Biological Entities and Regeneration by Design

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ABSTRACT **Regenerative design aims to reverse environmental degradation and generate net positive impact by developing systems that are mutually beneficial and co-evolving for natural and social components of the living environment. As a regenerative approach is not only related to design but also to humans and their activities, this chapter reveals the necessity to establish a new interconnectedness between design principles of environmental regeneration and a tendency to intensify positive environmental effects on humans. This paper identifies biological entities as significant agents in bringing the human perspective closer to the regenerative approach and accordingly explores their application in design by analysing characteristics and benefits of utilisation, and by providing different experimental examples developed by scientists, designers, and the members of academic community. In particular, this work studies design solutions based on the biological principles of growth and finally focuses on how building-integrated plant systems contribute to regeneration.**

KEYWORDS biological entities, greening systems, integration, project, regenerative design

1 Introduction

The performance of provisioning, regulating, supporting, and cultural and amenity ecosystem services (Gómez-Baggethun & Barton, 2013; Millennium Ecosystem Assessment, 2005) in the living environment is, to a large extent, influenced by interrelations established between environmental components. The balance between life processes and functions in the closed cycle of an urban ecosystem is a prerequisite of its sustainability and a challenging goal, especially in densely built areas.

In an urbanising world, the complex network of naturally unique places adapted to local conditions is replaced for a system that is relatively simple, uniform, and generic (Lyle, 1994). The needs of new urban citizens, changes in morphology patterns, and contemporary lifestyle demands all jeopardise the functioning of urban ecosystems, due to pollution increment, microclimate changes, intensification of urban heat island phenomenon, fresh water scarcity, biodiversity loss, etc.

Regenerative design can be understood as an examination, introduction, or mimicking of nature, its models, systems, and processes, with the aim to solve urban problems (Redi, Redi, Daničić, & Russo, 2011). This work investigates regenerative design by focusing on the specific context of biological entities that are believed to play a significant role in bringing the human perspective closer to environmental goals.

1.1 Regeneration by Design

Like in natural processes, regenerative design aims to create resilient systems that try to self-optimise, and not to maximise (Akturk, 2016). Thus, regenerative design is defined as the return to nature and its cyclical flows at sources, consumption centres and sinks, replacing present linear systems and throughput flows (Akihan, 2013).

Regeneration aims to reverse environmental degradation and negative impact by (re)developing interconnectedness between humans and nature. Therefore, a regenerative approach is not only related to design, but also to the activities of humans who, according to the biophilia theory, have an instinctive and innate need to connect with nature (Sayuti, Montana-Hoyos, & Bonollo, 2015). In the regenerative design process, all aspects of systems thinking are included, from resources to biological entities, to social systems (Nugent, Packard, Brabon & Vierra, 2016).

Although there are a number of definitions of regenerative design and regenerative development, the key points, according to Mang and Reed (2012b), include net positive goals for the built environment and the integration of human with natural living systems. Regenerative design is a system of technologies and strategies based on the understanding of the inner workings of ecosystems. It produces solutions to regenerate rather than to deplete underlying life support systems and resources within the socio-ecological wholes. In continuation, regenerative deve-

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lopment generates the patterned whole-system understanding of a place, develops strategic systematic thinking capacities, and promotes stakeholders' engagement to ensure regenerative design processes and to achieve maximum systemic leverage and support, which is self-organising and self-evolving (Mang & Reed, 2012b). Regenerative design and development therefore represent two distinct yet synergistic processes, both of which play an essential role in ensuring a greater scope, and neither of which is sufficient without the other (Mang & Reed, 2012b).

Pedersen Zari and Jenkin (2010) defined regenerative design as a means of achieving desired outcomes of regenerative development and explained how it attempts to create or restore the capacity of ecosystems and bio-geological cycles to function without human management. According to Cole (2012a, p. 1), "regenerative design relates to approaches that support the co-evolution of human and natural systems in a partnered relationship. It is not the building that is 'regenerated' in the same sense as the self-healing and self-organizing attributes of a living system, but by the ways that the act of building can be a catalyst for positive change within the unique 'place'".

Du Plessis (2012) framed regenerative design and development into a broader context of 'regenerative sustainability'. Indeed, different authors attempt to establish and define the relationship between sustainable and regenerative design. According to Akturk (2016), regenerative design could be considered as an added value, an extended significance of sustainable design. Although the application of sustainable design principles brings many improvements to conventional design in terms of conserving resources and reducing damage to the environment and humans, it only slows down the degradation of natural systems. Within the causal framework in which regenerative design emerged from the understanding of ecology and living systems principles (Akturk, 2016; Mang & Reed, 2012a), sustainable design can be described as a neutral basis permitting regenerative capabilities to evolve (Cole, 2012b; Mang & Reed, 2012b; McDonough & Braungart 2002; Pedersen Zari & Jenkin, 2008). From the perspective of regenerative design, sustainability should extend beyond net-zero impact to achieve net-positive benefits (Mang & Reed, 2012b; Pedersen Zari & Jenkin, 2009).

Design that follows the proportions, geometry, structure, processes, or functions of the systems found in nature, all at a microscopic scale, is materialised in various forms. In biomimicry, a product (object, element, or system) reacts to the environment by following the solutions typical of systems and organisms found in nature (Benyus, 1997), but the performance, according to the classical theory of life, does not encompass living (Gruber, 2008). On the other hand, regeneration refers to revival, renewal, restoration, healing, or improvement. If design products are not alive, and if regeneration represents basic characteristics of living systems and their cycles, then regenerative design should find the way to biological life. For that reason, the regenerative approach should consider the application of biological and bio-technical measures.

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2 Biological Entities and Their Characteristics Applied in Design

Biological entities display numerous properties that justify their actual introduction into design products. Individual characteristics of biological entities with potential application in design are the following: replication, movement, sensitivity, energy and water harvesting, maintenance of stable humidity and temperature and other thermal-related behaviour, bonding, self-healing, self-repairing, self-operation, self-stabilisation, self-organisation, optimisation, genetic programming, adaptation and resilience, and self-cleaning, among others.

On the other hand, growth represents a general common characteristic of living organisms. It includes different sub-features, which underpin the growing process. For instance, to grow, i.e. to develop from seed to full maturity, a plant may feature sensing, thermal-related behaviour, resource harvesting, self-healing, and adaptation. As a major principle, growth is translated into various contemporary design examples, although it was also known in earlier traditions of building with nature, e.g. in suspension bridges made from the aerial roots of living banyan fig trees, described by Myers (2012) as the 'Root bridges of Meghalaya'.

