Photosynthetic Architecture in times of Climate Change and other global disruptions.

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This paper discusses architectural experimentation's shift from a carefully designed spatial practice into a distributed set of dynamic processes unfolding in time. When linearity shifts into a convoluted set of feedback loops, circularity emerges as a fundamental paradigm. The paper discusses a set of project descriptions and recent case studies from the work of the PhotoSynthetica venture, bringing together the experimental practice of ecoLogicStudio and the pioneering research of the Urban Morphogenesis Lab at UCL and the Synthetic Landscape Lab at UIBK. These projects demonstrate how the practice of architecture constitutes a distributed form of emergent collective intelligence.

Keywords: *digital fabrication, computation, cyber-gardens, cognition, bio-digital architecture*

AN ANTHROPOLOGIC PERSPECTIVE ON SYSTEMIC ARCHITECTURE

Systemic architecture (Pasquero, Poletto 2012) acts like a living organism with its intelligent ability to sense the surrounding environment and adapt to it. It is dynamic and capable of recognising everything around as intertwined and in movement. Its intelligence invites us to observe it with attention, to interact with it and to grow and evolve with it. It is not only smart but also alive and, to a certain extent, autonomous.

Recent Anthropological studies in Architecture suggest a shift in perception which triggers the emergence of a hybrid design practice that is “reflexive toward its own disciplinary creations; participatory in its understanding of life; knowledgeable of the interrelationships between perception, culture, and materials; and active in creatively engaging with the continued enhancement of human life” (Anusas and Ingold 2014: 58). This cultural perspective influences the current definition of design morphology to evolve into a process of curated morphogenesis.

The word anthropology shares its Greek root with another term currently in demand, Anthropocene. This association brings a new twist to its meaning, evoking a new cultural context, the Anthropocene epoch, and the intelligence of modern technology, which determines it. Today we are witnessing an unavoidable “ontological turn”, because of unilateral globalization and “an explicit response to the crisis of modernity that expresses itself largely in terms of ecological crisis” (Hui, 2017).We now realize the necessity for this ontological shift especially as the management of the COVID19 pandemic presents the biggest global challenge humanity has faced since the Second World War.

GLOBAL CO(I)MMUNITY

The current epochal distortion in the planetary metabolism manifests itself as climate change. Recent global events have further accelerated perceivable changes. The Covid19 global pandemic strikes with "a domino effect of consequences, altering not only the movement of people, but affecting planetary cycles of energy, materialization, expenditure, and waste" (Bratton, 2020).

While undergoing changes of such enormous scale that current generations have never before experienced, we realize the impact of our planning over the Urbansphere is larger than we thought. As Bratton explains: "Our thinking and our interventions must be based on a higher resolution understanding of cyclical interrelations and physical economies, from scales of viral infection to intercontinental circulation and back again."

Far from being excluded from this ontological turn, humans are deeply involved as co-actors. This shift affects us on a personal level, as we start gaining a previously unknown sense of responsibility. That allows us to move beyond living in a world of causes and effects defined by hopeless searching for the "guilty" and the "responsible" for global disruptions. This is particularly relevant as we tend to cling to our preconstituted understanding of the world around us and any change is leading us out of the comfort zone.

However, it is now important for us to realize that the goal of resuming "normal life" after such crisis is not an adequate response (Hui, 2020), rather we are challenged to define a 'new normal' (Bratton, 2017). In other words the goal cannot be simply to survive the pandemic but to instil in us the ability to answer critical questions about the evolution of the Urbansphere (Poletto, 2018), the global apparatus of contemporary urbanity.

Designing for the planet, affecting its metabolism without "returning back to nature" brings up the question of artificiality. The problem of not embracing our artificiality while at the same time the realisation of the impossibility to "return back to nature" is confining us to inertia. The only way out may be, as suggested by Andy Clark, to realize that our true nature is cyborgian.Our true nature and purpose is "to enter into deep and complex relationships with non-biological constructs, props, and aids" (Clark, 2003).Responding to this realisation, we are moving away from the "human-oriented framework" of architecture to propose a new design science for the assemblage of human and non-human agents, mediated by inhuman apparatuses. (Pasquero and Zaroukas, 2016).

