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

BIORECEPTIVE DESIGN
A novel approach towards bio-digital materiality

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In a time of unprecedented urban development there is today an urgency to find new ways to improve the environmental quality of our cities. The present 'greening' of urban spaces is an on-going response to our dirty industrial past and present, with a drive to transform cities so that they have clean air and water, 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] Here 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 CO2. However, 'green walls', whereby plants and foliage are grown onto the sides of buildings as a kind of secondary skin, have been less successful and proven expensive to implement.[2] Maintenance costs are expensive due to the walls' vertical nature and the need to overcome gravity in a way that horizontal surfaces do not – primarily through mechanical irrigation.

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 facade itself acts as a host to propagate living microorganisms, cryptogams and other more complex plants.[3] One can 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 and mediating between internal and external conditions. Beyond the idea of 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 climate like in the UK, many types of cryptogams, including algae, fungi, lichens and mosses, are particularly important as they have many benefits over larger vegetative plants for use on buildings *[2]*. They propagate with spores and do not have root systems that can damage buildings. Such species behave like epiphytes, yet they are also lower plants that grow on substrates for structural support without necessarily affecting or damaging the host. They are hardier and need much less maintenance to survive and establish and, 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 bio-mimetic extrapolation from nature to architecture. It is a concept that in design terms derives from a specific phenomenon in nature, but goes beyond its formal or functional mimesis.[5] In the 20th century, architects such as Antoni Gaudi, Bruce Goof and Eero Saarinen, and engineers such as Felix Candela, Pier Luigi Nervi or Frei Otto have successfully applied structural and formal principles of nature and applied them to design. Today, however, bio-inspiration or replication tends to focus more on environmentally led performativity. Current bio-mimicry, 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, i.e. bio-colonized and with nature embedded in the depth of the architectural fabric.

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 microorganisms and cryptogams that are abundant in our 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 being understood.[7]

Microorganisms 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 these respectively as a natural succession. The way in which these microorganisms interact with the material substrate is defined by the mechanisms of their metabolism. Of the high diversity of species and dusts present in our 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 both the physical and chemical characteristics of the material substrate. Research has shown that in particular, physical characteristics of roughness and porosity create an ideal attachment system for spores and air dusts to settle. Also chemical properties of mineral composition and surface pH are key properties that affect bio-colonisation.[9]

Bio-colonisation 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 in to gaps and cracks of buildings inducing chemical and physical weathering. As a result, a lot of effort is put in façade design to prevent microbial growth to 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 20th century Modernist buildings, is that they feel like 'matter out of place'.[11] Buildings of that time that fill our contemporary cities, were depleted of any kind of ornamentation and therefore of important environmental defence mechanisms, making them more vulnerable to growth. This in turn made any growth patches look even more like imperfections or pathologies that affect the 'purity' and 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; also 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, including 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 bio-colonisation also create an additional layer to the material that relates to a feeling of protection and a sense that greenery has an inherent vitality. Vivid bio-colonisation has, most of all, connotations of environmental health and wellbeing. Noteworthy is also the rather nostalgic association of bio-colonised surfaces that uses a bucolic, idyllic vision of nature often experienced at historic palaces, gardens and ruins. 19th and early 20th century romanticism, for example, exploited imagery of nature gradually taking over man-made constructions, with rocks, walls, and staircases covered with moss and lichens. This is best seen in the romantic lush of secret gardens of Sintra in Portugal *[3]*, or the ruins of Harewood Castle in Yorkshire *[4]* that formed the focal point of its pleasure gardens in many romantic paintings of its time. For contemporary design, this highlights the significance of culture and aesthetics in the judgement of bio-receptive design, and ultimately the key importance for designers to question where and how buildings might be colonised or not.

The likelihood of a material to become bio-colonised might be determined by its bioreceptivity, which is becoming an increasing fundamental phenomenon in sustainable design and, not least, in all bio-digital 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, which is what affected many of the projects described later in this article. 'Secondary bioreceptivity', refers to the potential of biological colonisation of material that has changed over time due to external factors, and finally 'Tertiary bioreceptivity', which is 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 colonization occurs that is not related to the initial conditions of the material but is due to deposits such as soil, dust and other organic 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 facades 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 whereby materials and devices for implant must be physically and chemically suitable to achieve a mutually acceptable co-existence within the host. Understanding these characteristics and the ability to design for them is key:

> *'It is critical to recognize 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 these projects creates a sense of scaffolding which 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 microorganisms, algae, lichens and bryophytes to establish and grow.

