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1 Tomorro.w's City Vision: A vision of a city that exists within its ecological limits

2 Learning from nature

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As a tree responds to and moderates its surrounding environment, nature can become a key inspiration in developing mechanisms to reduce the impact of climate change and resource depletion.

(Experimenting with) Living Architecture: a practice perspective

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Today's challenge

> *In the 30 minutes in takes you to read this article the world's population will have risen by 5,000 people.*[1] – The Worldometer

By 2050, the human population will have surpassed 9 billion people with 70% of the world's inhabitants living in cities. With the collective impact of industrial processes this growth will strain our existing urban infrastructures and natural resources to unprecedented degree. Within the next few decades we will face life-threatening issues within our cities, such as climate change, resource shortages, waste disposal issues, pollution, traffic congestion, crime, and homelessness. Our cities will need to rapidly transform to address these new urban challenges.

Creating sustainable urban landscapes for a growing population while simultaneously cutting carbon emissions will be the primary challenge of the twenty-first century. It will require all members of society, from governments and industry to individual citizens to make sustainable change. How we govern, design, and inhabit our cities will have a fundamental impact on our collective future.

The construction industry will need to play a key role in this sustainable vision. In the UK, the construction industry accounts for approximately half of the UK's emissions of carbon dioxide, generated from depleting fossil fuels consumed in the construction and operation of buildings. With the UK committed to a carbon emission reduction of 80% by 2050, this pledge, translated in real terms for the construction industry, means that all buildings whether new or existing need to be carbon zero by around 2050 (the remaining challenges being in relation to infrastructure and non-regulated uses).[2] This is a considerable challenge for the industry.

The construction industry is a slow moving, litigious, and risk averse beast. It moves forward but looks backwards. For answers to new questions being raised, which demand a new set of solutions, it simply relies on the mindless repetition of Victorian methods. The effect is to stifle innovation.

At Astudio we look further afield to meet complex challenges and involve disciplines from way outside the construction industry to help drive change and build in ways that can address the need for environment enriching solutions.

Astudio are architects focused on reducing our buildings' impact on the environment. Our courage in the pursuit of new ways to reduce carbon and change behaviours gained us the coveted title of Architectural Practice of the Year in 2012. This unprecedented achievement led us to establish our Research and Development group, whose role is to investigate new ways of seeing and thinking about the challenges we face in the industry. With this group we explore visionary concepts that enable us to consider how we may cross boundaries taking us out of architecture and work with different fields of expertise that can help us solve sustainable construction in new ways. We look to the future to propose buildable solutions today.

For too long the industry has become accepting of the measure to count a building's cost rather than its benefit to its context. Right now, we assume that creating architecture inevitably damages the environment. Buildings as we know them are static, industrialised solutions – sites of extreme fossil fuel consumption with extensive carbon footprints. Functionally inert materials, engrained in traditional construction processes, form a barrier between human habitation and the natural environment. These buildings possess no capacity to engage with the environment they inhabit, instead detract from it because they are unable to offer anything back.

This condition is reinforced by the prevalent paradigm of sustainable design, which operates solely on the principles of resource conservation – essentially demonstrating a 'better' kind of industrialisation. Today's sustainable solutions are focused on reducing carbon emissions, conserving energy and water, and recycling our waste. Indeed, this strategy succeeds in slowing down the depletion of the planet's resources, but it does not address fundamental issues regarding long-term survival. Our current idea of 'sustainability' is based on entrenched

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industrial principles that rely on machine-inspired solutions to continually modify what already exists rather than exploring fundamentally different ways of thinking. This is a top-down approach to sustainability, which aligns with our Victorian methods of construction, simply imposing structure on the environment. Cities are not machines. They are dynamic living systems that require nurturing environments not austerity. Incremental thinking, doing more of the same is not going to help us achieve develop solutions. We need to adopt strategies that are visionary so that we can raise the game beyond what we presume possible – and explore new ideas and approaches that may lead to radical shifts in thinking, practice, and the way we live.