Sayuti et al. (2015) defined four groups of reasons from which designers embed living organisms in furniture: function & practicality, experimentation, aesthetic & semantics, and experience. The group function & practicality, which is the most closely related to the concept of ecological regeneration, encompasses reasons such as to learn, for farming or food, to purify air or water, to generate energy, etc. On the other hand, potential worldwide users of furniture with incorporated living organisms, as revealed in the study, believe that the greatest positive effects of indoor living organisms are to heal, calm, or lower stress. These contrasting results show that human relations towards other living organisms is rather emotional and personal, and point at the need to re-establish the boundaries of regenerative design.

Living organisms are introduced in various design disciplines, from industrial and furniture design, development of building materials and products, to whole building design or urban design. The major part of such achievements, regardless of the scale, belong to experimental design. As these bespoke solutions for the 'integration of life into design' (Myers, 2012) are difficult to typify, they rather invite an individual approach to every single project. For purpose of reviewing, classification may be made according to the introduced species or according to their characteristics. This work combines both typologies to present some recent experimental projects developed by scientists, designers, and academia.

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2.1 Bioreceptivity: Microorganisms

The term 'bioreceptivity', coined by Guillitte (1995), refers to the ability of a given material to be colonised by living organisms. Guillitte proposes an ecological relationship between living organism and material system, thus suggesting a fruitful dialogue between fauna, flora, and its substratum. Cruz (n.d.) customised the general idea and tried to overcome the *Innovation Inspired by Nature* (Benyus, 1997) with the concept of nature-integrated design. In doing so, he defined *Bioreceptive Design,* which "explores the emergence of a new bio-digital, material phenomenon that is changing the environmental performativity of architecture" (Cruz, n.d.). Bioreceptive design intends to generate a new interface between architecture and nature that is the result of integration between external environment, materiality, and the tectonic dimension.

'Bioreceptive concrete facade panels', developed by R. Beckett and M. Cruz in 2015, are aimed towards the facilitation of the colonisation of microorganisms on surfaces, and to overcome expensive maintenance and complex irrigation of green walls. For this to happen, a biologically receptive concrete material has been developed. To promote micro-organism proliferation, concrete has been manipulated by modifying pH value, porosity, and water retention features.

By embedding calcite-precipitating bacteria that is resistant to harsh environments into a concrete mixture, the researchers from Delft University of Technology have developed 'Bio-concrete', a type of self-healing concrete usable in the reparation of existing structures and the construction of new structures with enhanced durability (TU Delft, 2015). In another large-scale project 'Dune', the same ability of bacteria to produce calcite via microbial-induced calcite precipitation was envisaged to quickly transform sand into sandstone in order to control the spread of the deserts (Myers, 2012).

In parallel, scientists are exploring the ways to adapt certain types of bacteria as bioindicators of indoor pollution. For example, the bacterium *Brevundimonas* "could be genetically modified to change colour in the presence of a heavy metals. Other types of bacteria might be grown decoratively on walls or roofs to signal levels of harmful pollutants in cities." (Armstrong & Spiller, 2010, p. 916) This symbiotic behaviour is particularly interesting when it entails the introduction of microbes into architectural materiality.

2.2 Meteorite: Cyanobacteria and Microalgae

Scientists around the world have set the year 2030 as a deadline for sending humans to Mars, and oxygen production represents one of the most problematic issues in achieving this ambitious goal. Since 2015, the National Aeronautics and Space Administration (NASA) and its partner company Techshot are using cyanobacteria and microalgae to develop an oxygen production facility for a Martian colony (Puiu, 2015).

This extraordinary mission triggers new scenarios of possible futures that dissolve the boundaries between artificial and natural, life and death. On the one hand, there is an urge to survive, and on the other hand the fascinating and visionary conquest of new territories. This context has inspired architect Carmelo Zappulla to design a life-giving artificial *Meteorite* machine capable of producing oxygen and food through photosynthesis, i.e. a photo-bioreactor synthesising natural, technological, social, and aesthetic dimensions (Fig. 2.1).

FIG. 2.1 The Meteorite prototype
(Copyright Carmelo Zappulla, 2017)

Algae represent a great resource on Earth, as together with cyanobacteria they generate between 70-80% of oxygen. For that reason, their conscious planetary application could ensure the absorption of carbon dioxide and increase the presence of oxygen in the air. Although current oxygen levels are dropping at a rate that is too slow to affect the climate in the modern world (Poulsen, in: Zielinski, 2015), microalgae could still be used for increasing oxygen levels, reducing global warming and preventing consequences of climate change in future (Greene, in: Borkhataria, 2017). Besides the fact that algae produce more oxygen than other plants, they can also be used for production of biofuels and protein-rich foods.

In the context of this scenario, the Meteorite becomes a provocation, aiming to draw attention to environmental imbalance on the planet. The Meteorite is a liquid techno-garden that informs in real time about the present amounts of oxygen and biomass (proteins and pigments).

At the urban scale, the Meteorite can contribute to the construction of a collaborative public space capable of raising awareness about environmental problems, while cultivating oxygen and food.

Meteorite capsules contain billions of microscopic organisms, comprising *Chlorella Vulgaris* and *Synechocystis 6803*, determined in collaboration with Dr Paolo Bombelli from the Department of Biochemistry at the University of Cambridge. Chlorella is a spherical one-cell alga with a diameter of about 1/20th of hair's breadth. It is marketed as a food supplement and labelled as 'super food' for its high protein content (40-50%) and vitamins. Synechocystis is a spherical cyanobacteria with a diameter of about 1/50th of a hair's breadth, capable of producing a precious blue pigment called Phycocyanin. This water-soluble pigment belongs to the Phycobilin protein family and is essentially used as a natural dye in many food products. Both Chlorella and Synechocystis can generate oxygen and remove carbon dioxide from the atmosphere. By absorbing light, these organisms break molecules of water into electrons, protons, and oxygen through a process called *water photolysis*. The Meteorite uses light and these photosynthetic organisms to generate about 10 litres of oxygen per day. Considering the occupied area, the amount of oxygen produced by the Meteorite is 8-10 times greater when compared with the amount produced by a coniferous forest.

