remains at the ZKM Museum, Karlsruhe, Germany, 2017

Figure 08. ecoLogicStudio, superTree, ZKM Museum, Karlsruhe, Germany, 2018. An architectural apparatus that repurposes the tree to optimise its infrastructural operations as part of the present and future Urbansphere

This is due to the exceptional properties of the algal organisms whose cells are entirely photosynthetic. By comparison, large plants devote more than 90 percent of their mass to infrastructures that sustain the needs of their complex organisms, but have no direct contribution to solar energy capturing and air filtration.

Moreover, PhotoSynthetica brings algae farming to cities with a dramatic increase in farming efficiency compared to current industry standards, as algae feeds on what buildings expel, especially heat and CO_2 emissions. In this sense, the project promotes the emergence of regional and local circular economies. Additionally, algae is a key material ingredient in the manufacturing of future biofoams and bioplastics. If we consider that the global algae farming industry is already worth one billion dollars, it is easy to predict the economic benefits that PhotoSynthetica could potentially bring to cities and local communities.

The PhotoSynthetica project also enables a sustainable food revolution with food security for the areas of the world that are particularly affected by the effects of climate change. Fresh and organic foods are often more expensive than less healthy options and animal-based proteins have an enormous impact on the environment. Affected by increasing drought and flooding, traditional agriculture is failing in many areas. The algal output of our test bed is equivalent in vegetable protein production to the two kilograms of meat per day —enough for twelve adults and with no animals being killed. Therefore, PhotoSynthetica enables growing high-quality, urban vegetable proteins in an extremely efficient way.

Conclusion

In conclusion, we believe that a key purpose of our practice is to train our sensibilities, as well as the ones of our partners and clients, to recognise the emerging patterns of reasoning across disciplines, materialities and technological regimes, thus expanding the practice's repertoire of aesthetic qualities in lieu of ecological design. Here, aesthetic is intended as a metalanguage, enabling a more complex level of communication with nonhuman partners. It is no longer, therefore, a case of architecture being inspired by other disciplines, such as biology and computer science, striving to become biomimetic or biophilic… rather, it is time to realise what architecture can give to other disciplines, precisely because of its self-contained materiality in terms of contributing to their actualisation in a new and reimagined spatial reality. Architecture as an embedded algorithm acquires its own nonhuman biointelligence and sensibility, which must be patiently trained, understood and cultivated.

For this reason, we feel that it is critical to avoid the trap of simply borrowing new tools and technologies, applying them to the solution of ever-increasing architectural challenges. On the contrary, it is critical to deploy them as techniques to access the nonhuman, the collective, and to shift our perspective beyond the boundaries of the rational. Such a shift has the power to greatly expand the space of solutions by reproblematising given problems. We need to ask new questions before providing solutions to what we consider is known. There has never been a better time for architects to claim this fundamental societal role.