With global warming increasing, amplifying extreme weather conditions and frequency, buildings can no longer remain static and unresponsive to their surrounding environment. Architecture must become adaptive, reactive to changes in climate, and reducing CO^2, not generating it. For us to continue to exist on this planet the production of architecture itself must enhance not just our own survival but the infrastructures and ecosystems on which our prosperity depends. This means we need architectures that do not just take from our environment, but also give back to it, in ways that are ecologically meaningful. We need to move away from ideas of sustainability that think in terms of closed loop ecologies, that assume life runs like a machine, but nourish open systems that can flourish under the right condition, that can adapt and change to their differing circumstances. We need to create flexible, resilient, and efficient urban models, that underpinned by new technology and social change can become thriving, productive urban communities where people and nature can flourish alongside each other *[1]*.

In this vision, the city is a living system of exchange between people and their surroundings so that they are no longer simply consumers of their biosphere, but contribute – and become a productive part of it. Such a transition will be possible by adopting a visionary approach to architectural practice enabled by new ways of thinking about the relationship between architecture and the environment, made tangible through new kinds of technologies that possess lifelike qualities and a broad range of associated cultural and social changes that will result from the new opportunities that they provide access to. This approach is living architecture.

Lessons from nature

> *The role of green infrastructure in addressing the challenges of the 21st century cannot be underestimated* [...] *It is a natural, service providing infrastructure that is often more cost effective, more resilient and more capable of meeting social, environmental and economic objectives than 'grey' infrastructure.* [3]

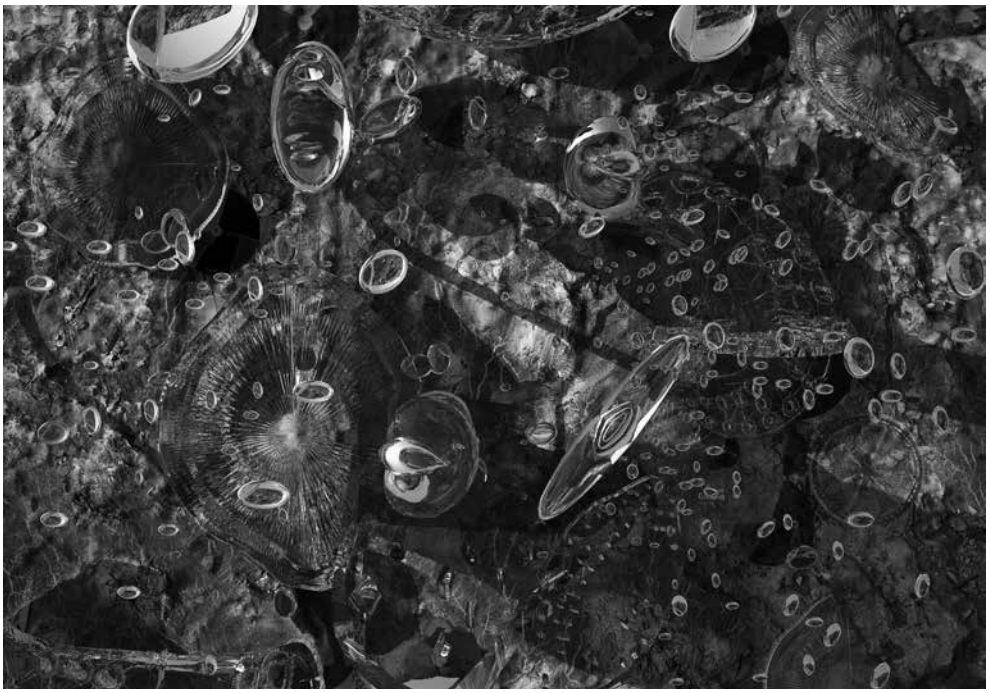
Nature's brilliance is its astonishing ability to survive extreme changes in environment. This resilience is delivered through a capacity to adjust to climate change, moderate potential damages, take advantage of opportunities, or cope with consequences; in short, the capacity to adapt. Living systems, unlike the majority of our machine-like building stock contributes positively to the biosphere, playing an essential role in wider ecosystems linked together through nutrient and energy flows. It is this collective nature that guarantees survival. American conservationists David Suzuki and Wayne Grady, when talking on the resilience of trees, explained: 'No tree is an island; it is a communal citizen and derives [...] benefits from cooperation, sharing, and mutual effort' *[2]*.[4]

By incorporating fundamental dynamic processes found in living systems, architecture has the potential to adapt or respond to changes in climate, seasons, or extreme acts of nature, just as our natural

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3 Future London: Envisioning a new relationship with nature

4 Ecological Infrastructure: The boundary between architecture and nature blurs in this image, which simultaneously depicts both a view of the River Thames under the microscope, and an aerial plan of a city.