Like the Pallasites, the Meteorite is comprised of glazing components encapsulated in metallic matrix. The vitreous part consists of glass incubators in which microalgae are grown. Growth is stimulated by pumped air and integrated lighting systems, and monitored with sensor equipment. Sensors measure the amount of produced oxygen (or carbon dioxide) in real time, and the results are shown on a display. Cyclical weekly harvests of algae allow the estimation of the production rate of protein and the precious blue pigment.

The Meteorite was developed through a parametric design process, which synthesised computer numerical control (CNC) steel manufacturing of the external structure, made by F.lli Perin, and Murano blown internal capsules made by Berengo. Altogether, the Meteorite is the product of creative dialogue between contemporary digital manufacturing and millenary craftsmanship.

2.3 Bio-Machines at the IAAC

Is there any sharply defined boundary separating the natural from the artificial? Is it inevitable to treat the products of human activity as artificial and, thus, as irremediably detached from nature?

The design studio G2 at the Institute for Advanced Architecture of Catalonia (IAAC), directed by Claudia Pasquero and Carmelo Zappulla, investigates the urban environment from an essentially non-anthropocentric point of view, on the basis of the belief that it is impossible to draw neat boundaries between nature and artifice,

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landscape and city, and ultimately between biosphere and urbansphere. The studio is an inclusive design research environment, where learning represents progressive experience aimed towards individual and collective development, and research combines both experimentation and simulation. The experiments are designed to build understanding of various phenomena by identifying cause-effect links. They focus on observation and exemplify different configurations of a research problem. Therefore, the experiments implement analogue research techniques that help to determine the design of an apparatus - a device that integrates all features and parameters of a specific phenomenon. Experiments also resort to the aid of digital fabrication, glass craft, biotechnologies, digital video, and photography. On the other hand, simulations (by using computational models, simulation software, modelling techniques and digital video) represent and describe phenomena through virtuality. Both analogue and digital processes constitute research framework. Data integration between experiment and simulation processes provides a fruitful overview of the components and their relationships.

The studio is mainly focused on four research lines:

- **'Animal Behaviour'** (Von Frisch, 1974) which examines the behaviour of arthropods, their social organisation and three-dimensional construction abilities;
- **'Bio Regeneration'** concentrated on the active remediation of the environment by removing contaminants or by consolidating the environment with the use of biological systems;
- **'Bioluminescent Tectonics'**, which integrates living organisms able to produce light (e.g., fungi, bacteria, insects, Dinoflagellate, or jellyfish) with a designed material system; and
- **'Biophotovoltaics'** (University of Cambridge, Department of Biochemis -try, n.d.) – living solar panels that transform solar energy captured by plants into electrical power through electrochemical reactions.

Animal Behaviour

If human beings are part of nature, then the objects that humans make should also be a part of nature. Human architecture should not be viewed as something different from the architecture of other species, such as wasps, ants, or bees. By studying animal architecture, it is possible to explore how digital and animal inspired fabrication techniques can be combined to produce architectural material systems. To that end, the project *Bee++* examines the honeybees as insects that possess collective intelligence and inhabit a colony. To deepen and describe different aspects of colony behaviour, two different algorithms were used. Simulations were carried out on both macro and micro levels, by recreating the comportment of honeybees in landscape, i.e. by mimicking the way in which they deposit the wax. Research combines simulation with experimentation: while simulation represents specific environmental conditions, experiments reproduce them. But how can the behaviour of honeybees be reproduced?

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Bee ++ speculates on behaviour patterns used to shape a new material system. An XY wax extruder has been built and programmed to pour natural wax onto jute fibres that follow the patterns used by honeybees. The result is a new natural composite whose texture and pattern are generated by same algorithm used to describe the paths that bees trace while fabricating the hive (Fig 2.2).

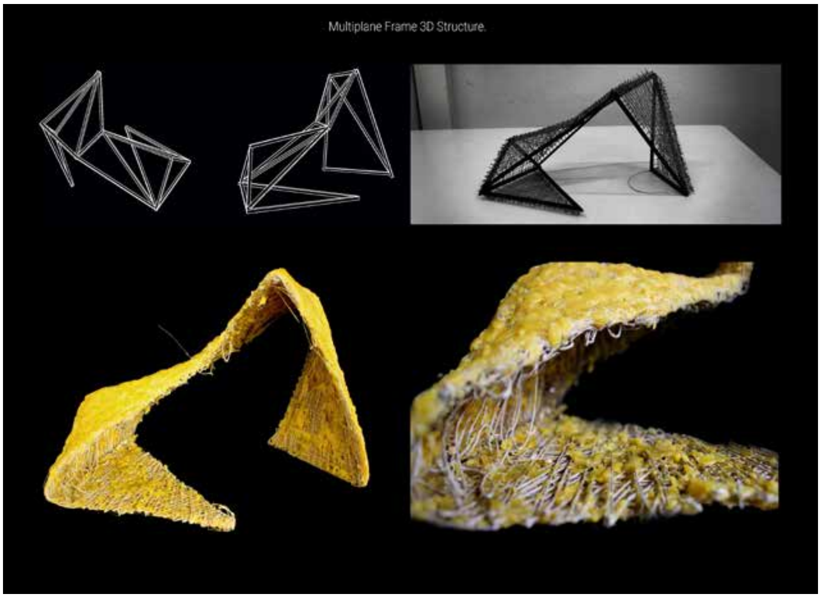

FIG. 2.2 Multiplane Frame 3D structure of the Bee++ *(Image courtesy of Institute for Advanced Architecture of Catalonia)*

Bio Regeneration

Mankind interacts with the environment insofar as both are constitutive parts of one single system. In spite of this, human societies exploit the environment with the sole aim of producing wealth. Consequently, the natural environment is at the same time human habitat and a source of profit, and this leads to the paradox that is the root of the unbalanced use of energy and matter within the biosphere, thus causing the rupture of the relationship between artefacts and the environment. To re-engage humans successfully in the balanced functioning of cities, the importance of 'analogue' experiences, as a means to tangible and material experiences of the world, must be re-discovered.

Algaetecture eco-machine (Fig 2.3) is a wastewater treatment device with *Chlorella Vulgaris,* a system capable of purifying greywater, producing oxygen, absorbing carbon dioxide and generating biomass. Thorough laboratory research and an extensive testing process have been carried out on this microalga to examine its growth mechanism and metabolism of waste materials. To determine the best conditions for wastewater processing, a matrix device that controls various parameters of algae growth (such as the type of lighting, light intensity, temperature, nutrients, type of water contamination) has been developed.