ONTOLOGICAL TURN

As architects, we are often called upon designing large unmovable artefacts, in Italian "beni immobili". Nevertheless, every interaction they enable or trigger, with or without us noticing, becomes part of an evolutionary progress, a process of becoming of an architectural prototype (Pasquero, Poletto, 2012).

Figure 1
Urban Algae Folly Aarhus by ecoLogicStudio, Aarhus, Denmark, 2017, photo ©NAARO

Architectural experimentation shifts from a carefully designed and crafted artefact in space into a distributed set of dynamic processes unfolding in time. This kind of processes are smart, but unlike in the known archetype of smart architecture, they constitute a distributed form of emergent collective intelligence (Fig.1).

The notion of intelligence we recall here is rooted in collective behaviour of decentralized, self-organizing systems, natural or artificial (Dorigo, 2017), that continually learn from feedback, experience and even failure to produce just-in-time knowledge for better decisions than its separate elements acting alone (Glenn, 2009) could ever achieve.

In this sense, we are prototyping the unpredictable, with no decisive end in its creation, embarking in a process that necessarily contains a series of successful steps as well as multiple failures. However, from this perspective even failures contribute to the progress of an experimental practice that becomes the core of architectural design itself. Experimenting it's about not knowing the final result, therefore it calls for experiencing the progression itself.

Figure 2
Urban Algae Folly Aarhus by ecoLogicStudio, Bio-Digital Systems Detail, Aarhus, Denmark, 2017, photo ©NAARO

An experimental practice allows us to embed the processes of experimentation into spatial context, for example by engaging urban public spaces as open-air laboratories. Building and constructing with a vision but without predefined knowledge of where the whole process will lead us, we continuously test the interaction with the environment, as well as the application of digital and bio-technologies in the urban realm to evolve the methods and protocols of what we call a "collective urban cultivation" (Fig.2).

"An extended cognitive system" (Clark, 2003), that is conscious of its interconnectedness with the environment creates a constant exchange with it, sourcing and feeding us back with information, matter and energy. The evolution of such bio-digital system raises our awareness resulting in a bio-technological network of information. Everything is part of the making of architecture, including our response and other forms of human-nonhuman exchange. Different components may have different meanings and purposes in their dependence or relationship with parts of the architectural ecosystem.

Figure 3
Aarhus Wet City, Network Threshold, Aarhus Denmark, 2017, ©ecoLogicStudio

ecoLogicStudio's Photosynthetic projects create a transversal, non-hierarchical connection between various layers of research to helps us move beyond mere numerical data and statistics. They attempt to exclude nothing and include all. "Sustainability is either of everything, or it is nothing" (Ingold, 2019), and everything is interconnected in trans-scalar correlations, that might be revealed only if explored through different set of lenses, thus unveiling a novel bioinformational landscape (Fig. 3, 4).

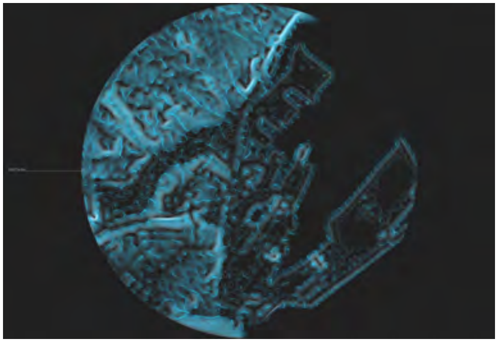


Figure 4
Aarhus Wet City, Water Flow, Aarhus Denmark, 2017, ©ecoLogicStudio

In this paper we are attempting to illustrate this landscape through a series of living sculptural prototypes and bacteriological gardens.

PHOTOSYNTHETIC ARCHITECTURE

The Photosynthetica Consortium, established in 2018 and including London-based ecoLogicStudio, the Urban Morphogenesis Lab (Bartlett School of Architecture, University College London (UCL)) and the Synthetic Landscape Lab (University of Innsbruck, Austria), has been pursuing architecture as a research-based practice, exploring the interdependence of digital and biological intelligence in design by working directly with non-human living organisms.