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green landscapes respond to the availability of water, sunlight, and wind. As expert moderators of environment, nature can become a key inspiration, or indeed component, in developing technological systems and processes to help reduce the impact of climate change. Instead of our buildings remaining inert they could employ the design of responsive surfaces and building systems to actively moderate and contribute to the surrounding environment.

Historically nature and biology have often been inspiration for architecture. The study of nature as organic form has informed the work of many great architects, take singularly Antoni Gaudí, purveyor of Catalan Modernism, who adapted the language of nature into structural form. However, these great works only emulate natural patterns and strategies, and they do not fundamentally alter the way the buildings are made or perform. Today, there is growing acknowledgment of the importance of ecological or 'green' urban strategies as a method to ensure the health and sustainability of our cities. The healing potential of green spaces is readily exploited; nature incorporated into pop up gardens, green walls, balconies, and roofs is increasingly commonplace. Sometimes these are thoughtfully integrated; too often these 'greenings' offer nothing more than visual benefit, requiring excessive water irrigation and human management. But the incorporation of green landscapes can offer great transformative value when integrated correctly. Trees, grass, and vegetation can absorb carbon dioxide and improve air quality, reduce the heat island effect, slow rainwater run off to prevent the flooding of the sewers, even filter and recycle grey water, as well as providing the important facility of beautifying our urban environments to make them more enjoyable and safer environments in which to live and work *[3]*.

At the start of the third millennium we are establishing new ways of integrating biology and architecture. Our relationship to the natural world and the city environment is changing. Major cultural and technological developments in our cities are impacting a worldview that is less defined by objects but increasingly shaped by connectivity. Our cities are becoming progressively networked, connected by the Internet of Everything, sensors technologies, data sharing: the ubiquitous smart phone. We are increasingly understanding more about nature, and how to manipulate it, through the advances in biotechnology and the emergence of synthetic biology. Our cultural notion of the natural realm as wild and unspoilt is transforming. Whereas traditionally nature and technology were seen as opposed, today nature and technology appear increasingly unified and collaborative. Architect Liam Young, of 'Tomorrow's Thoughts Today' explains: 'What we've realised is that there's no nature anymore – at least not in the sense that we culturally define it.' He concludes, 'What there is, is technology. Engineered networks, augmented environments, invisible fields – infrastructure has exploded into bits, to roam the earth in an architecture of everywhere.'[5] We are emerging from the machine age of the Industrial Revolution; and the twentieth-century Information Revolution, to a new era in which some predict biological engineering will be the foremost driver of change *[4]*.

Synthetic biology is a field that is driven by its potential. It is a technology that currently does not formally exist in architectural practice. It provides a space for architects and designers to envision a new future that proposes new relationships with nature to create forms, processes, and systems to improve the sustainability and resilience of our built environment. Uniting biology and architecture through engineering, advances in biotechnology have developed the means to design and construct new architectural materials and technologies bestowed with the dynamic properties of living systems. These

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living technologies allow design professionals to move beyond inert building materials, or mechanised or visual representations of nature, instead collaborating directly with living systems, proposing sustainable solutions from active building envelopes, to biofuels. Ultimately it provides the opportunity to create new living architectures, which embrace some of the qualities of the natural realm such as uncertainty and rapid change.