FIG. 2.3 'Algaetecture' eco-machine
(Image courtesy of Institute for Advanced Architecture of Catalonia)

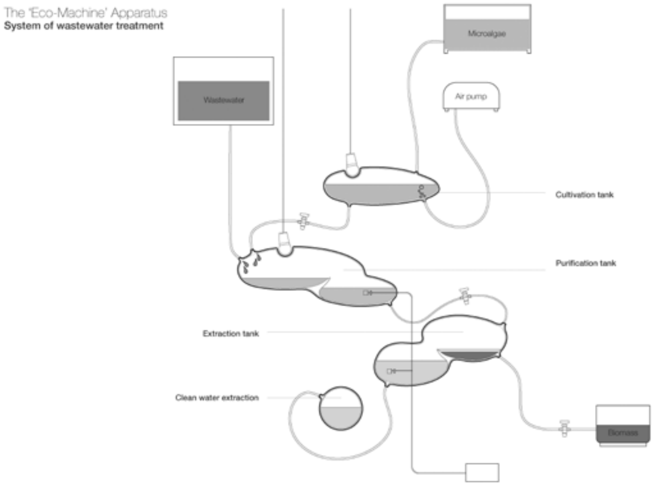

FIG. 2.4 Eco-machine apparatus
(Image courtesy of Institute for Advanced Architecture of Catalonia)

Based on experiments and data collection, water purification phases are developed in a three-step loop, as 'cultivation tank', 'purification tank', and 'extraction tank' (Fig 2.4). The inputs to the eco-machine are wastewater, light, and air, while the outputs are clean water and biomass. This device, depending on the requirements for quality and quantity of wastewater to be treated, can vary in dimension and number of components, and therefore it allows for the adjustment of the scale and the repetition of purification process until desired output quality has been obtained. Eco-machine can be multiplied into a network of components and adapted to different environments and different scales.

Strip MYCO_Puncture is an attempt to solve the problem of coastline erosion of Barcelona's urban beach, which is subjected to continuous loss of sand and replacement with new material from abroad. The proposed solution applies *Mycelium,* a mass of branching hyphae, the vegetative part of a fungus colony. Firstly, the growing behaviour of this living material in a sandy substrate was studied, and numerous experiments preceded by sand cohesions tests were carried out. The results demonstrated Mycelium's ability to grow in the sand and seawater solution. Subsequently, a matrix device was designed and built to inoculate Mycelium at different depths and at precise points, following geometric 3-dimensional reticular patterns. Later, the growth of underground material and its ability to propagate and bond within the sand were analysed. Successive activities were focused on the design of the 'Mycelium Spore Inoculator', which aimed to populate Barcelona's beach at strategic points. It is foreseen that the inoculated Mycelium could grow into dynamic and living structures that would strengthen over time and digest organic debris from the city (Fig 2.5). Thus, the project Strip MYCO_Puncture would not only transform geomorphologies of the coastline dynamics, but also create a synergy between material system and detritus of the urban fabric.

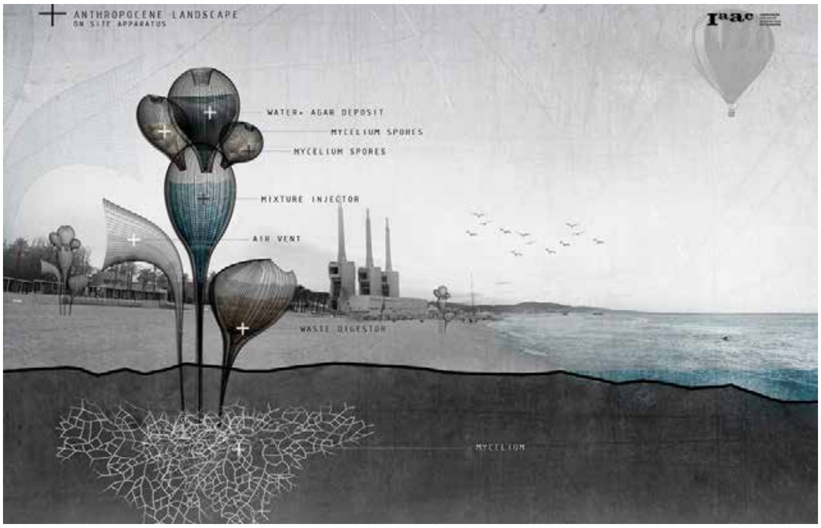

FIG. 2.5 On site 'Mycelium inoculation apparatus' *(Image courtesy of Institute for Advanced Architecture of Catalonia)*

Bioluminescent Tectonics

Bioluminescence is a spectacular phenomenon occurring in marine and land organisms. Moreover, it can also represent a way to reduce overall energy dependence. To that end, the scholars from the Syracuse University (2012) believed that they could create a bioluminescent, 20-30 times more efficient than any previously made. Lighting that does not require any energy can be created by using nanotechnologies to harness the bioluminescence of fireflies.

In a different way, the project *Living Light* focused on symbiotic behaviour of the bioluminescent bacteria, *Vibrio Fischeri.* The interest in developing the project was focused on the way that bacteria communicates in order to produce light. When cell density of bacteria is low, they do not produce any light, but by means of communication known as quorum sensing, they are able to signal a single cell to sense the number of surrounding bacteria and make a coordinated response to glow. All bacteria have a chemical correspondence between each other. A species-specific language indicates the presence in the colony. Therefore, the first important step was to design an incubator that controls environmental parameters of *Vibrio fischeri* and monitors its growth (Fig. 2.6 and Fig. 2.7).