Cementitious materials are of great significance to the discipline of 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] But 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 environmentally creating conditions for some microorganisms to colonise its surface. This growth considerably alters the appearance of concrete - 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 bio-colonisation on facades, from the small-scale design of the surface geometry to its application on building panels, is being tested and understood for it to become usable in the construction industry.[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? And 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, which 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 on to the facing surface of the panels that serve to define areas of growth, channelling rainwater to specific growth areas. This allows creating areas of shade and protection in some parts whilst exposing other areas. It also creates an aesthetic aim towards the positive connotations described earlier. Some of the ordered, yet intricate patternisation of the panels relies on motifs that resembled art nouveau and art deco vocabulary, aiming to control what otherwise could be negatively perceived as a random and ugly looking growth pattern. The panels are designed to have northwest facing orientation and to be fabricated using a layered concrete casting method in to 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 12-month period.

The accomplishment of this, as well as in 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 follie for the London Olympics in 2012 *[8]*.[21] While the design of the structure was developed in London, the 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 multi-disciplinarily approach, as well as recursive method of scanning – scripting – fabricating – growing, implies a simultaneous 'bottom-up' and 'top-down' approach. In many cases the growth of vegetation is monitored and scanned so 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 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 in 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 much more specific evaluation of textural and geometric morphologies of façade components (meso) that measure the very specific 'microclimates' on the surface. Numerical analysis of moisture retention and movement can also be achieved with multi-physics software. Physical testing and evaluation of fabricated prototype designs is then fed back in to 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 and understanding of the design.

For preparatory research work for such projects, indoor and outdoor lab experimentation is a key aspect. 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 right chosen spot allows for careful observation procedures and predictions of how nature responds to certain changes of material and climate.

Bioreceptive design differs from common Bio-design[23] that is widely explored in the arts and is by and large un-computational. 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 entitle '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] Also the architect John M. Johansen defined a new type of architecture that he defined as 'molecular nanoarchitecture structures' and spoke about 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 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 by Alan Turing's mid 20th century computational experiments in what he called 'Diffusion Reaction Theory of Morphogenesis in Plants'[26], as well as Aristid Lindenmayer's geometric branching models, which created the precursors to what today are some of the most used procedural growth algorithms, including L-System; Diffusion Limited Aggregation; Venation System; 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.

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 bio-scaffolds specifically stems from research done in the field of tissue engineering where work has focussed on the aim of developing biological substitutes which are biocompatible and 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 in to the body, the idea of a bio-scaffold is inherent in the condition of bioreceptivity of materials that work as hosts for species to grow according to pre-determined 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. Modern fabrication techniques mean form creation is almost unlimited. 3D printing especially now allows for the creation of complex geometries with detailed internal matrixes, which can be defined using engineering principles of architectured materials, which can either augment or decrease the growth of species in areas. Bio-scaffolds can be understood in architectural, biological and/or mechanical terms. For architecture, bio-scaffolds 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/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 pre-determined 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. Bio-scaffolds 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, bio-scaffolds can be a more permanent system, which acts a delivery system for growth stimulating factors - remaining as part of the object throughout it's 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.

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 bio-scaffolds 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, covered in an abundance of algae, lichens and mosses's 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 its 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 surface 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 utilised platform 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 de-powdering. 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 stabilize the 3D printed MPC. The design of the bricks follows 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 designed 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 multi scalar 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 on-site encapsulation. The fabrication platform of the whole panels was composed of a Kuka robotic arm as a positioning system with a bespoke double extrusion head to control of height and speed of deposition. Algorithmic growth patterns evolved the negative spaces and channels between the filamentous geometries which were interpreted by the robot in form of various degrees of 'curly' geometries that depend 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 for incubating and growing mycelium spores seeded in to these filamentous scaffolds led to a novel feedback system. Mycelium spores were manually placed in to the initial scaffold and incubated under optimal laboratory conditions for 1 week. The components were then scanned using an AriusTechnology scanner and the subsequent point cloud data reintroduced in to the computational algorithm that defined the next geometry to be fabricated directly on top of the existing component. The pieces were then re-incubated and the cycle repeated, creating a multi-layered and multi-material 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 prototype for biomass production and wastewater treatment. Bottom up material design utilised 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 utilising algae growth for potential energy have used 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 some form of 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 to such projects as it inverted the idea of a container by growing terrestrial rather than aquatic algae on the gel surface itself. The multi-layering 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 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 algorithm's 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 a tessellation of elements across a building envelope. These lightweight elements were seeded, incubated and planned to be attached to a building, allowing them to be easily removed for re-incubation or cleaning and replacement. Geometric design of the components utilised 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.