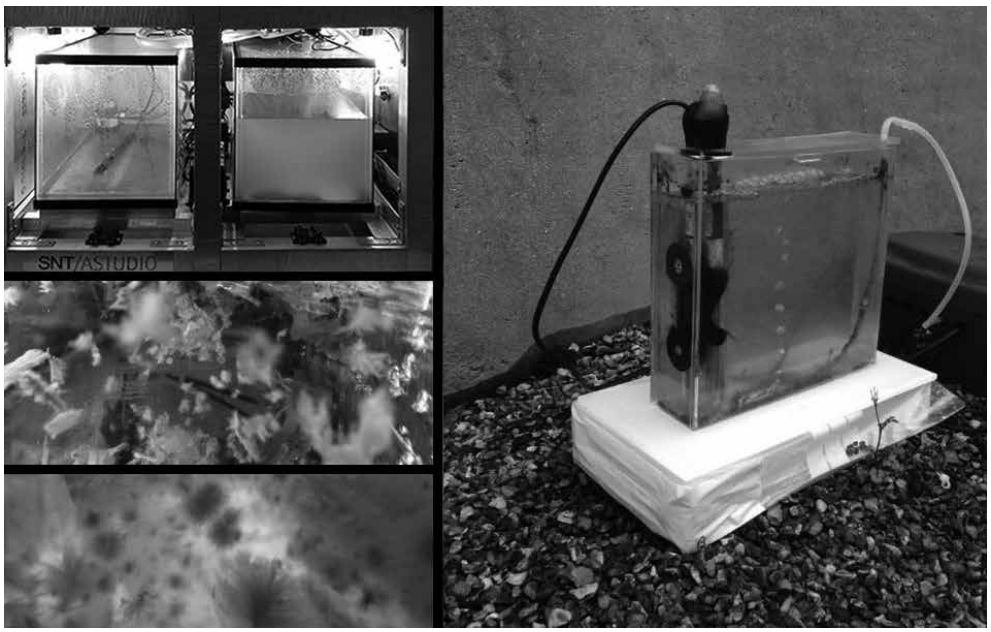
Living systems can be engineered using different approaches of synthetic biology, from non-genetic processes (that is, through the manipulation of environment or direct modification through common methods such as 'gardening'), or genetic methods, which regularly bring about concern for public health and safety.[6] At Astudio our work with living architecture explores the potential of non-genetic processes in synthetic biology. By looking to the future to build workable solutions today, we design with nature in mind: incorporating, manipulating, and constructing biological systems for useful purposes. The following sections will explore the potential of synthetic biology to improve the resilience of our future built environment, documented through examples of our practice-based research and future speculations.

Living skins

Building envelopes or 'skins', as the crucial interface between interior and exterior space – between human habitation and the 'natural' world – play a fundamental role in the vision of a living architecture. As an important environmental moderator, a building's skin impacts transition between environments, affecting heat, light, and air quality inside and outside a building. Successful performance of this interface can regulate and reduce energy consumption used in the heating, cooling, ventilating, and lighting of buildings, affect occupant comfort and productivity, as well as impact the external surrounding environment and climate. Optimising the responsiveness of this interface will be key to increasing the resilience of our new and existing building stock.

Rather than constructing building envelopes with traditional inert surfaces, a 'living skin' incorporates dynamic physical and chemical processes found in living and natural systems. Utilising a range of biological or synthetic-biology based technologies this living cladding would have the ability to transform the performance of buildings within their environmental context. Just as a tree, or our own skin, responds to and moderates its internal and surrounding environment, a living building envelope would be active and adaptable to changes in climate and extreme weather conditions. This envelope would possess the capacity to transform buildings into positive generators, producing heat and providing cooling, capturing carbon dioxide and other pollutants from the atmosphere, and contributing to a new urban ecology *[5]*.

Astudio in collaboration with Brunel University and the Centre for Process Innovation (CPI), is developing a living skin technology with the intention of optimising the performance of building envelopes. The team is developing a marketable photobioreactor façade system for the production of biofuel and has recently commissioned the first operational industrial algae production unit in the UK.[7] The PBR façade design uses the process of photosynthesis to cultivate algae in uniquely designed photobioreactors, capturing carbon from the atmosphere. Using certain strains of algae with reduced hydrocarbon chains for quick growth, the intention is to produce biofuel as an output to fuel the building, offsetting the building's carbon footprint and energy needs. As a multifaceted renewable energy source, the photobioreactors act as solar thermal collectors providing heat for the building and shading the interior from the sun. As levels of solar radiation increase, the algae increases its growth rate, consequently its density and shading potential, adapting in real time to changes in external environmental. This process can be



5 Algae experiments with Sustainable Now Technologies and Brunel University

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manipulated to accurately regulate the internal temperature of the building. When designed within a holistic building engineering strategy this living architecture can impact all areas: water filtration, power, heat, and light. A truly dynamic element *[6]*.[8]