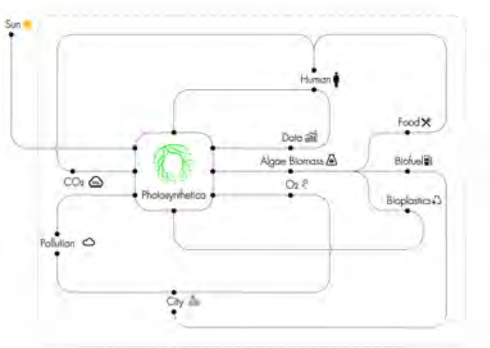


Figure 5
PhotoSynthEtica Circular Metabolism, diagram, ©ecoLogicStudio

The photosynthetic projects discussed here merge biological and artificial life in richly articulated architectural components receptive to urban stimuli; these seek to conjure a new circularity of information, matter and energy where what one system emits the other feeds onto (Fig. 5).

Photosynthetic architectures are powered by microalgae organisms. One of the oldest organisms on Earth micro-algae and cyanobacteria are able to grow in every aquatic habitat. The projects are developed in "collaboration" with these living organisms, turning the prototype into a performative living sculpture, where the notion of "living" takes on a new form of artificiality.

The intricate morphology of PhotoSynthetica Tower for example, and its sheer scale, promotes a significant microclimatic effect. The prevailing winds generate enough draft and turbulence to force 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 (Fig.6).

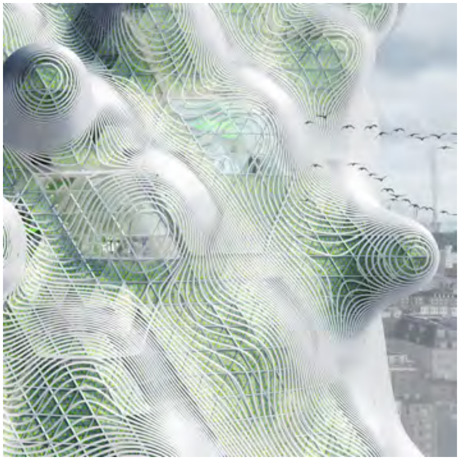


Figure 6
PhotoSynthetica Tower, visualisation by ecoLogicStudio, 2019

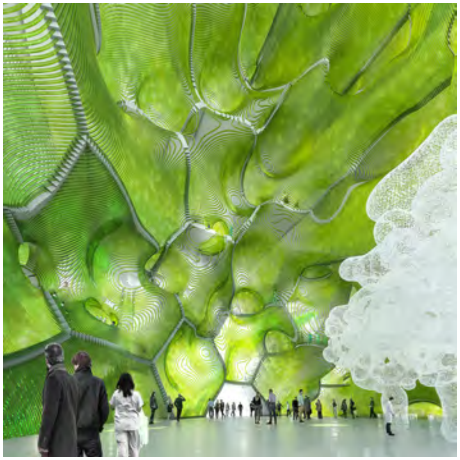


Figure 7
PhotoSynthetica Tower, visualisation by ecoLogicStudio, 2019

Some components of the system are designed as photo-bioreactors. These are custom-printed bioplastic containers that focus sunlight to feed living micro-algal-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 photo-bioreactor, thus coming into direct contact with the voracious microbes. CO2 molecules and air pollutants are captured and stored by the algae and grow into new biomass. Freshly photosynthesized 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 supports air circulation within a shared public space (Fig.7).

Design wise the Photosynthetic Architecture system integrates three layers of functionality:

- Wetware: the selection and management of the microalgae cultures.
- 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.
- Hardware: the artificial habitat for cultivation of living cultures, or photo-bioreactor. The project combines digital design and fabrication technologies to optimise aesthetic qualities and environmental performances into an architecturally integrated system.

The system embodies multi-generational long-term benefits of adopting a carbon absorbing technology.

Algae primarily function as metabolic machines, deployed to convert and digest pollutants found in the air and in the waterways by means of the process known as photosynthesis. CO2 emissions are adsorbed and oxygen is released back to the atmosphere. We have tested the system in two 1:1 scale pilots, in Dublin and Helsinki. In Dublin 2sqm of Photosynthetica membrane, containing about 50l of living cultures, did adsorb about 22Kg of CO2 per year, equivalent to the average mature tree. A mature tree once integrated in a building could reach a total weight 100 times higher. This demonstrate the potential of building integrated algae powered photosynthesis (Fig.8).

