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The emergence of bioreceptive design is a new material phenomenon that is changing the environmental and biologically-integrated performativity of architecture.

Bioreceptive design: a novel approach to biodigital materiality

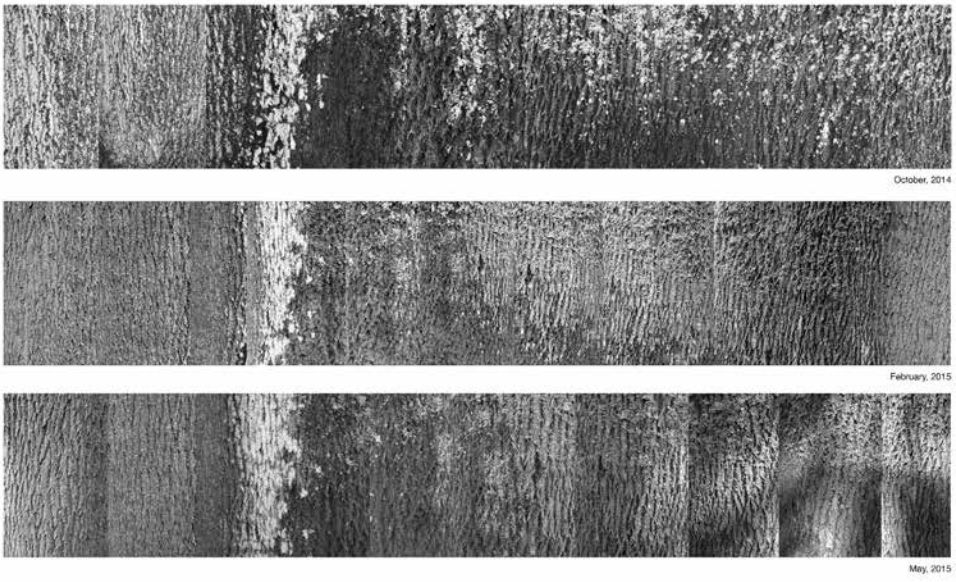
Marcos Cruz and Richard Beckett

Today, at a time of unprecedented urban development, there is urgency to improve the environmental quality of cities. The present 'greening' of urban spaces is an ongoing response to a dirty industrial past and present, with a drive to transform cities to have better air and water, more tree-lined streets and open parks. But the amount of urban public green space varies massively between cities around the world and increasing this, or designing for it, is a particular challenge where there is pressure for space, resources, and development. The architectural fabric itself – building envelopes, roofs, and façades – has been targeted as an opportunity for additional greening.[1] A number of strategies integrating vegetation and other photosynthetic systems onto buildings have been developed, which provide passive climatic control as well as aiding storm-water management and creating new ecological habitat, in addition to lowering atmospheric CO_2. However, 'green walls', where plants and foliage are grown on the sides of buildings as a kind of secondary skin, have been less successful and have proven expensive to implement.[2] Maintenance costs are significant due to the need to overcome gravity, primarily through mechanical irrigation.

Architectural bark

Where the metaphor for green walls might be seen as that of the 'garden' bolted onto a vertical surface, a more biologically intelligent idea might be that of tree bark *[1]*, whereby the building material or façade itself acts as a host to propagate living micro-organisms, cryptogams, and other more complex plants.[3] It is possible to observe here a paradigm shift from the notion of skin, one of the most used metaphors in contemporary architecture, to that of an architectural bark, which is more receptive, mediating between internal and external conditions. Beyond being a defence mechanism and an internal-external regulation system, the bark allows for growth to happen on the immediacy of the architectural skin. Architectural barks offer a different interface for material-tectonic-environmental negotiations to take place between nature and architecture via specific biomaterial performativity.

In temperate climates, like that of the UK, many types of cryptogams – including algae, fungi, lichens, and mosses – have benefits over larger vegetative plants for use on buildings *[2]*. They propagate with spores and do not have root systems that can damage



1 Tree Bark. 180 degree photo taken in November, February, and April showing variations of cryptogamic cover surfaces on an ash tree at Wakehurst Place, Sussex, UK.

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2 Retaining wall along railway line in Finsbury Park with moss propagation.

buildings. Such species behave like epiphytes, yet they are also lower plants that grow on supporting substrates without necessarily affecting or damaging the host. They are hardier and need much less maintenance to survive and establish. More importantly, they can absorb large amounts of pollutants, such as oxides of nitrogen and carbon, which are particularly predominant in our cities. A team of researchers at the Max Planck Institute and University of Kaiserslautern in Germany has assessed the importance of cryptogams in fixing carbon dioxide and nitrogen from the atmosphere and how this is influencing global and regional biogeochemical cycling of these vital chemicals. They estimated that cryptogamic covers take globally up around 3.9 Pg carbon per year, which corresponds to approximately 7% of net primary production by terrestrial vegetation. Nitrogen uptake by cryptogamics, on the other hand, is of approximately 49 Tg per year, suggesting that cryptogamic covers account for nearly half of the biological nitrogen fixation on land.[4]

The architectural bark is not to be understood solely as a biomimetic extrapolation from nature to architecture. In design terms, it is a concept that derives from a specific phenomenon in nature but goes beyond its formal or functional mimesis.[5] In the twentieth century, architects such as Antoni Gaudí, Bruce Goff, and Eero Saarinen, and engineers such as Felix Candela, Pier Luigi Nervi, or Frei Otto have successfully applied structural and formal principles of nature to design. Today, however, bioinspiration or replication tends to focus more on environmentally-led performativity. Current biomimicry, as promoted by science writer Janine Benyus, on the other hand, proclaims the understanding of 'nature as mentor',[6] which risks not only an overtly prescriptive vision for design but also a narrow field of applications, mainly in product-based design. The architectural bark, on the other hand, allows for more complex applications, being nature-inspired and simultaneously nature-integrated, that is, biocolonised and with nature embedded in the depth of the architectural fabric.