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 of subjects. But all the projects discussed have shown that bioreceptive design has to carefully consider 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 continually 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 bio-digital 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 bio-scaffolds 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 (specie) to synthetically stable (architecture).

At an architectural scale, it is not the intention that all areas of the designs should become 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 as 'enhancing' or 'inhibiting' areas. It remains as a necessary challenge for multi-disciplinary teams of designers, biologists and engineers to define these areas based on aesthetics, material, morphological and biological, as well as scale variability. In this sense, rather than letting walls, facades 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 and 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 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 idea of current green walls, as it does not need any maintenance of irrigation for nature to regulate itself. Ultimately, bioreceptive design of newly bio-compatible scaffold systems allows nature to grow according to its own rules in a reciprocal response to parameters of a bio-digital 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', *Nature Geoscience* (5th July 2012), p. 459.

[5] This principle reflects what has previously stated in Marcos Cruz and Steve Pike's *AD – Neoplasmatic Design* (John Wiley, 2008); as well as William Myers's *BioDesign* (Thames and Hudson, 2012).

[6] Janine Benyus, *Biomimicry – Innovation Inspired by Nature* (William Morrow / imprint of Harper Collins Publishers, 1997), preface.

[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', *Science of the Total Environment*, Vol. 426 (1 June 2012), p. 10.
[8] See Christine Gaylarde and L.H.Glyn Morton, 'Deteriogenic biofilms on buildings and their control: A review', *Biofouling: The Journal of Bioadhesion and Biofilm Research*, Vol. 14, Issue 1 (1999).
[9] See J.J. Ortega-Calvo; X. Ariño; M. Hernandez-Marine; C. Saiz-Jimenez, 'Factors affecting the weathering and colonization of monuments by phototrophic microorganisms', *Science of the Total Environment*, Vol. 167, Issues 1-3 (May 1995), pp. 329-341.
[10] This term is originally used by Adrian Forty in his chapter on 'Hygiene and Cleanliness' in *Objects of Desire - Design and Society since 1750* (Thames and Hudson, 1986), pp. 156-181.
[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* (Routledge, 1966), p. 165.
[12] This analysis derives from Marcos Cruz's descriptions about 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* (Ashgate, 2013), pp. 41-66.
[13] See definition of Inhabitable Flesh in the Introduction of Ibid., pp. 1-34.
[14] See Olivier Guillitte, 'Bioreceptivity: a new concept for building ecology studies', *Science of the Total Environment*, Vol. 167, Issues 1-3 (May 1995), pp. 215-220.
[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* (Academic Press, 1996), p. 11.
[17] See James Mitchell Crow, 'The concrete conundrum', *Chemistry World* (March 2008), pp. 62-66.
[18] Invitation text for the conference *Concrete – a Culture History* held at the RIBA in London on July 7th 2015.
[19] Sandra Manso Blanco, *Bioreceptivity Optimisation of Concrete Substratum to Stimulate Biological Colonisation* (PhD Thesis: Universitat Politècnica de Catalunya, 2014).
[20] An interal 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 Sandra Manso Blanco's Thesis *Bioreceptivity Optimisation of Concrete Substratum to Stimulate Biological Colonisation* (PhD Thesis: Universitat Politècnica de Catalunya, 2014).
[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 description of William Katavolos's work in William W. Braham; Jonathan A. Hale, *Rethinking Technology – A Reader in Architectural Theory* (Routledge, 2007), p. 140.
[25] For more see http://johnmjohansen.com/Nanoarchitecture.html
[26] *Collected Works of A.M.Turing – Morphogenesis*, ed. by P.T. Saunders (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] and Richard Beckett [UCL])
Sponsors: Bartlett School of Architecture; Grymsdyke Farm; Innsbruck University
[28] S. Levenberg; R. Langer, 'Advance in Tissue Engineering', *Current Topics in Developmental Biology*, Vol. 61 (February 2004), p. 113.
[29] B. P. Chan and K.W. Leong, 'Scaffolding in tissue engineering: general approaches and tissue-specific considerations', *European Spine Journal*, Vol. 17, Supplement 4 (December 2008), p. 467.
[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 re-used and re-cycled 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 develop by BiotA Lab at the Bartlett with Sul Ah Lee, Tae Hyun Lee, Dan Lin, Wen Cheng in 2014-15.