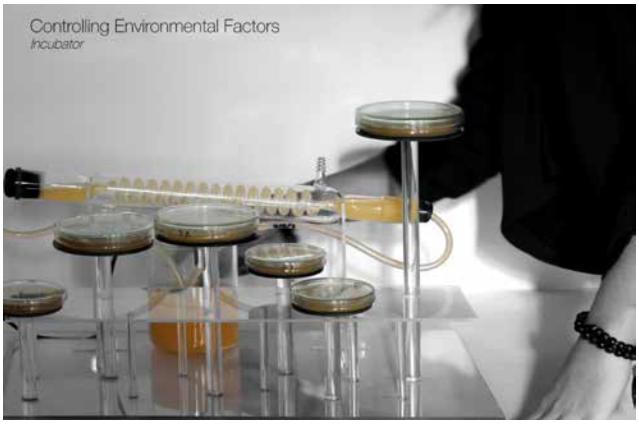

FIG. 2.6 Vibrio fischeri incubator *(Image courtesy of Institute for Advanced Architecture of Catalonia)*

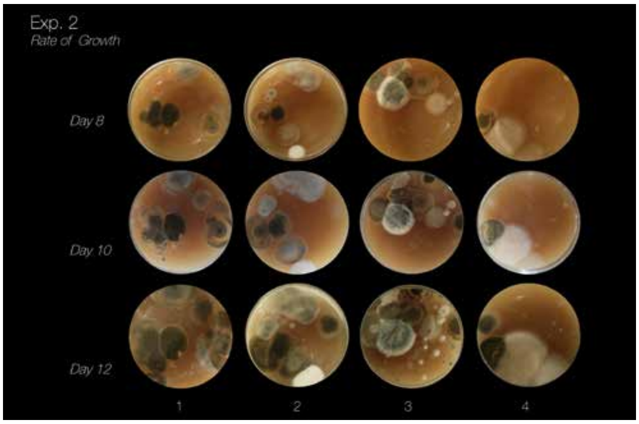

FIG. 2.7 Rate of growth of Vibrio fischeri *(Image courtesy of Institute for Advanced Architecture of Catalonia)*

Once the knowledge about bacteria behaviour was deepened, the potential colonisation of human bodies was speculated upon, and the bioluminescence wearable device was designed. Designed and craft-built blowing glass capsules that house bacteria represented the core of the device. The light is activated by movement, thereby allowing a symbiotic relationship to develop between the human body and the fabricated piece.

Biophotovoltaics as Productive Landscapes

To harvest electrical power from plants, biological photovoltaic devices belonging to the electrochemical system, sometimes called 'living solar cells' (Rosenbaum, Schröder, & Scholz, 2005), can be used. The *Electromoss* project has been developed by using this knowledge.

In general, moss and plants use photosynthesis to convert carbon dioxide into organic substances. On the other hand, the bacteria present in soil decompose these organic compounds by liberating electrons. Thus, if bacteria are added to moss cultivation, electrons can be collected and electrical power produced (Bombelli, 2012). The main elements of such bio-electrical systems are anodic material (moss), the anode (water and carbon fibres), and the cathode (Fig 2.8).

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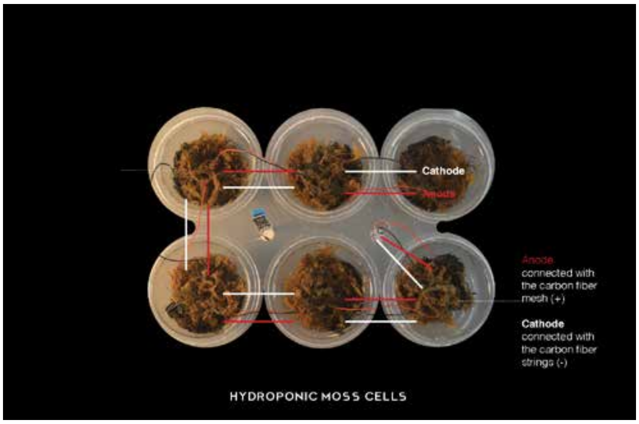


FIG. 2.8 Bio-electrical system used in 'Electromoss' project *(Image courtesy of Institute for Advanced Architecture of Catalonia)*

FIG. 2.9 'Electromoss' prototype *(Image courtesy of Institute for Advanced Architecture of Catalonia)*

The first part of the project focused on the cultivation of hydroponic moss *Sphagnum flexosum* on a bio-gel medium. An apparatus was set to control humidity, nutrients and light, and to monitor the amount of energy produced. According to the results of the experiments, an area of 314cm^2 of moss could produce an average voltage of 2.1V per week. Furthermore, a glazing prototype at 1:1 scale was produced (Fig 2.9), and the concept of an energy garden that can multiply its dimension according to the energy necessities was envisioned.

At the large scale, Electromoss looked for the mechanisms of local production of energy, food and bio-materials in the urban environment, focusing on how these bottom-up processes could contribute to urban morphogenesis of contemporary cities.

How can a landscape be transformed into a productive one? How do water, solar energy, wind or biological processes affect sustainable design cycles for structures and landscape? In 2014, IAAC students had a possibility to explore the transformation of a real site into self-sufficient land in the Torre Baró neighbourhood in Barcelona. Within the experimental spatial context intended for the *Torre Baró Productive Landscape*, the students applied biophotovoltaic (BPV) cells to the landscape. After extensive experimentation to determine the optimal plant species and the ways of increasing bacterial concentration in soil, a sophisticated landscaping strategy was developed. The solution for the techno green island integrated vegetation, electrical circuits, rain water recollection, and a leisure program. BPV cells, as envisioned by the project, adapt their morphology to existing topography and generate a network of nodes connected by paths (Fig 2.10).

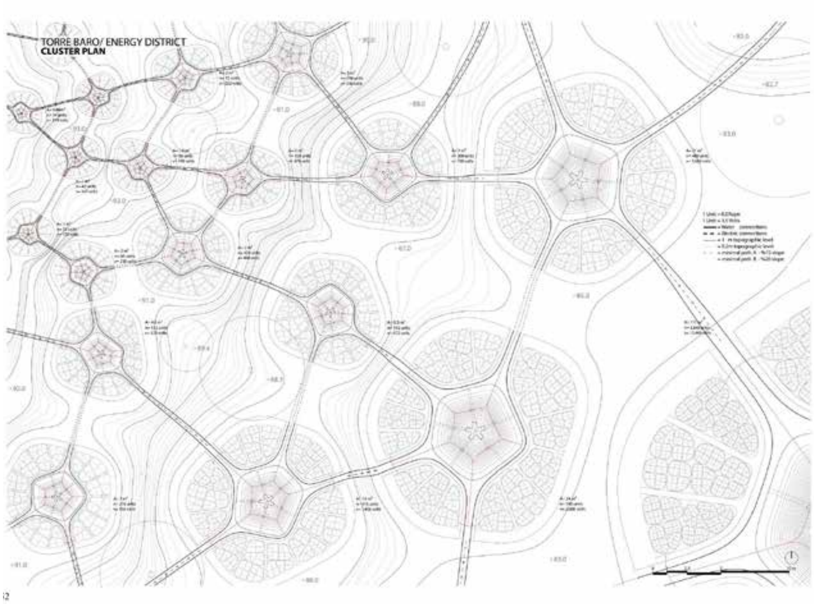


FIG. 2.10 Torre Baró Productive Landscape *(Image courtesy of Institute for Advanced Architecture of Catalonia)*

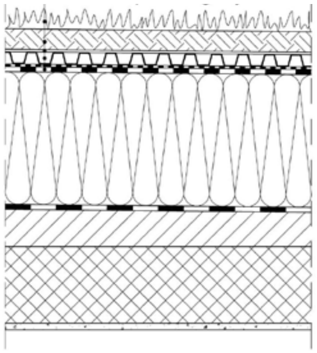
3 Contribution of Biological Entities to Regeneration: Integrated Greening Systems Case Study

The application of the principle of growth on green roofs and vertical greening systems integrated with the building envelope accounts for a measure with high regeneration potential, aesthetic pleasure, and economic support (Juric, 2016).