Biocolonisation

Surface growth of plants upon a material is known as biological colonisation. Buildings – or more specifically building materials – are all prone to vegetative covers at some point in time, especially micro-organisms and cryptogams that are abundant in air, water, and soil systems. The creation of diverse microbial communities that are in competition and/or synergy with each other on the surfaces of materials is only recently in the process of being understood.[7] Micro-organisms are pioneer organisms, and studies investigating biofilms and the types of species present on colonised building materials show the initial colonisers tend to be phototrophs – algae and cyanobacteria which only require inorganic materials for growth.[8] When established, heterotrophic organisms such as lichens and mosses then follow as a natural succession. The way in which these micro-organisms interact with the material substrate is defined by the mechanisms of their metabolism. Of the high diversity of species and dusts present in urban air, it is the specific environment at the material surface that then acts as a selection factor in determining the predominance of particular strains. This level of adaptability is demonstrated where, through their metabolism, species can cause the chemical conditions to change towards ones that are more favourable to the species. Observation of such growth on buildings show clearly that colonisation is more likely to happen on some materials than others and that this is dependent on the physical and chemical characteristics of the material substrate. Research has shown that particular physical characteristics of roughness and porosity create an ideal attachment system for spores and air dusts to settle. Chemical properties of mineral composition and surface pH are also key properties that affect biocolonisation.[9]

Biocolonisation is often seen on older buildings such as churches and castles and also commonly on roof tiles and statues. This 'growth' can have both positive and negative connotations depending on the viewer. Colonisation in a negative sense can be associated with biodeterioration and biofouling, whereby the originally 'clean' surface of the materials become blemished and stained, making buildings look dirty and unkempt. In addition, plant roots can work their way into gaps and cracks in buildings inducing chemical and physical

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3 Romantic gardens with well of Palacio da Regaleira, Sintra, Portugal.

4 Gardens of Harewood House, UK.

weathering. As a result, much effort is put into façade design to prevent microbial growth and maintain the integrity of materials while safeguarding a much desired 'aesthetic of cleanliness'.[10] Formal strategies to remove growth, such as the use of biocides, external paints and crack fillers all aim to maintain a sense of clean and 'untouched' appearance. The problem with the random look and irregular nature of growth patterns, especially in twentieth-century Modernist buildings, is that they feel like 'matter out of place'.[11] Buildings of that time were largely depleted of ornamentation and therefore of important environmental defence mechanisms, making them more vulnerable to growth. This in turn made growth patches look even more like imperfections or pathologies affecting the pseudo 'health' of the architectural skin. Blotches, speckles and spots of cryptogamic growth evoke visual associations with epidermal disorders, similar to acne or skin sores and rashes; chromatic variability of growth material recalls pigment deviations in skin; and the more three-dimensional the excretions or protuberances of growth, the more the disturbing its visual impact.[12] Current design trends, however, are reconsidering such preconceptions in favour of potentially more natural and thus 'impure' aesthetics: more three-dimensional and complex rather than flat; figurative and recognisable rather than abstract; and visceral rather than epidermal conditions. Walls are gaining a sense of 'inhabitable flesh'.[13] Positive associations of biocolonisation create an additional layer to the material which relates to a feeling of protection and a sense that greenery has an inherent vitality. Vivid biocolonisation has, most of all, connotations of environmental health and wellbeing. Noteworthy is also the nostalgic association of biocolonised surfaces following a bucolic, idyllic vision of nature often experienced at historic palaces, gardens, and ruins. Nineteenth- and early twentieth-century romanticism, for example, exploited images of nature gradually taking over manmade constructions with rocks, walls, and staircases covered with mosses and lichens. This is best seen in the romantic lush of the secret gardens of Sintra in Portugal *[3]*, or the ruins of Harewood Castle in Yorkshire *[4]*, which formed the focal point of its pleasure gardens in romantic paintings. This highlights the significance for contemporary design of culture and aesthetics in the judgement of bioreceptive design, and ultimately the key question for designers about where and how buildings might be colonised.

Bioreceptivity

The likelihood of a material to become biocolonised might be determined by its bioreceptivity; an increasing fundamental phenomenon in sustainable design and, not least, in all the biodigital materiality discussed in this article. The bioengineer Olivier Guillitte defined this term as 'the aptitude of a material (or any other inanimate object) to be colonised by one or several groups of living organisms without necessarily undergoing any biodeterioration'.[14] The same material may be colonised differently in different geographical locations, or even at different facing orientations. As the degree of colonisation on surfaces is dependent on both the inherent properties of the material itself and environmental conditions, this area of work asks design to explore the relationship between the material substratum and areas of the surface that enhance or inhibit growth, as well as specific environment and organisms that thrive in it. Such phenomena, involving designing with living organisms, will never be a static condition. Seasonal changes in environmental conditions, physical and chemical variations of materials that occur over years, and changes that occur as species and other organisms compete and interact with the material, suggest that bioreceptivity is an inherently time-based, yet self-regulating condition in sustainable design.

Guillitte defined three types of bioreceptivity based on this evolving condition. 'Primary or intrinsic bioreceptivity' describes the initial potential of a material to be colonised, as affected many of the projects described later in this article. 'Secondary bioreceptivity' refers to the potential of biological colonisation of a material that has changed over time due to external factors. Finally, 'tertiary bioreceptivity' describes the colonisation potential of a material that has been changed due to human activity such as painting or polishing. Guillitte also defines an 'extrinsic bioreceptivity', which is when a type of colonisation occurs that is not related to the initial conditions of the material but is due to deposits such as soil, dust, and other organic

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particles accumulating on the material surface upon which species can grow. This type of receptivity is especially important for architecture as it affects the slow and long-term evolution of roofs, walls, and façades of buildings – especially those with a high-level textural and topological variability.[15]

For a material to be bioreceptive, it has to be biocompatible with particular types of species that will colonise it in a specific environment. Biocompatibility is well explored in the biomedical field where materials and devices for implant must be physically and chemically suitable to achieve a mutually acceptable coexistence within the host. Understanding these characteristics and the ability to design for them is key:

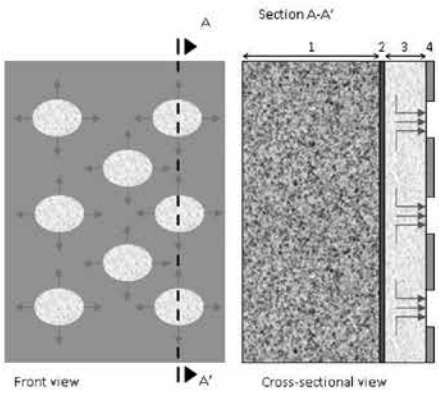
> *It is critical to recognise that synthetic materials have specific bulk and surface characteristics that are property dependent. These characteristics must be known prior to any [...] application, but also must be known in terms of changes that may take place over time* in vivo. *That is, changes with time must be anticipated at the outset and accounted for through selection of biomaterials and/or design of the device.*[16]

But the physical dynamics of bioreceptivity within an architectural context are less well understood. There are currently a range of building components and façade elements that are being designed to be bioreceptive using principles of careful physical and chemical control of the surface and bulk properties of the material. The material design in all of these projects creates a kind of scaffolding that aims to provide surface roughness, pH levels, and optimised porosity values along with water absorption, distribution and retention properties to provide optimal conditions favourable for micro-organisms, algae, lichens, and bryophytes to establish and grow.