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Author Biographies

Marcos Cruz is a Professor of Innovative Environments at the Bartlett, UCL where he is also Director of BiotA Lab. His research is focused on design driven by advances in computation, biotechnology and the environment, fields that he believes are radically changing the future of architecture. His research on Neoplasmatic Architecture won the RIBA's Research Award in 2008. In addition to the Directorship of the Bartlett (2010-14) where he run MArch Unit 20 for over 16 years, he has also taught at UCLA, University of Westminster and IaaC Barcelona. Back in 2000 he was one of the key designers of the Kunsthaus Graz lead by Cook / Fournier. Cruz also co-founded the atelier marcosandmarjan with whom he has built over 20 installations and buildings. He is author and editor of numerous books and marcosandmarjan work was featured in major publications, including *Digital Architecture Now* (Thames and Hudson 2008), *Chernikov Prize* (ICIF / Tatlin 2011), *Futuristic – Visions of Future Living* (DAAB Media 2011) and *Archilab – Naturalising Architecture* (FRAC 2013). Cruz is currently PI 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 initially studying biochemistry and working in R&D for Glaxosmithkline as a material scientist before going on to study and teach architecture at UCL. His investigations into architecture have remained cross-disciplinary focusing on the contemporary discussion on digital architecture and novel fabrication alongside the impact of biotechnology on architecture and more specifically, investigations into the use of living or semi-living materials in our built environment. This background acquires him with a cutting edge expertise in the field of computational data production, 3D printing and digital manufacturing as a material and technical innovator. He co-founded design/fabrication consultancy Arch-T in 2013 working at a range of scales and industries from architecture to fashion including their recent design collaboration as material designers, developing novel 3D printed fabrics with Pringle of Scotland 2014-2015 which has gained international acclaim. Beckett is currently working on an EPSRC "Design the future" research grant.

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CAPTIONS:
Image 1 - Tree Bark
180 degree photo taken in November, February and April showing variations of cryptogamic cover surfaces on an ash tree in Kew Wakehurst

Image 2 – Wall with algae propagation

Image 3 – Gardens of Palacio da Regaleira, Sintra Portugal

Image 4 – Gardens of Harewood Castle, UK

Image 5 – Bio-receptive concrete façade panel
SEED funded project at the Bartlett school of Architecture, UCL (2015)
Research team: BiotA Lab / Marcos Cruz, Richard Beckett, Sandra Manso Blanco.

Image 6 – Bio-receptive concrete layering
SEED funded project at the Bartlett school of Architecture utilizing Sandra Manso Blanco's material PhD research on bioreceptive concrete.

Image 7 – Casting process of façade panels
SEED funded project at the Bartlett school of Architecture, UCL (2015)
Research team: BiotA Lab / Marcos Cruz, Richard Beckett, Sandra Manso Blanco.

Image 8 – Alga(e)zebo: Algae photo-bioreactors at Euston Square Gardens, London UK

Image 9 – Computational simulation with Houdini
The use of a fibrous structure provided the opportunity for a porous multi-dimensional 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 enriches the geometry.

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

Image 11 – Sandstone bricks for moss growth

Image 12 - Cellulose screens for mycelium growth

Image 13 - Hydrogel screens for algae growth

Image 14 - Lightweight concrete components for cryptogam growth

Image 15 – Robotic printing of hydrogel screens for algae growth

Image 16 – Robotic printing of cellulose screens for mycelium growth