This living, or 'bioresponsive', façade system combines both biological and technical systems, which adapt to, and harvest from, the immediate climatic environment. Another example of the application of dynamic skin technology is GLASSX, a 5cm-thick glazing unit licensed to Saint Gobian, that provides thermal storage through the use of a salt hydrate phase change material (PCM). The glass provides thermal storage equivalent to a concrete wall of 20cm thickness, passively providing heat and cooling over the course of a day. Solar heat is stored in the PCM during daytime by means of a melting process. During night-time the stored heat is delivered to the interior during salt recrystallisation, a process of active night purging. While not a 'living' material, it demonstrates the dynamic properties of living systems in response to changes in external environment. The building fabric provides an active response to temperature changes, moderating heating and cooling within a building, and providing thermal storage for energy conservation.[9]

Living structures

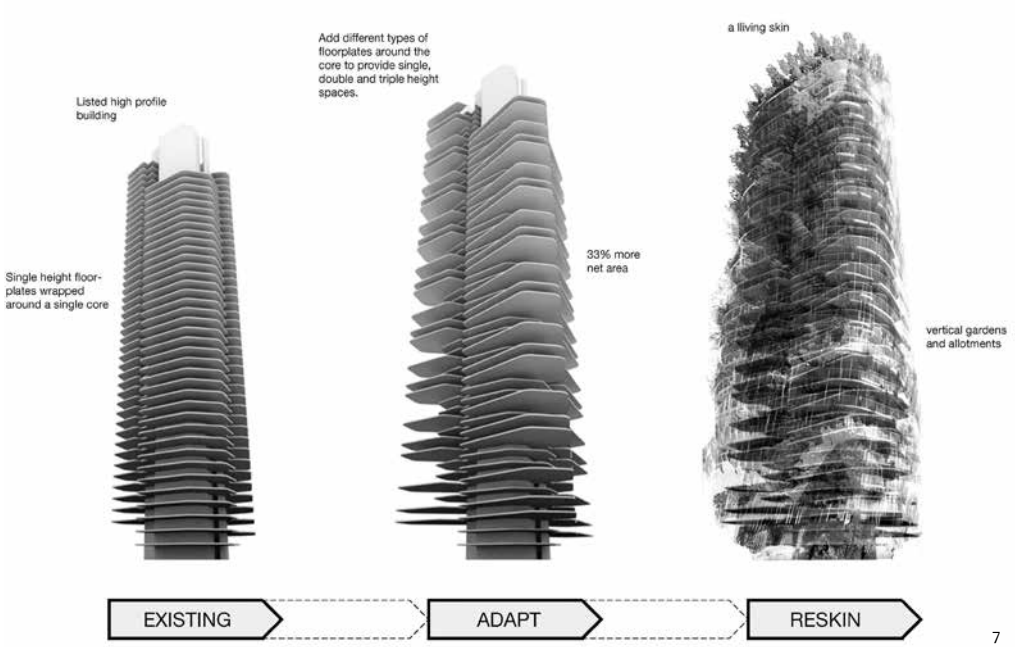
Synthetic biology techniques offer the ability to transform not only the resilience of the skin of the building but the structural skeleton as well. A collaborative work between Astudio and Rachel Armstrong, Professor of Experimental Architecture at Newcastle University, explores the potential of synthetic biology to upgrade existing buildings.[10] With 50–70% of existing buildings expected to still be in use in 2050, this represents the biggest challenge facing architects today. The challenge of upgrading the existing building stock to meet increasing environmental targets is still relatively unknown territory compared to the new construction of carbon zero buildings. The challenge will be to reduce energy demand by retrofitting energy efficient building envelopes, systems, and appliances (lighting alone accounts for up to 10% of a cities energy demand). Additionally, the ongoing maintenance and repair of these buildings can be 2–3% of the original cost of a new building every year. With maintenance costs increasing with building age, the work of the collaboration looked to explore ways of introducing self-healing systems into an architectural structure. The work looks to upgrade existing concrete frames of buildings using carbon-nanotube based materials to improve the mechanical strength of the concrete and extend the framework to accommodate a new dynamic skin. This 're-skin' proposal aims to transform underperforming buildings into energy-efficient, fit-for-purpose spaces that make a positive environmental impact. This regenerative capacity, not only has the potential to improve structural stability and energy consumption but has the means to impact the commercial value of a building, renew an image, and through doing so regenerate areas of the city without the unsustainable process of demolition *[7]*.