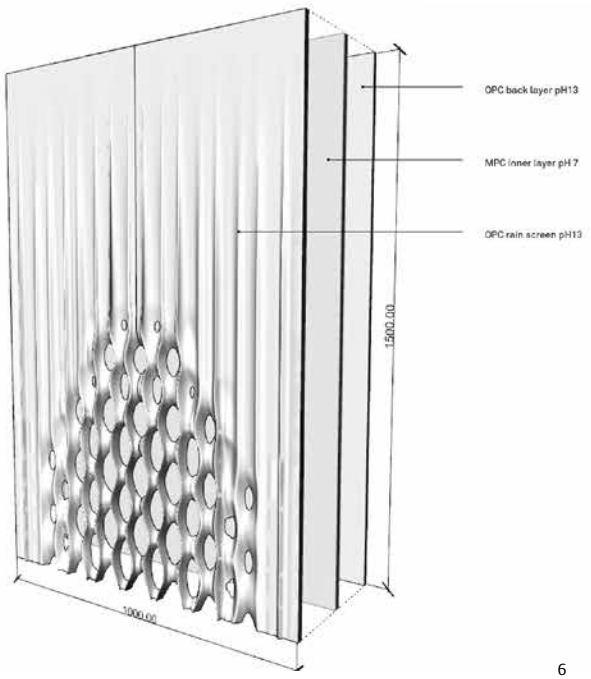
Cementitious materials are of great significance to architecture and design; especially concrete, which not only is the most used material today[17] but arguably also 'the world's most emotionally loaded material'.[18] Typically, Portland cement is too alkaline for living systems to survive. Gradual degeneration affects its consistency decades after having being exposed to the environment, making it less alkaline and creating environmental conditions for some



5



1) *Structural function:* Ordinary Portland Cement;
2) *Anchoring and sealing function:* interface;
3) *Non-structural function:* Bioreceptive mortar with water retention capabilities;
4) *Absorption, water retention and water addressing:* Coating.
Water



PERSPECTIVE

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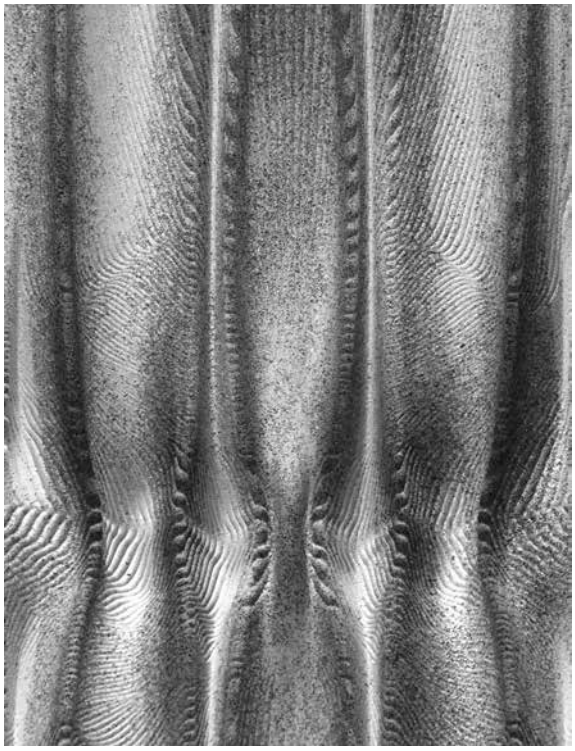
6 Layering of façade panels. SEED-funded project at the Bartlett School of Architecture, UCL, using Sandra Manso Blanco's PhD research on bioreceptive concrete.

7 Façade panel cast with expressive tool path for slowing down water and create grip surfaces for cryptogamic growth. EPSRC funded project 'Computational Seeding of Bioreceptive Materials', Bartlett School of Architecture, UCL (2016).

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micro-organisms to colonise its surface. This growth alters the appearance of concrete considerably – which is perceived by many as looking ugly and inhuman. A significant step was made by the Spanish biologist Sandra Manso Blanco who tested and developed a new type of bioreceptive concrete that provides a biological substratum for growth of photosynthetic systems to proliferate without affecting structural concrete.[19] This pivotal research has led to several research projects that have been developed in the BiotA Lab at the Bartlett School of Architecture, UCL, where the impact of biocolonisation on façades, from the small-scale design of the surface geometry to its application on building panels, is being applied.[20] But the application of Manso's preliminary material tests in architectural façade components raises fundamental research questions about how much biomass such bioreceptive components can really produce in a large scale? It also questions the material performance of water absorption, retention, and distribution within the bioreceptive substratum of the panels, as well as thermal benefits once the components are fully-grown. Ultimately, it brings about aesthetic questions of how new bioreceptive designs will be accepted by a wider audience *[6]*.

The most recent research in the BiotA Lab explores the use of bioreceptive magnesium phosphate concrete (MPC) for application as a façade panel prototype for buildings, derived directly from Manso's research. The research examines the potential for growth at the interfacial layer between the architectural surface and its immediate ecology *[7]*. The panels aim to provide a primary protective layer for a building, but also to act as a host system to support the growth of cryptogams on the outer substratum layer of the architecture itself. This growth of phototropic organisms serves to improve the thermal properties of the panel as well as providing solar absorption and to absorb CO_2 and other pollutants from the environment. Digital design methods and fabrication techniques are being employed to manufacture the panels, exploring how three-dimensional geometries can augment the biological growth and improve panel performance. Observations of tree barks led to the design of geometry types that, along with controlled material application, can serve to define more clearly where areas of growth occur on the panel or not. Features such as fissures, depressions, and striations are designed onto the facing surface of the panels, serving to define areas for growth, channelling rainwater towards them. This allows the creation of areas of shade and protection in some parts whilst exposing other areas. It also pursues an aesthetic aim, towards the positive connotations described earlier. Some of the ordered, yet intricate patterning of the panels relies on motifs that resembled Art Nouveau and Art Deco vocabularies, aiming to control what otherwise could be negatively perceived as a random and ugly looking growth pattern. The panels are designed to have northwest orientation and to be fabricated using a layered concrete casting method into CNC-milled moulds. The panels are then seeded with a mix of algae cells and moss spores using a novel robotic seeding method allowing for precise deposition and amounts of microbial matter in to the growth areas. The seeded panels are prepared to be located outside to undergo environmental monitoring and measurements over a twelve-month period.