In general, the structure of a green roof consists of vegetation, substrate, filter, drainage, and a root barrier placed over a waterproofing layer (Vijayaraghavan, 2016) (Fig. 3.1).

The main types of green roofs, according to their characteristics, structural complexity, and function are intensive and extensive (Table 3.1), while semi-intensive green roofs are defined as a variant between the two (Berardi, Ghaffarian Hoseini, & Ghaffarian Hoseini, 2014; IGRA, n.d.). The prevalent use of extensive green roofs is explained by the potential for application on existing buildings. In comparison with intensive type, extensive roofs are characterised by a lighter structure, lower capital costs, easier installation, and a lower level of maintenance (Wilkinson, Lamond, Proverbs, Sharman, Heller, & Manion, 2015). Because of their shallow substrate layer, extensive roofs support vegetation species such as grasses and short-sedum. Extensive green roofs can be designed as accessible and inaccessible, flat or sloped vegetated surfaces with an optimal inclination of up to 45° (Optigreen, n.d.).

While extensively vegetated covers can be added later, intensive green roofs should be well detailed in early design stages because of their heavy weight and structural support requirement. The thick substrate layer in an intensive roof structure allows for the planting of shrubs and trees. Considering the structure and applied vegetation, intensive roofs are mainly flat and accessible, which, besides ecological gains, adds social benefits through its utilisation. Economic benefits of intensive vegetated roofs are achieved despite high initial investment.



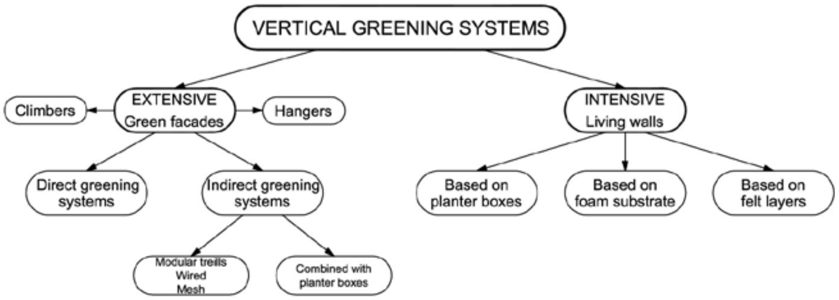


FIG. 3.1 Typical green roof structure. Layers from top: vegetation; substrate; filter layer; drainage layer; root barrier; waterproofing layer.

FIG. 3.2 Vertical greening systems classification *(According to Perez et al., 2011; Perini et al., 2011; Virtudes & Manso, 2016)*

Vertical greening systems are characterised by the distribution of plants on vertical surfaces. Through their application, a number of environmental, social and economic benefits are achieved (Sadeghian, 2016). Depending on the growing method, vertical greening systems can be classified as green façades (extensive systems) and living walls (intensive systems) (Perez, Rincon, Vila, Gonzalez, & Cabeza, 2011; Perini & Rosasco, 2013) (Fig. 3.2). For both types, the main part of vertical structure consists of vegetation and substrate layers.

BASIC CHARACTERISTICS	EXTENSIVE GREEN ROOF SYSTEMS	INTENSIVE GREEN ROOF SYSTEMS
Diversity of plants	Moss, herb and grass	Lawn, perennials, shrubs and trees
Substrate thickness [mm]	Shallow substrate layer (≤ 150)	Deeper substrate layer (≥ 150)
System build-up height [mm]	60 – 200	150 – 1000
Weight [kg/ m²]	60 – 150	≥ 180
Implications for existing buildings	Usually without additional support	Mostly require additional support
Construction	Moderately easy	Technically complex
Accessibility	Both accessible and inaccessible	Accessible
Roof coverage	Cover large expanses of rooftop	Cover less expanses of rooftop
Roof slope [°]	≤ 45 (Optimal)	≤ 5 (Flat roof)
Investment costs	Low	High
Maintenance	Low	High
Irrigation	Often not necessary	Necessity of irrigation systems
Benefits	Ecological and economic	Ecological, economic and social

TABLE 3.1 Basic characteristics of extensive and intensive green roof types *(according to Berardi et al., 2014; IGRA, n.d.; Wilkinson et al., 2015; Wilkinson & Reed, 2009)*

In comparison with green roofs, vertical greening systems have greater potential for achieving environmental benefits as the surface of façade(s) is in most cases larger than the roof surface. However, vertical greening systems are used to a much lesser extent due to complexity of measures needed to secure successful integration with the building structure and the adequate performance (Riley, 2017).

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Green façades refer to scattered vertical distribution of climbers or hanging plant species (Virtudes & Manso, 2016). The plants attach to the surface directly or indirectly, and are supported by cables or a trellis. Indirect greening systems can be combined with planter boxes at different heights along a façade (Perini, Ottelé, Haas, & Raiteri, 2011). In comparison to living walls, green façades are characterised by lower capital cost, easier installation, and a lower level of maintenance. The application of these systems provides similar benefits to living walls, albeit to a lesser extent.

Living walls (also known as vertical gardens) comprise modular panels, where every panel contains its own substrate layer. Considering the principles of growth and conception, living walls are based on: a) planter boxes filled with potting soil, b) foam substrate with supporting steel baskets, and c) felt layers working as substrate and waterproofing, and supported by plastic sheets (Perini et al., 2011). In contrast to their high potential for achieving primarily environmental benefits, the disadvantages of living wall applications include high capital cost, rather complex installation (especially within the existing buildings), and a higher level of maintenance in comparison to green façades.