Armstrong, a scientist and sustainability innovator, has been developing an approach to synthetic biology that explores the potential of 'lifelike' systems called protocells. These non-genetic molecules, which are not technically alive as they possess no DNA, can be chemically programmed to display the characteristics and behaviours of living systems. Through the interaction of oil and alkaline solutions at a molecular level, new features arise through the protocells' capability for self-organisation which exhibit 'a range of lifelike behaviours such as movement, sensitivity and the growth of micro structures'.[11] The characteristics of protocells have allowed Armstrong to speculate on a range of uses, including the development of protocell-based coatings or paints. These water-based protocell coatings, once exposed to carbon dioxide form a crystalline microstructure akin to limestone, over the surface of which it was painted. While the reality of creating a smart, self-regenerating protocell



6 Algae Photobioreactor Façade, Hong Kong Science Park Proposal

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7 Tower 42: Re- Skin Project

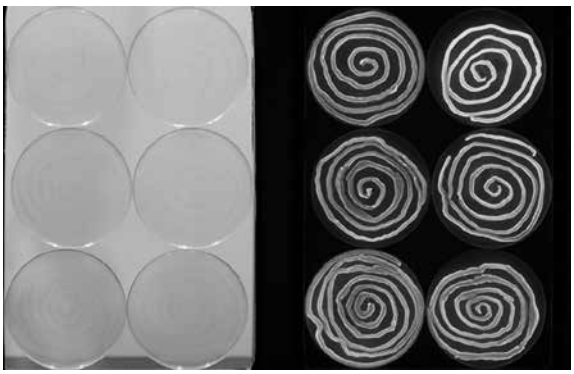
8 Bacteria Bioluminescence research with biologist Dr Simon F. Park and Brunel University

paint is years away protocell paints offer 'the capacity for a unique growth of materials but also potential applications in healing "broken" buildings, by which molecular interactions detect and deposit material into stress fractures to from "scar tissue" at the microscale'.[12] Protocells may have the capacity to grow structures to stabilise unsafe buildings devastated by seismic activity, or, as exemplified by Armstrong, reinforce the sinking timber foundations of Venice disintegrating from centuries of contact with salt water and water-borne organisms.[13] Applied to existing housing stocks as a painted coating, it could offer a method of continued carbon sequestration.

While protocell technology may be twenty years in development, the potential of synthetic biology to grow resilient structures is being explored through a number of alternative methods today. Sustainable construction materials are being developed by harnessing biological organisms such as fungi as alternatives to plastics or bricks. In 2014, New York architecture studio 'The Living' completed MoMA PS1 gallery pavilion, a cluster of circular towers built from bricks that had been grown from corn stalks and mushrooms. The pavilion was entirely biodegradable, creating no waste, no energy needs, or carbon emissions.[14]

Another design studio, 'Officina Corpuscoli', are also researching how fungal organisms may be used as construction material, claim that biologically produced materials can be 'completely non-harmful [...] Once disposed of they just become new nutrients for new life'.[15] They describe mushroom mycelium as natural, self-assembling glue. Grown from crop waste, the network of mycelium filaments is transformed into a durable, structural, and waterproof material when baked.

Around the world, researchers are developing concrete technology to reduce embedded carbon, increase water resilience and actively heal. Researchers from TU Delft in the Netherlands have developed



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BioConcrete, a concrete that can heal itself using bacteria.[16] When cracks form in the concrete naturally over time, water enters and opens calcium lactate capsules that are dispersed throughout the concrete mix. The bacteria then germinate, multiply, and feed on the lactate, and in doing so they combine the calcium with carbonate ions to form calcite, or limestone, which closes up the cracks. Other researchers from Universitat Politècnica de Catalunya have developed an alternative version of 'biological concrete' that captures rainwater to create living walls of moss and fungi.

The growth of waterproof or water responsive structures can provide resilience in areas prone to drought or flooding. Protocell technology has the ability to transform the properties of materials in the presence of water, allowing them to float or expand. Materials can be engineered to absorb and store water in the advent of excessive rainfall or flooding, to expand into cracks and gaps to act as barriers to water flow, and raise bridges over flowing water courses. In countries experiencing the effects of water shortages, building skins can be designed to conserve and recycle water. Living technologies embedded in the fabric of the building can recycle the grey and black water used within the building, filtering through living materials that purify the water. Water could be sourced, stored,

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and processed locally instead of increasing demand on the district sewer system. Reservoirs built into the building fabric could be used to cool interior and exterior spaces through both convention cooling and water misting.