7

Interdisciplinary methods

The accomplishment of this, as with any bioreceptive design project, relies on the implementation of interdisciplinary work methods, requiring knowledge in high-end computation (integrating various software packages and environmental analysis tools), manufacturing (3D printing and robotics), design engineering, along with lab protocols and biology. Such cross-disciplinarity and complementarity of workflows between different expertise and strands of research has, for example, been experienced in the Alga(e)zebo folly for the London Olympics in 2012 *[8]*.[21] While the design of the structure was developed in London, structural calculations were done by engineers in Vienna, material and fabrication experiments with perforated double-steel curvature carried out in Germany, and algae bioreactors prepared and tested back in London. Bioreceptive design then moves beyond a 'top-down' design approach where architectural forms are exclusively modelled. The multidisciplinarily approach, as well as recursive methods of 'scanning – scripting – fabricating – growing' implies simultaneously a 'bottom-up' and 'top-down' approach. In many cases, the growth of vegetation is monitored and scanned so as to influence the scripts that result from each growth moment and the environmental vicissitudes that determine the growth. Once fabricated, the designs, structures, scaffolds, prosthetics, incubators, etc. are

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8 Alga(e)zebo by marcosandmarjan at Euston Square Gardens, London, UK. Algae photo-bioreactors inserted in double-steel corteen structure by marcosandmarjan and Richard Beckett.

then manufactured to grow species with the intention to either enhance or diminish its growth. This is again scanned while determining a different scripted outcome.

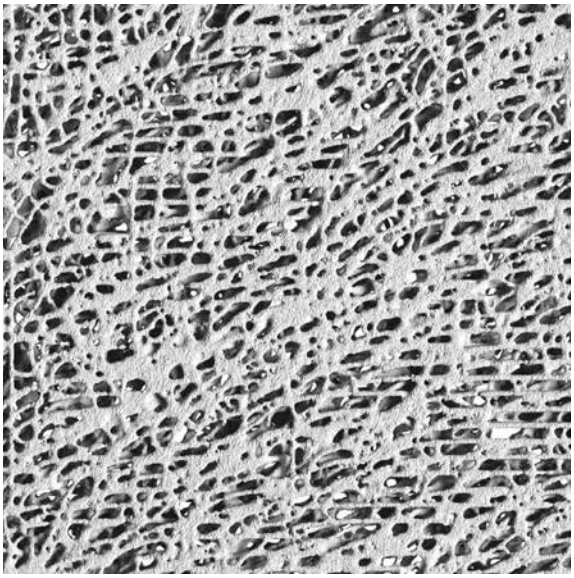
At the same time, bioreceptive design is highly dependent on the implementation of sophisticated environmental simulations and analysis that allow for evaluating and determining the design outputs according to climatic factors, including humidity and temperature. But while common sustainable design relies primarily on the analysis of environmental conditions on a building scale, new bioreceptive design suggests that material and environmental conditions need to be taken into account on various scales simultaneously. Building orientations and exposure to climate (macro) are commonly analysed with software such as Ecotect, Diva plug-in for Rhino, Ladybug, and Honeybee plug-ins for Grasshopper, or ADMS. These techniques can work in tandem with a more specific evaluation of textural and geometric morphologies of façade components (meso) that measure the specific 'microclimates' on the surface. Numerical analysis of moisture retention and movement can be achieved with multiphysics software. Physical testing and evaluation of fabricated prototype designs can then be fed back into such systems, preserving the 'bottom up' approach. Such analytic tools should be complemented with additional monitoring and testing of material performativity, including the porosity and pH level of surface and bulk properties via porosimetry and x-ray tomography (micro). In cementitious materials, for example, tests need to take in account the type of hydraulic binder, aggregate size, water/cement ratio and amount of cement paste.[22] The combination of all these material and environmental factors analysed on various scales allow for a more complete understanding of the design.

Laboratory experimentation is a key aspect of preparatory research work for such projects, both indoor and outdoor. While indoor (mainly *in vitro*) growth procedures have the advantage of sterile surroundings that allow for growth in isolation of species – essential for scientific experimentation – outdoor labs are specifically chosen natural conditions in which nature works in its entirety and with all its levels of complexity. A well-chosen spot allows for careful observation procedures and predictions of how nature responds to certain changes of material and climate.

Modelling growth

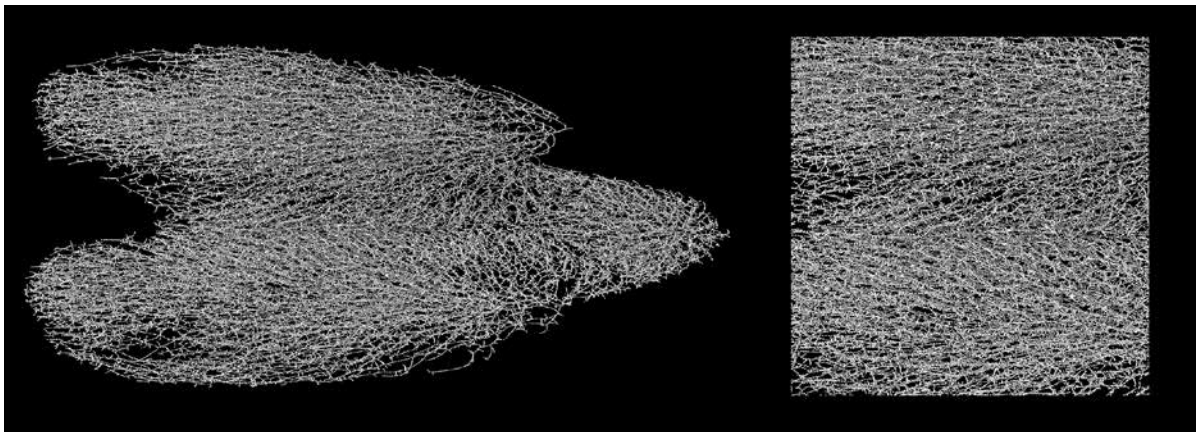
Bioreceptive design differs from the common biodesign[23] that is widely explored in the arts and is by-and-large uncomputational. Bioreceptive design is specifically architectural in its application, material-driven, and dependent on the use of sophisticated computation for both simulation and fabrication purposes *[9]*. Exploring self-generative processes using computational design tools can grow and evolve three-dimensional complex geometries as an alternative approach to manually drawing and modelling form. In the 1960s, the architect William Katavolos, in his manifesto essay titled 'Organics', described a new type of 'chemical architecture' in which furniture, buildings, and even cities could be grown from genetically-engineered and pre-programmed polymers and seeds.[24] And the architect John M. Johansen defined a new type of architecture that he defined as 'molecular nanoarchitecture structures' and spoke of the possibility of growing an entire house with all its inner complexities from genetically pre-programmed seeds.[25] Today, even when far from achieving such visions, new computational systems can begin to shape form from self-emergent logics, but also in response to environmental factors such as sunlight, or nutrient availability or physical factors such as gravity or wind loading via simulations. This introduces a parameter-driven, evolutionary, and responsive dimension to the design process.