Figure 8
City Curtain PhotoSynthEtica by ecoLogicStudio, Helsinki, Finland, 2019, photo ©Tuomas Uusheimo

Algae have the capacity to digest and break down not only CO2 but also other air pollutants such as NO2, and SO2. Current research indicates that algae have the potential to capture trace metals dissolved into the environment by biosorption and bioaccumulation processes (Malinska and Zabochnicka-Swiatek 2010).

Figure 9
Urban Algae Folly Aarhus by ecoLogicStudio, Top View, ETFE Photobioreactors, Aarhus, Denmark, 2017, photo ©NAARO

Typical air quality monitoring stations capture ground level ozone (O3), sulfur dioxide (SO), carbon monoxide (CO) and nitrogen dioxide (NO), measured in parts per millions, as well as fine particulate matter (PM) such as PM2.5 and PM10, whose concentration is measured in micrograms per cubic meter. These concentrations have been driving the design of PhotoSytheticas systems and the algal density in its bioreactors (Fig.9).

Grown algae can be harvested as superfoods, supplementing the protein intake from animal product, leading to more sustainable food production and supply chains. The nutritional composition of microalgae is made up mainly of proteins, carbohydrates, lipids and trace nutrients, including A and B vitamins and antioxidants which makes them one of the most nutritious aliment on Earth.

Figure 10
City Curtain PhotoSynthetica by ecoLogicStudio, Helsinki, Finland, 2019, photo ©Tuomas Uusheimo

Algae growth is dependent on amount of CO_2 that is fed with, but also depend on environmental conditions, which can be systematically optimized within an architectural organism in order to maximize the growth rate and pollution absorption. There are many variables to be considered ranging from the location's natural habitat and climate, to choosing the specific algae, and providing it with right conditions of appropriate solar radiation, temperature, pH. Coupling algal growth with building operations affords a renewed level of efficiency, since building emitions sustain accelerated algal growth. It is a new kind of architectural symbiosis (Fig.10).

BIO-ARCHITECTURAL SYMBIOSIS

The latest material embodiment of this concept in the work of ecoLogicStudio, is a bio-digital sculpture titled "H.O.R.T.U.S. XL Astaxanthin.g" (Fig.11). It was first presented at the Centre Pompidou in Paris in 2019 as a part of the seminal exhibition titled "La fabrique du vivant". 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. This positive feedback loop 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 3Dimentional substratum inspired by coral morphogenesis. The result is a set of digital meshes that are subsequently analysed, and two of them are selected as inner and outer layers of the 3D printed substratum for the sculpture. Each vertex of the mesh represents a virtual version of a coral polyp.

Figure 11
H.O.R.T.U.S XL Astaxanthin.g by ecoLogicStudio, Centre Pompidou, Paris, France, 2019, photo ©NAARO

The substratum is further developed into a 3D printable structure. This structure, as in the case of corals, is developed to support the proliferation of colonies of cyanobacteria that will inhabit its individual cells (bio-pixels). Each cell is therefore occupying the interstitial space between inner and outer layer. These two layers are then translated into a porous field of contour lines indexical of incoming solar radiation. The curvilinear profiles provide partial enclosure to the cells while enabling light penetration and oxygen/CO_2 exchange.

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

Each layer is 400 microns thick with triangular infill units of 46 mm. It is printed in 105 hexagonal blocks of 18.5 cm each side producing an overall substratum that is tall enough to enclose an adult human and that reaches 317cm in its tallest point (Fig.12).

Figure 12
H.O.R.T.U.S XL Astaxanthin.g by ecoLogicStudio, Cybergardening process, Centre Pompidou, Paris, France, 2019, photo ©NAARO

Photosynthetic cyanobacteria cultures are then inoculated, on a bio-gel medium, into the individual triangular cells, or bio-pixels, forming the units of biological intelligence of the system. Their metabolisms, powered by photosynthesis, convert radiation into actual oxygen and biomass. The density-value of each bio-pixel is digitally computed in order to optimally arrange the photosynthetic organisms along surfaces of progressively higher incoming radiation. The cyano-bacteria's unique biological intelligence is now gathered and organized by means of the latest innovation in 3D printing (Fig.13).