Although building integrated greening systems could be applied worldwide, the distinctiveness of their design should reflect specific climate characteristics. For securing efficiency in greening systems performance, it is necessary to consider location properties and local plant species (Getter, Rowe & Cregg, 2009; Riley, 2017; Speak, 2013). Custom design adjusted to the specificities and uniqueness of a certain place is in accordance with the principles of regenerative design. Future development of greening systems should be researched through hybrid solutions, including vegetation and photovoltaic elements. Hybrid systems have a great potential for widespread utilisation, considering that photovoltaic systems are already a mature and widely used technology, and that greening systems can act as an accessory in providing regenerative development (Stamenković, Antolović, Kostić & Mitković, 2017; Vijayaraghavan, 2016).

3.1 Provision of Ecosystem Services

Integrated greening systems have a significant potential for urban heat island mitigation, runoff water control, air and noise pollution reduction, and the increment of biodiversity.

Temperature increase in urban areas, known as the urban heat island (UHI) phenomenon, negatively affects the quality of air and water, creates pressure on urban ecosystems and contributes to climate change. UHI occurs as a result of human activities, excessive materialisation of the built environment and excessive utilisation of surface materials with low albedo. On typical roof surfaces, albedo values range from 0.1-0.2 for bitumen, tar, and gravel, to 0.7-0.85 for greenery (Berardi et al., 2014). Even in urban areas that are not affected by the UHI, greenery plays a significant role in temperature regulation

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on a micro scale, as demonstrated by the examples of neighbourhoods with similar morphological characteristics and differences in terms of existing greening systems (Fikfak, Kosanović, Konjar, Grom, & Zbašnik-Senegačnik, 2017). Greening systems regulate ambient temperature by evapotranspiration and by creating shadows. A wider application of envelope-integrated greening systems would contribute to temperature regulation on an urban level.

Regarding water management, greening systems affect both quality and quantity of runoff water. By covering impermeable building surfaces with greening entities, storm water is retained and its distribution to the sewerage systems in delayed, and by so doing reduces the load on infrastructure and the risk of flooding. In controlling runoff, green roofs are more efficient than vertical systems. Because of the storage capacity of the substrate layer, intensively vegetated horizontal surfaces could reduce up to 100% of runoff (Rowe, 2011). Generally, greening systems improve the quality of runoff water through absorption of pollutants, but the exact performance will depend on substrate layer composition. When the ion concentration in runoff water is high, greening system components act as a sink, thereby lowering the presence of ions. On the other hand, if the concentration of ions in runoff water is substantially lower than in a substrate medium, then some ions will be leached from substrate. As a result, the outgoing runoff water will have a higher concentration of ions than the incoming water (Vijayaraghavan, 2016).

Greening systems are considered to be a clean and practical technology for air purification. Plants have the ability to reduce air pollution directly and indirectly. They absorb gasses through stomata, retain particulate matter on leaves, decompose certain organic compounds, and regulate microclimate (Rowe, 2011; Yang, Yu, & Gong, 2008). Surface temperature decrease by transpiration cooling and shading in turn decreases photochemical reactions that participate in forming the air pollutants. Reduction of the need for air conditioning and lower energy demand will result in lower emissions from power plants (Rowe, 2011). To that end, vegetation is not only important for oxygen generation but also for carbon dioxide reduction.

Greening entities have a great potential to reduce sound pressure in the built environment, having regarded increased envelope insulation and the absorption of sound waves diffracting over roofs and in front of façades. As the vegetation layer displays better sound insulation properties at high frequencies, this imperfection can be improved by multi-layering and by applying denser coverage (Sekulić, 2013). The role of substrate in noise reduction is, however, the most significant, and is most efficient at low frequencies (Connelly & Hodgson, 2008).

The loss of biodiversity in densely built areas causes damage to basic ecosystems processes and cyclic closed loops. Therefore, habitat creation and protection aim to mitigate the adverse effects of urban settings (Bianchini & Hewage, 2012b). Although greening systems as artificially created natural environments play an important role in the growth of urban biodiversity, they cannot replace nature as functional

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habitat (Speak, 2013). The increase of biodiversity within urban ecosystems improves ecological quality and health, and additionally provides emotional, intellectual, social, and physical benefits to humans (Sadeghian, 2016).

3.2 Provision of Health, Well-Being and Other Social Benefits

Human health and well-being directly depend on provided ecosystem services. By applying greening systems in urban areas, positive impact on the ecological state of the environment and on human health is achieved. Since accessible greening systems encourage social interaction and physical activity, they also affect the well-being of users. Conducted studies indicate a favourable effect on preventing the spread of diseases and potentially on life expectancy (Zhou & Parves Rana, 2012). Green areas within a hospital environment accelerate patients' recovery, especially when visual contact with the outdoor environment is established (Nurmi, Votsis, Perrels, & Lehvävirta, 2013; Wang, Bakker, De Groot, & Wörtche, 2014). Knowing that human health is a "state of complete physical, mental and social well-being and not merely the absence of disease or infirmity", urban greenery also provides a number of psychological benefits (Zhou & Parves Rana, 2012). Greening systems have the greatest visual impact of all sustainability measures introduced to the buildings (Jungels, Rakow, Allred, & Skelly, 2013). The presence of vegetation provides distinct senses of colours, shapes, textures, and sounds (Zhou & Parves Rana, 2012). Greenery systems in densely built areas contribute to stress relief, mental fatigue relief, increase in attention and productivity, achievement of satisfaction, improvement of educational processes, etc. (Al Horr et al., 2016; Wang et al., 2014; Zhou & Parves Rana, 2012).

The integration of greening systems into built structures enhances visual experience. Intensified implementation would contribute to the establishment of visual identity of larger urban areas. The aesthetics of greenery systems are often excluded from common benefit analyses due to the lack of adequate quantitative indicators for evaluation (Bianchini & Hewage, 2012b; Nurmi et al., 2013), but it certainly forms part of regenerative design framework with immeasurable values included.

According to the properties, intensive accessible roofs are similar to parks. Therefore, they provide an optimal spatial setting for the enhancement of physical activity, recreation, and social interaction. The necessity for usable green areas is justified by the fact that about 60% of the population is physically inactive, which represents the main risk to the health (Goode, 2006). Where outdoor space is more frequently used and a similarity with the natural environment is achieved, social interactions are more intensive and a sense of community is more likely to be developed. This indicates the significance of green roofs from the social aspect of research.