In order to model growth, specific algorithms are defined based on mathematical models of growth systems that exist in nature. These algorithms exploit



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9 Computational simulation with Houdini software. The use of a fibrous structure provided the opportunity for a porous multidimensional mesh to be occupied by meta-ball aggregates. These fibrous assemblages allowed for aggregates to be attached following an extra torsion, or noise, in between the solid entity and the surface structure. This created an additional layer of morphing surfaces that further enriched the geometry.

10 Computational simulation with Houdini software. The design derived from a self-generative branching system that defined the overall complexity and intricacy of the pervious material structure.

a procedural approach, building geometries recursively from base elementary rules where repetition of these basic functions repeat and layer together resulting in more and more complex forms throughout the generations of the algorithm. Seminal influences have been Alan Turing's mid-twentieth-century computational experiments in what he called 'Diffusion Reaction Theory of Morphogenesis in Plants',[26] as well as Aristid Lindenmayer's geometric branching models that created the precursors to what today are some of the most used procedural growth algorithms, including L-System; Diffusion Limited Aggregation; Venation System and; Grey-Scott Reaction Diffusion. In practice, such systems have a large amount of parameters that can be adjusted, and the simulation run again.

In this context, digital simulations imply two distinct, yet complementary principles. On the one hand, simulations can generate form. Scripts derived from the specific growth patterns can be use to create self-emergent processes that lead to morphological iterations. This is, to a large extent, an inside-out process that is vital to define the outer contour of each project *[10]*. On the other hand, simulations are used to show real growth that will emerge on the surfaces of designs. These simulations are illustrations or predictions that are dictated by the behavioural understanding of species, environmental factors, and specific location. In addition to the use of self-generative design tools are digital fabrication processes that enable the high-resolution manufacturing of designs in various scales and add another level of complexity to the design. The careful choice of tool paths in CNC milling, for example, as it happened in the Algae-Cellunoi wall construction exhibited at Archilab in 2013, not only changed the surface roughness, but also increased substantially the three-dimensional depth of the overall geometry.[27] 3D printing and robotic printing in particular is important for the making of bioreceptive scaffolds with a high level of filigree on which plants can flourish.

Bioscaffolds

To grow architecture from living cells is an intriguing proposition, but raises the problem of how one might grow cells or tissues in to specific, defined, and even complex geometries. One solution to this is to design a scaffold system in and on which the cells can grow and proliferate but where the overall geometry is designed and formed by the geometry of the scaffold. The notion of bioscaffolds stems specifically from research done in the field of tissue engineering which has focussed on the aim of developing biological substitutes that are biocompatible and which serve functionally to restore, replace, or regenerate damaged tissues.[28] In such cases, the scaffold – typically made of a biomaterial, has a structural function providing mechanical support for cell attachment and subsequent tissue development.[29] Furthermore, these scaffolds exhibit voids and pores so that the tissues or cells grow throughout the volume of the scaffold, which eventually degrades, leaving the grown cells occupying the space defined by the scaffold. In the field of architectural design, without the complexities of tissue engineering and without the need for implanting into the body, the idea of a bioscaffold is inherent in the condition of bioreceptivity of materials that work as hosts for species to grow according to predetermined geometries not available in nature.

Primarily, the material itself, providing it has the right bulk properties of roughness and porosity levels, can become the direct scaffold for growth where the designer can define the overall geometry. Contemporary fabrication techniques mean that form creation is almost unlimited. 3D printing in particular now allows for the creation of complex geometries with detailed internal matrices, which can be defined using engineering principles of architectured materials that can either augment or decrease the growth of species in areas.

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Bioscaffolds can be understood in architectural, biological, and/or mechanical terms. For architecture, bioscaffolds can be designed according to the notion of scalar hierarchies. The lower level is defined by the properties of the material chosen, which should have a degree of porosity but not at the expense of mechanical strength. The medium level describes how the geometry of the material property space of the larger level volume is filled. Rather than being solid, this internal geometry is designed as spatial lattices as such to facilitate tissue or cell integration upon seeding. Typically this means that a level of cellular or porous structure exists that allows for the movement of water, nutrients, and cells throughout the volume. The larger level defines the overall geometry of the object in its final form. Providing a structural framework on which cells can grow, this allows a predetermined geometry to be achieved which may or may not be typical in nature. In biological terms, the materials used to fabricate the scaffold should be compatible with the cells or tissues that are to be grown. The material can be a nutrient source for the developing cells, which can be absorbed or metabolised, degrading as the cells grow. Bioscaffolds can be biodegradable or rigid (non-degradable). When biodegradable – in some cases working as implants – they can work as temporary scaffolds, temporary barriers, or multifunctional scaffolds. On the other hand, bioscaffolds can be a more permanent system that acts a delivery system for growth stimulating factors, remaining as part of the object throughout its lifespan. In mechanical terms, the scaffold should provide the mechanical strength and form of the geometry and for long enough that the cells can grow.

Bioreceptive design projects

A number of projects are being developed with researchers and students in the BiotA Lab at the Bartlett focused on creating bioreceptive designs with integrated bioscaffolds that are both biodegradable and rigid. These projects combine processes of self-emergent design, digital fabrication, and material and environmental testing while being done with a variety of materials, ranging from magnesium phosphate to sandstone, cellulose-filament composites, and hydrogels. The projects aim at creating new façade prototypes that can potentially increase green surfaces in our cities.

One of the first projects focused on design engineering bioreceptive bricks to support moss growth *[11]*.[30] Complex three-dimensional geometries increased the overall surface area available for microbial growth within the bounding box volume of the elements. Real world observations of sandstone rocks in Kew Gardens, London, which were covered in an abundance of algae, lichens, and mosses proliferating upon the material substratum, created the material test bed of the project. Following extensive material testing, a mix of MPC and sandstone was employed to achieve comparable values in terms of mineral composition and pH levels to that of the original rocks. The material composite was developed chemically to acquire a rather neutral pH level of 7–8, optimal values for the colonisation of the chosen moss species including *Atrichum Undulatum* and *Hedwigia Ciliata* (White-tipped Moss).