The scales of architectural detailing and the urban microbiome become compatible for the first time in history, conjuring a new form of bio-digital 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 bio-digital environments 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.

Algae is contributing to city´s extended metabolism by filtering its pollution, cleaning wastewaters, digesting urban waste and growing into biomass. One of the most direct implications of algal biomass is that they can be converted into a spectrum of biofuels such as methane produced by anaerobic digestion of the algal biomass, biodiesel derived from microalgal oil, bioethanol derived from microalgal carbohydrates or photobiologically produced biohydrogen (Malinska and Zabochnicka-Swiatek 2010).

Figure 13
H.O.R.T.U.S XL Astaxanthin.g by ecoLogicStudio, Inoculation process, Centre Pompidou, Paris, France, 2019, photo ©NAARO

Another signifcant use of biomass is high-protein animal feed and human super-food products, activating new pollution-to-food feedback loops, significantly affecting the overall urban metabolism, and reducing its footprint. The high nutrient concentration in spirulina contains three times the amount of useable protein as beef, per 100 grams. Further variety of algal bio-mass applications generate a circular economy loop, where nothing is wasted and all by-products have further use.

This urban dimension of architectural symbiosis has been recently explored as an extension of H.O.R.T.U.S. XL Astaxanthin.g project research in Tokyo at the Mori Art Museum. Suspended at the 53rd floor of the Mori Tower and with the backdrop of Tokyo's urban sprawl the sculpture materializes its urban dimension. 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 bio-digital 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 bio-citizens. Alongside humans they all contribute to the new formation of Tokyo's own synthetic urban landscape.

HUMAN - INHUMAN BIOSPHERE

Such relations with inhuman species woven into city fabric require us to participate and engage with new, redefined human behavioural patterns developing a compassion towards other species and living organisms that supports the functional diversity of the Urbansphere (Fig. 14).

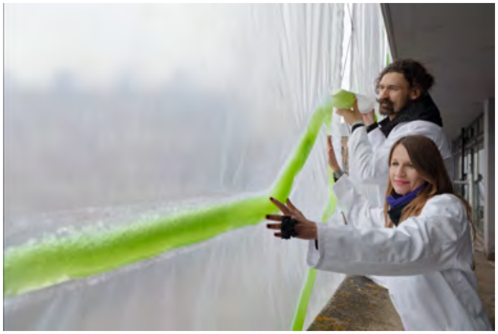
Figure 14 PhotoSynthEtica Dublin by ecoLogicStudio, Dublin, Ireland, 2018, photo ©NAARO

Compassion from Latin compati, means literally "to suffer with". However here it is not only about feeling the pain of the other but the authors refer to a more profound intention of being motivated to relieve it. Seemingly, we have developed more compassion towards our devices then towards fellow human beings or other species.

In this respect one of our new strands of research focuses on biometric sensor mapping of human perception and relation to immediate environment. This bio-digital conversation aims to unfold new layers of information towards understanding the complex informational network of behaviour of species. While creating this link we not only engage in studying the other living organisms, but at a same time we are sensing the Self. When we experience an arousing stimulus, like an evocative question, a startling noise, or even a disturbing thought, our body generates a variety of psychophysical responses (Montgomery & Laefsky 2011). By monitoring these phenomena by biometric sensor technology, biofeedback, we can learn and train ourselves, we can grow our prefrontal cortex and improve our emotional state.