Living landscapes

During floods, it isn't just buildings that need protecting, our landscapes also need protection. Synthetic biology could be used to prevent soil erosion by re-engineering bacteria in soils. The engineered bacteria would produce a plant hormone that promotes root growth to protect plants from being uprooted and washed away in flash floods.[17]

Soils provide ecosystem services critical for life. Maintaining the health of soils is essential if we are to safeguard our future, retain food security, and mitigate soil, water, and air pollution. With the pressure of an increasing population new technologies and techniques are continually being developed to optimise soil performance – to produce more food and fuel with less – less land, less water, less energy, and fewer nutrients. New innovative soil management strategies that can mitigate pollution, while also enhancing ecosystem performance, are being developed. One example is 'Carbon Prophet',[18] a government-funded project, which provides farmers and landowners with a new income stream by selling captured carbon to companies that want to offset their emissions. By increasing the soil fertility of land, soil improves its capacity to absorb and fix carbon, acting as a carbon sink. Working with Astudio, 'Carbon Prophet', have been exploring the potential of manipulating soil fertility in both rural and urban environments as part of building development landscape strategies to offset carbon generated during construction.

The engineering of bacteria in the breakdown of organic waste offers an exciting potential for the production of soil in cities. By processing organic waste locally, inhabitants of the city can take ownership of their waste generation and collectively reap the benefits from localised waste to energy processing and urban food production. Living skins and building systems could possess the potential for the onsite processing of organic waste, in turn generating nutrient rich fertiliser and biogas, or compost and heat. Through the manipulation of bacteria in the organic waste make up, direct heat or biogas output can be controlled and fed directly into the building systems as a renewable energy source. The subsequent by-products of compost or fertiliser can then be used in the local production of food and biomass.

Bacteria offer further potential for infrastructural scale application of living technologies. Research is being conducted into the use of bacteria to create zero-electricity light sources exploiting the natural phenomena of bioluminescence in octopus, jellyfish, or mushrooms. Bacteria lighting has the potential to redefine streetlight infrastructure, light building façades and interior spaces without impacting the environment, and provide lighting solutions for areas without electricity *[8]*.

As the examples of 'designed' bacteria have shown, synthetic biology can deliver the means to transform the infrastructure of our cities. Living technologies can provide renewable energy sources, generate heat, stimulate plant and food growth, and absorb carbon dioxide and other pollutants. If we can learn to



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9 Future Nature: A Living Architecture

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harness the properties of living systems in the technology of our cities, living architecture could play an important role in the future resilience of our built environment. Understanding how architecture and technology may possess the characteristics of living systems design professionals have the potential to transform the built environment from its static, polluting state to an active, responsive, ecologically connected environment which makes a positive impact on the planet. Living technologies promise an implementable solution for issues of environmental responsiveness and sustainability in our cities. From the futuristic visions of protocell technology, to the current manipulations of algae, salt, soil, fungi and bacteria, synthetic biology has the ability to confer lifelike qualities on our buildings, to induce regenerative and responsive capacities to fight climate change and resource depletion.

Living architecture in the transformation of the fabric of our cities is only one step on the path to future resilience. It needs to be a social vision that does not pit humanism against environmentalism but finds common ground where the needs of humans and nonhumans can be met through urban development. It requires a sustainable urban model that responds to issues of climate change and resource depletion, urbanisation, and population growth, by balancing the social, environmental, and economic needs of happy and sustainable cities. This is a vision of the city as a literal, living organism, in which mankind and nature live symbiotically side by side, and through holistic design we have chance to ensure our survival for generations to come. Let's learn how to work alongside nature, as after all, it is the only truly sustainable and resilient material system we have *[9]*.

Notes

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Emma Flynn leads Research and Development at London-based architecture practice Astudio. A practicing architect and design researcher, Emma's work broadly focuses on the future architectural landscape in relationship to nature, exploring environmental responsiveness and resilience in the context of climate change and resource depletion. Emma is an architect who also writes, curates exhibitions, and teaches at various schools of architecture.

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