Aggregate sizes and water content were carefully explored in order to achieve suitable porous surfaces and bulk properties. This included water retention, surface roughness, and capillary action for these specific moss species, as well as maintaining a suitable particle size and powder flow behaviour for the 3D printing. The platform used was a ZCorp 510 machine that printed in 0.25mm layers using an organic binder at various deposition rates and amounts. Once printed, the bricks were removed and dried at 30 degrees for 2 hours prior to depowdering. Further steps in the manufacturing of the bricks included bioengineering the sandstone mortar with different types of bacteria in order to find new ways to structurally stabilise the 3D-printed MPC. The design of the bricks followed sediment branching geometries that were developed via computational simulations with Spatial Colonisation System and Diffusion-Limited-Aggregation algorithms. The coral-like branching geometries had both primary and secondary structural elements. These followed a rule of distance between each line (branch) that enabled the swollen material during the 3D printing to keep sufficient interstitial spaces for moss to grow.

A second project explored robotic extrusions of cellulose-based materials as a physical and nutritional architectural scaffold for the growth of mycelium within defined areas upon larger architectural screens and façade panels *[12]*.[31] The project addressed issues of bridging the biological scale in design from the microscopic, within a petri dish, to the macro scale of architectural application. It differed from previous projects that integrated fungi in buildings, such as Steve Pike's 'Contaminant', as it used complex computational algorithms of filamentous geometries. It also differed from the mycelium bricks by Ecovative that were grown throughout to achieve maximum solidity and homogeneity.[32] The robotically extruded mycelium screens were inspired by fungal spore growth to explore multiscalar geometric design applied to multi material fabrication. They also used mycelium as binding elements while exposing the previously incubated mycelium in its stable and fully-grown condition on the panels without the need of onsite encapsulation.

The fabrication platform of the panels was composed of a Kuka robotic arm as a positioning system with a bespoke double extrusion head to control height and speed of deposition. Algorithmic growth patterns evolved the negative spaces and channels between the filamentous geometries, which were interpreted by the robot as various degrees of 'curly' geometries that depended on the careful calibration of distance, speed and size of printing nozzle. These augmented the porosity and bioreceptivity of the channels for mycelial growth. Pore size gradients defined by material permeability (micro) and geometry (meso), along with variation in percentage cellulose allowed for design strategies that served to augment or restrict the mycelium growth in specific areas. Laboratory based processes

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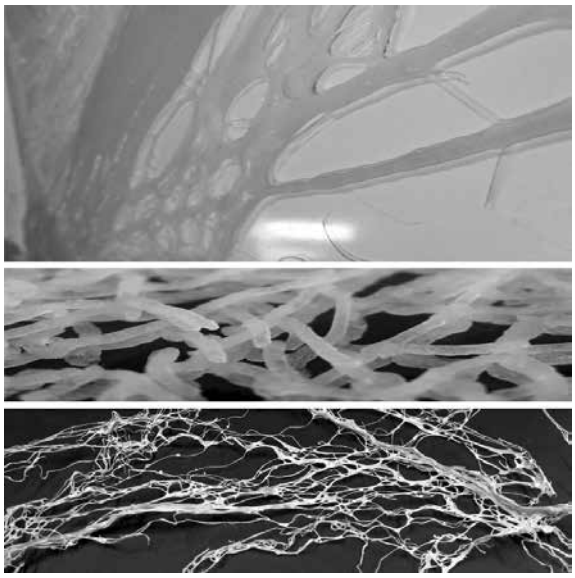
11 3D printed bioreceptive sandstone brick for moss growth.

12 Screen made of a cellulose composite for mycelium growth.



12

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13

13 Hydrogel screens for algae growth.

14 Lightweight concrete components for cryptogam growth.

for incubating and growing mycelium spores seeded into these filamentous scaffolds led to a novel feedback system. Mycelium spores were manually placed into the initial scaffold and incubated under optimal laboratory conditions for one week. The components were then scanned using an AriusTechnology scanner and the subsequent point cloud data reintroduced into the computational algorithm that defined the next geometry to be fabricated directly on top of the existing component. The pieces were then reincubated and the cycle repeated, creating a multilayered and multimaterial screen composite.

A third research project focused on the design and manufacturing of a new type of environmentally responsive screens *[13]*.[33] It explored a novel bioreceptive gel based material fabrication process tailored for direct 3D printing of algae cells within semi solid hydrogel composites, including Curran and Sodium Alginate. The project was aimed at medium scale architectural panel screens that could host and provide the nutrients for the growth of algae species as an aesthetic and/or functional



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prototype for biomass production and wastewater treatment. Bottom-up material design used water primarily as a life sustaining element to promote the growth of *Chlorella Sorokiniana*, while at the same time controlling the percentage of water content to control viscosity for fabrication and exploring the principles of variable hydration. To date, many architectural proposals using algae growth for potential energy have employed the notion of containment. This includes the Urban Algae Farm in Milan by EcoLogicStudio[34] and, more so, the BIQ façade by Arup / SSC / Colt for an experimental housing project in Hamburg, where the algae cells were cultured in a liquid within a container with clear tubular bioreactors or flat transparent panel containers.[35] Such bioreactor systems are heavy due to large amounts of water, energy intensive in terms of pumping and circulation and expensive to run and maintain. The proposed hydrogel panels, on the other hand, created an alternative, inverting the idea of a container by growing terrestrial rather than aquatic algae on the gel surface itself. The multilayering of hydrogel printing allowed for the lower (back) layers to dehydrate and become rigid, providing a structural support for the upper (front) layers, which could be moisturised according to variable air humidity or rainfall. This allowed to define stiffness gradients providing structural and non-structural areas towards an architectural proposition where the hydrogel created its own scaffold on which algae growth could switch on and off according to variable climate conditions.

The geometries used in the hydrogel panels were tailored to provide a large surface area for biomass growth whilst remaining lightweight, requiring little maintenance and potentially being recyclable as a system. Fibrous geometries defined by the fabrication technique and inspired by natural algal formations in aqueous environments were explored through particle simulations and cell division algorithms using Houdini software. The linearity of the geometries provided a perfect network of channels for water to irrigate the whole panel according to gravity, humidity, wind, and solar conditions. The design patterns were later decoded for a UR10 robotic arm to print the panels. The robot had a positioning system with a bespoke pneumatic deposition container and nozzle that digitally controlled the hydrogel in terms of height and speed of material deposition.