3.3 Provision of Economic Benefits

Economic benefits of greening systems refer to the evaluation of financial gains at both urban and building levels. The initial benefit should relate to the advantages of greening systems relative to other measures that aim to reduce the costs of water and air purification, redesign of the sewerage system, sound protection, etc. The main constraint is that the initial economic benefit is not currently taken into consideration in practice, although the concepts of regenerative design and development highlight the need for assessment. Other important benefits of greening systems at building level are energy savings, extended lifespan of the envelope, and increased property value (Berardi et al., 2014; Bianchini & Hewage, 2012b; Perini & Rosasco, 2013; Perini & Rosasco, 2016; Riley, 2017).

In greening systems framework, the improvement of building thermal performance results from optimisation of the balance between shading, insulation, and thermal mass. The extent to which energy demand for space heating and cooling could be reduced depends on climatic conditions, building characteristics, and the type of greening system applied. Although energy savings can be achieved in all climates, the best thermal performance is registered in hot and humid climates, as greening systems provide an efficient cooling effect. The results of conducted studies indicate the reduction of energy demand for air conditioning of about 50% in the Mediterranean climate (Berardi et al., 2014; Perini & Rosasco, 2013).

Since greening systems represent an additional top layer of building envelope, they reduce possibilities for damage from ultraviolet radiation, acid rains, ice, air pollution and daily temperature fluctuations (Perini & Rosasco, 2016; Rowe, 2011), and therefore decrease maintenance costs and increase, or even double, envelope lifespan (Berardi et al., 2014; Bianchini & Hewage, 2012b; Perini & Rosasco, 2016; Rowe, 2011).

Different studies confirm that the value of buildings with integrated greening systems is increased because of introduced 'nature' and its positive effects on air quality improvement, noise protection, visual experience, etc. (Bianchini & Hewage, 2012b; Conway, Li, Wolch, Kahle & Jerrett, 2010). The average value increase for a building with integrated greening system(s), according to the published results, amounts to 10.5% (Bianchini & Hewage, 2012b; Perini & Rosasco, 2013). Although greening systems have higher capital costs compared to other types of roofs and façades, it is justifiable to invest in their construction; after the period of investments return, building integrated greening systems continue to provide economic gains on the basis of quantitative evaluation of ecological and social benefits. This fact confirms the achievement of net-positive goals, which is a fundamental postulate of regenerative design.

4 Discussion and Conclusions

Reed (2007) developed the trajectory of environmentally friendly design and differentiated the transitions from green (characterised by relative improvement), to sustainable (neutral), restorative (assisting the evolution of sub-systems), reconciliatory (where humans are integral part of nature) and ultimately to regenerative design (where the co-evolution of the whole system exists). Green design aims to reduce the degenerative consequences of human activities on ecological systems and to improve the health and comfort of residents (Cole, 2012b; McDonough & Braungart 2002; Reed, 2007). The difference between green, sustainable, and regenerative design approaches is described as doing less harm, doing no harm, and doing some good, respectively (Cole, 2012b). While sustainability is an overarching, globally scaled approach, 'green' and 'regenerative' are complementary approaches to design in the specific context that supports sustainability (Cole, 2012b).

Regenerative design has been identified as a way of maintaining balance and sustainability in urban ecosystems, i.e. a complex approach dealing with the intricate relations within different segments of the environment. Biological entities and their multi-layered purpose provide a comprehensive response to the intricacy of regenerative design.

Vegetation is an important criterion in the ecological evaluation of urban areas (Kosanović & Fikfak, 2016). In densely built urban areas, the role of greening systems is central to the regenerative design framework, as they do not only prevent the degradation but also contribute to the improvement of the overall existing ecological conditions (Kosanović, 2007). Although the research on greening systems has increased in terms of knowledge and technology in recent years, these issues at the same time continue to interfere with personal perceptions and perspectives. This indicates the necessity of providing whole system thinking, and further leads to the more general question about how the regeneration concept is perceived by humans as participants.

The active role of humans in the regenerative framework is purposefully defined. Regeneration, therefore, ultimately intends to bring the needs of citizens into a long-lasting synergy with the requirements for natural integrity. Therefore, humans, at the current point of development, need to recognise (again) their positioning within the living systems and to understand the complex patterns of dynamics (Roetzel, Fuller & Rajagopalan, 2017) in which they are embedded. Bringing humans back to their biological nature ultimately opens a new debate on the relationship to contemporary technologies. In addition, between design that regenerates the environment by involving humans and their activities, and the perspective that looks for ways to intensify positive effects of nature on humans, a new integral framework needs to be defined. The introduction of biological entities into design is believed to represent a significant agent in the integration process.

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Acknowledgements

Author Carmelo Zappulla acknowledges the following projects from the programme Master in Advanced Architecture at the Institute for Advanced Architecture of Catalonia (IAAC):

Algaetecture (2015/2016). Students: Andre Resende, Mohamad Atab, Hsin Li, Stefan Fotev, Sureshkumar Kumaravel and Yasamin Khalilbeigi. Staff: Claudia Pasquero (tutor), Carmelo Zappulla (tutor) and Maria Kupstova (assistant);

Bee++ (2015/2016). Students: Burak Paksoy, Michel Alazzi, Nikolaos Argyros, Firas Safieddine and Sameera Chukkapalli. Staff: Claudia Pasquero (tutor), Carmelo Zappulla (tutor) and Maria Kupstova (assistant);

Electromoss (2015/2016). Students: Carlos Daniel Gómez, Anastasia Marcella, Fabio Menezes, Monika Koeva, Sahana Sridhar and Fernando Baptista. Staff: Claudia Pasquero (tutor), Carmelo Zappulla (tutor) and Maria Kupstova (assistant);

Living Light (2015/2016). Students: Thora H. Arnardottir, Karthik Dhanabalan, Jessica Dias, Noor El-Gewely, Maryann Ewais and Ingried Ramirez. Staff: Claudia Pasquero (tutor), Carmelo Zappulla (tutor) and Maria Kupstova (assistant);

Strip MYCO-Puncture (2016/2017). Students: Sebastian Amorelli, Montakan Manosang, Ricardo Mayor Luque, Samarth Agrawal and Pranav Kashyap. Staff: Claudia Pasquero (tutor), Carmelo Zappulla (tutor) and Maria Kupstova (assistant); and

Torre Baró Productive Landscape (2014). Students: Josep Alcover Llubia, Joy Alexandre Harb, Shruti Ramachandran, Yanna Haddad, Zoi Dalfni Arnellou. Tutors: Claudia Pasquero and Carmelo Zappulla.

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