"How we relate to each other is part of how we relate to the city" (Bratton, 2020), and we humans have been protecting ourselves from the outer world through layers of artificial skins (clothes) and prostheses (phones) and incubators (buildings). Historically one of the defining qualities of architecture is its permanence, its hardness and its resistance to change and movement, protecting us from the outer world and from wild nature. The resemblance of breathing photosynthetic architecture to the human body's metabolic functions potentially allows humans to relate to the surrounding and transcend the seeming detachment imposed by the architectural envelope. Through a combination of human and non-human interfaces we are merging the natural with artificial realms. The aim is to realize the outer world can be a safe place for us, we can take an active part in its circular metabolism. As humans' internal emotional state directly influences our behaviour, the emotional evolution as a response to urban stimuli is one of the aspects of Photosynthetic Architecture that can evolve into a powerful mechanism of behavioural shift within the Urbansphere (Fig. 15).

Figure 15
PhotoSynthEtica Dublin by ecoLogicStudio, Detail of Inoculation Process, Dublin, Ireland, 2018, photo ©NAARO



Our Autonomic Nervous System reacts to stress aiming to re-establish homeostasis, a steady state on a psycho-physiological level, by regulating heart activity, skin conductivity and skin temperature. Therefore the most common and suitable sensors to measure arising stimuli are associated with physiological signals such as Galvanic Skin Response (GSR), Electroencephalogram (EEG), Electromyography (EMG), Electrocardiogram (ECG), Skin Temperature (ST), Heart Rate Variability (HRV), Blood Volume Pulse (BVP), and even Respiration Rate.

Galvanic Skin Response (GSR) is the most common one, used alone orin combination with other sensors. It is a measure of skin conductance, that is, of the electrodermal activity (EDA) of the skin due to the variation in human body sweating. Research combining the body temperature (ST) and skin conductance (GSR) shows that: when a negative experience occurs, the skin conductivity increases and the measured skin temperature decreases (Zeile et.al. 2015).Sweating is controlled by the sympathetic nervous system and skin conductance is an indication of psychological or physiological (sometimes called emotional) arousal. The micro-pulses of sweat is released after a 1- to 2 seconds delay from apocrine sweat glands that are tied to the arousal systems in the body via adrenaline and other hormones. With each pulse of sweat, skin resistance decreases suddenly and creeps slowly back up as the sweat evaporates. Each pulse of sweat increases the electrical conductance of the skin, and when this conductance is measured and tied to arousing stimuli, it's referred to as galvanic skin response (GSR).

The unconscious signals released by human body are an emotional reaction in form of variety of psychophysical responses to any stimuli. The visualizations of measured spatial perception in some sort of "emotional cartography" using biometric Galvanic Skin Response (GSR) sensor in combination with Global Positioning System (GPS) shows that the stimuli are usually in correlation with environmental pressures, such as, in cities, traffic loads, startling noise and environmental pollution (Nold, 2009). However we shall take in consideration that even a disturbing thought that can be triggered by memory and our internal emotional wellbeing can influence the sensor data collection and as a consequence the way we respond to urban environment.

The specific emotion can be specified by using Russell's circumplex model of emotion (1980), which represents emotions along a bi-dimensional representation schema, including valence, the pleasantness of an emotional state in horizontal and arousal, the intensity of activation of the emotional state in vertical axes. The early cognitive representations of urban space started with "mental maps" by Kevin Lynch in 1960s. In the 1970s these "mental maps" or "cognitive maps" evolved by cartographic representation into behavioural geography defining that human spatial behaviour is dependent on the individual's cognitive map of the spatial environment (Roger Downs & Stea 1973). They discovered that human behaviour is dependent on the individual's cognitive map of the spatial environment.

CONCLUSION

To conclude, while most of urban mapping is driven by a human-centric approach calling for citizen-centred perspective in urban planning (Zeile et.al. 2015) the authors suggest asking the following question: how can we consciously evolve our behaviour, shifting our perception of the absolute spaces and therefore influence our impact upon the environment?

The results of our experimentation suggests a clear direction: by dissolving the human I-ness complex that still frames contemporary architecture and move away from pure anthropocentric methodologies. That is to adopt a human - inhuman relationship towards a new epoch of shared Biosphere.

As such the Photosynthetic architectures presented in this paper operate as embedded algorithms within the so called Urbansphere, and acquire a non-human sensibility that we are beginning to "cultivate". Experiencing these spaces stimulates us, as humans, to engage with Urbanspheric processes. We thus evolve our own sensibility and develop a renewed understanding of ourselves in relationship to the planet we inhabit.

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