A fourth project explored the notion of bioreceptivity through the design and fabrication of lightweight aggregate concrete façade components that acted as a physical scaffold upon which a second bioreceptive coating could be applied *[14]*.[36] Explored as a series of 'plug-in' façade components, the project proposed the tessellation of elements across a building envelope. These lightweight elements were seeded, incubated, and planned for attachment to a building, allowing them to be easily removed for reincubation or cleaning and replacement. Geometric design of the components used cell division algorithms to define growth areas and particle flow techniques considering directional water channelling to these growth areas. Endolithic blob geometries were also 'grown' and defined by environmental feedback from solar/shading analysis and predominant wind directions. Rigorous and extensive material design controlling aggregate size and water content was explored to achieve a gradated control over surface roughness and porosity related to moisture uptake. High surface roughness and high moisture uptake defined a secondary bioreceptive condition whereas smooth surfaces and low porosity defined non-bioreceptive areas. These principles were then materialised through a series of casting experiments in order to develop fabrication strategies that could be extrapolated to other designs and scale components.

A new paradigm for sustainable architecture

As seen in all the research projects, the shift from skin to bark and material bioreceptivity has brought about a new paradigm for sustainable architecture defined here as bioreceptive design. All projects were determined by novel computational methods and manufacturing processes, while at the same time relying on a complex interdisciplinarity. But all the projects discussed have shown that bioreceptive design has to consider carefully the transition and interaction between biological (plants) and synthetic (inert) systems. This integration of small-scale growth systems in large-scale architectural structures is undoubtedly one of the biggest challenges for all designs. The visions of Peter Cook's Veg House project, which he has been developing since the 1970s, has highlighted the potential beauty – but also complexity – of integrating different scales and intertwining nature and architectural artifice into a new hybrid biodigital materiality. In bioreceptive design, growth patterns were tested on small scale and *in vitro* (from molecular to petri dish scale), making it hugely unpredictable when trying to incorporate these procedures into the scale and complexity of buildings. What can be successfully grown under environmentally controlled conditions will not necessarily succeed on a larger scale and in an outdoor context. As a consequence, bioreceptive projects tend to look for new solutions that can bridge scale and material differences. Possible solutions include building bioscaffolds as transition paths that are created as geometric derivatives from the species own geometries. For example, the filamentous geometry of fungi or mosses suggests a mirrored and/or negative geometry into which these species can grow, creating a contiguous and seamless gradient from naturally grown (species) to synthetically stable (architecture).

At an architectural scale, it is not the intention that all areas should be fully grown and covered. Selected areas of growth, as opposed to complete coverage, demands the design and careful control of growth and non-growth areas or, as they are otherwise defined, 'enhancing' or 'inhibiting' areas. It remains as a necessary challenge for multidisciplinary teams of designers, biologists, and engineers to define these areas based on aesthetics, material, morphological and biological, as well as

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15 Robotic printing of hydrogel screens for algae growth.

16 Robotic printing of a cellulose composite screen for mycelium growth.



scale variability. In this sense, rather than letting walls, façades or any other mechanism become colonised randomly, design should choreograph the bioreceptive surface and bulk properties of the materials in what could be considered a new, ever-evolving, and changing ecological map of architecture. Physical properties relating to water retention and pH level are key to determining areas of growth or inhibition of species but one should also consider morphological variations including the size and depth of surface geometries which can also stimulate diverse intensities of growth within an outdoor environment. Areas of shadow, areas of protection, crevices that trap dust and nutrients and water channels are all typological variables that occur on tree barks that provide very specific conditions at the material surface which allow for or restrict growth.

In the future, advances in robotic printing and milling will allow for increasingly complex design methodologies to integrate large data sets and improve accuracy, precision, and speed for

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fabrication *[15]*. It will also allow for the ability to monitor and adapt during fabrication a sense of 'operating' *in vivo* on bioreceptive components. Feedback systems can be integrated in to the fabrication stage which can add material where it is needed to provide more scaffold, or subtract material where it is not needed and robotically 'seeding' living cells, or more nutrients in to specific areas that have the best chance for growth to occur both in the lab or once established in the external environment *[16]*. By designing for microbial colonisation using a predominantly bottom-up, yet in steps also top-down, process, biocreceptive design defines an architecture of 'impure aesthetics' where the material substratum, in supporting and enhancing growth, goes beyond the current idea of green walls because it does not need any maintenance of irrigation for nature to regulate itself. Ultimately, bioreceptive design of newly biocompatible scaffold systems allows nature to grow according to its own rules in a reciprocal response to parameters of a biodigital materiality.

Notes

1. Marc Ottelé, *The Green Building Envelope: Vertical Greening* (PhD thesis: Technical University of Delft, 2011), p. 2.
2. Ibid.
3. Note that in tropical environments, tree barks can create prolific ecosystems where numerous plant parasites are formed of complex plants with a substantial growth bulk.
4. Wolfgang Elbert, Bettina Weber, Susannah Burrows, Jörg Steinkamp, Burkhard Büdel, Meinrat O.Andreae, Ulrich Pöschl, 'Contribution of Cryptogamic Covers to the Global Cycles of Carbon and Nitrogen', in *Nature Geoscience*, 5 July (2012), 459–62 (p. 459).
5. This principle reflects what has previously stated in Marcos Cruz and Steve Pike's *AD – Neoplasmatic Design* (London: Wiley, 2008); as well as William Myers's *BioDesign: Nature + Science + Creativity* (London: Thames and Hudson, 2012).
6. Janine Benyus, *Biomimicry: Innovation Inspired by Nature* (London: Harper Collins Publishers, 1997).
7. A. Z. Miller, P. Sanmartin, L. Pereira-Pardo, A. Dionisio, C. Saiz-Jimenez, M. F. Macedo, B. Prieto, 'Bioreceptivity in Building Stones: A Review', in *Science of the Total Environment*, 426, 1 June (2012), 10.
8. Christine Gaylarde and L .H. Glyn Morton, 'Deteriogenic Biofilms on Buildings and their Control: A Review', in *Biofouling: The Journal of Bioadhesion and Biofilm Research*, 14:1 (1999), 59–74.
9. J. J. Ortega-Calvo, X. Ariño, M. Hernandez-Marine, C. Saiz-Jimenez, 'Factors Affecting the Weathering and Colonization of Monuments by Phototrophic Microorganisms', in *Science of the Total Environment*, 167:1–3, May (1995), 329–41.
10. This term is used by Adrian Forty in his chapter on 'Hygiene and Cleanliness', in *Objects of Desire: Design and Society since 1750* (London: Thames and Hudson, 1986), pp. 156–81.
11. The anthropologist Mary Douglas uses this expression in relation to the cultural construction of 'dirt' in her seminal book *Purity and Danger: An Analysis of Concepts of Pollution and Taboo* (London: Routledge, 1966), p. 165.
12. This analysis derives from Marcos Cruz's descriptions of the aesthetics of flesh, where he refers to a long-standing cultural construct of clean and pure aesthetics in architecture. For more see Section 1 of his book *The Inhabitable Flesh of Architecture* (Aldershot: Ashgate, 2013), pp. 41–66.
13. See the definition of 'inhabitable flesh', Ibid., pp. 1–34.
14. Olivier Guillitte, 'Bioreceptivity: A New Concept for Building Ecology Studies', in *Science of the Total Environment*, 167:1–3, May (1995), 215–20.
15. Ibid., p. 216.
16. Buddy D. Ratner, Allan S. Hoffman, Frederick J. Schoen, Jack E. Lemons, *Biomaterials Science: An Introduction to Materials in Medicine* (London: Academic Press, 1996), p. 11.
17. James Mitchell Crow, 'The Concrete Conundrum', in *Chemistry World*, March (2008), 62–6.
18. Invited text for the conference *Concrete: A Cultural History* held at the Royal Institute of British Architects in London on 7 July 2015.
19. Sandra Manso Blanco, *Bioreceptivity Optimisation of Concrete Substratum to Stimulate Biological Colonisation* (PhD Thesis: Universitat Politècnica de Catalunya, 2014).
20. An internal SEED-funded project at the Bartlett led to 'Computational Seeding of Bioreceptive Materials', which is an ongoing ESPRC-funded research project (2015–17) developed by Marcos Cruz, Richard Beckett, Sandra Manso Blanco, Chris Leung, and Bill Watts, with the support of the industrial partner Laing O'Rourke.
21. Alga(e)zebo, one of the Mayor of London's 'Part of Wonder: Incredible Installations'. Design team: marcosandmarjan; Manufacturer: Formstaal / CSI, Stralsund Germany; Engineering: Bollinger, Grohmann und Schneider, Vienna Austria; Photobioreactor: Richard Beckett with UCL Algae.
22. Information derived from Manso Blanco, *Bioreceptivity Optimisation of Concrete Substratum*.
23. This term has been widely disseminated through the exhibition and publication *Bio-design: Nature Science Creativity*, curated by William Myers in 2012.
24. See the description of William Katavolos's work in William W. Braham and Jonathan A. Hale (eds.), *Rethinking Technology: A Reader in Architectural Theory* (London: Routledge, 2007), p. 140.
25. Available online: <http://johnmjohansen.com/Nanoarchitecture.html> (accessed 7 March 2016).
26. P. T. Saunders (ed.), *Collected Works of A. M. Turing: Morphogenesis* (Amsterdam: North Holland, 1992).
27. Algae-Cellunoi wall installation for the Archilab exhibition at the FRAC in 2013. Design team: marcosandmarjan with Guan Lee and Richard Beckett; Collaboration: Olivia Pearson, Emu Masuyama, Jessie Lee, Keith McDonald, Jonas Brazys, Cullum Perry; Fabrication: Grymsdyke Farm, DMC London; Algae Technology: Marin Sawa with Nixon Group and Hellgardt Group (Imperial College, London) and Richard Beckett (UCL). Sponsors: Bartlett School of Architecture; Grymsdyke Farm; Innsbruck University.
28. S. Levenberg and R. Langer, 'Advance in Tissue Engineering', in *Current Topics in Developmental Biology*, 61, February (2004), 113.
29. B. P. Chan and K.W. Leong, 'Scaffolding in Tissue Engineering: General Approaches and Tissue-specific Considerations', in *European Spine Journal*, 17, Supplement 4, December (2008), 467.

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30. The project of bioreceptive bricks was develop by BiotA Lab at the Bartlett with Zhixiong Yang, Chang Lui and Chae Ah Ahn in 2014–15.
31. The project of robotically extruded mycelium screens was develop by BiotA Lab at the Bartlett with Cheng-Hsiang Lew, Xia Chen Wei, You-Han Hu, and Yuan Jiang in 2014–15.
32. The project *Hy-Fi* designed by David Benjamin in 2014 explored the use of mycelium bricks to build a pavilion in New York as an experiment with reused and recycled mushroom materials.
33. The project of hydrogel algae screens was develop by BiotA Lab at the Bartlett with Shneel Malik, Soo Hyung Kin, Sunbin Lee, Yuxi Lu in 2014–15.
34. EcoLogicStudio completed a range of installations exploring algal cultivation within architecture. The Urban Algae Farm done for the Expo Milan 2015 used bag bioreactors incorporated in to the structural elements of the folly.
35. The BIQ façade is a seminal project constructed in 2013 in which algal strains are cultivated in flat panel bioreactors integrated on to the façade of the building and harvest.
36. The project of lightweight biocereptive façade components was developed by BiotA Lab at the Bartlett with Sul Ah Lee, Tae Hyun Lee, Dan Lin, Wen Cheng in 2014–15.

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Marcos Cruz is Professor of Innovative Environments at the Bartlett, UCL, and Director of BiotA Lab. He researches design driven by advances in computation, biotechnology, and the environment. His research on Neoplasmatic Architecture won the RIBA President's Award for Research in 2008. In addition to the Directorship of the Bartlett (2010–14) where he has run MArch Unit 20 for over 16 years, he has also taught at UCLA, University of Westminster and IaaC Barcelona. Cruz also cofounded the atelier marcosandmarjan with whom he has built over twenty installations and buildings. He is currently Principal Investigator of a major EPSRC 'Design the Future' research grant.

Richard Beckett is an architect, lecturer, and Director of BiotA Lab at the Bartlett, UCL. He has a multidisciplinary background, studying biochemistry and working in R&D for Glaxosmithkline as a material scientist before studying and teaching architecture at UCL. His research focuses on digital architecture and novel fabrication techniques and, more specifically, investigations into the use of living or semi-living materials in the built environment. He has expertise in the field of computational data production, 3D printing, and digital manufacturing. He cofounded design/fabrication consultancy Arch-T in 2013 working at a range of scales and industries from architecture to fashion. A recent design collaboration, developing novel 3D printed fabrics with Pringle of Scotland 2014–15, found international acclaim. Beckett is currently working on an EPSRC 'Design the Future' research grant.

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