URBAN AND REGIONAL AGRICULTURE

BUILDING RESILIENT FOOD SYSTEMS

EDITED BY PETER DROEGE

Urban and Regional Agriculture

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Edited by

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Contents

SECTION 3 DESIGNING URBAN AND REGIONAL AGRICULTURE

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Chapter 21

Living architecture: metabolic applications for next-generation, selectively programmable bioreactors

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INTRODUCTION

Modern-day inhabitation, in nations with advanced economies, and increasingly so in emerging market and developing economies (IMF, 2015), requires an enormous amount of resources for supporting the desired 'lifestyles,' such as climatized interior environments, electrification of lighting, appliances, and other electronic devices (Hidetoshi, 1996; Wei, 2007), or water consumption (Worldometers, 2017; Statista, 2013). Large-scale infrastructures and services have been conceived and constructed to deliver a constant supply of electricity, (natural) gas, and water to buildings and to take away copious amounts of human- and building-generated waste. Because of global lifestyle choices, and lack of concerted effort to combat their negative impacts, we find ourselves living in the era of the Anthropocene: defined by compromised planetary environmental conditions, and challenged ecosystems, brought forth through accumulated human activity.

Johan Rockström (Rockström, 2009) argues that there are nine 'planetary boundaries' that should not be transgressed to stay within the 'safe operating space' of Earth's natural system. Of the nine boundaries that are formulated, three have already been trespassed, including rate of biodiversity loss, interference with **nitrogen and phosphorus** cycles, and climatic change.

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A breach of even one boundary could, and eventually will when not sufficiently addressed, lead to an overall toppling of the entire system which is largely defined by codependencies of its different subsystems. The nine boundaries comprise of:

1. Climate change
2. Rate of biodiversity loss
3. Nitrogen cycle and phosphorus cycle
4. Stratospheric ozone depletion
5. Ocean acidification
6. Global freshwater use
7. Change in land use
8. Atmospheric aerosol loading
9. Chemical pollution

Rockström calls for a concerted effort to stop, even reverse, the pattern of ever-increasing devastation and destruction in these nine categories, with elevated importance on the three which have already been trespassed. For this chapter, the H2020 FET-OPEN Living Architecture (Living Architecture, 2016) project is being used as showcase for metabolic applications. This project demonstrates that it can have an impact on improving current nitrogen and phosphorus cycles, and on climatic change largely caused by greenhouse gases. Furthermore, its widespread use could have a profound impact on the global use of freshwater and chemical pollution.

NITROGEN AND PHOSPHORUS CYCLE

Nitrogen and phosphorus naturally exist and are critical for the health of human beings, plants, and the environment (Sengupta, 2015). Both elements are widely used in agricultural applications. Human-made synthetic fertilizers have both nitrogen and phosphorus.

Agricultural systems, largely industrialized and centralized today, are losing a large percentage of these nutrients in agricultural run-off. This creates environmental implications both on the production of synthetic fertilizer and further down the line, when these water flows enter natural waterways, where they have a detrimental effect on local ecologies through eutrophication. This process is common throughout the world and is caused when algal growth and algal blooms take over bodies of water, due to a high concentration of nutrients in the water. The decay of dead algae causes oxygen depletion and reduces its availability for other forms of aquatic life.

Nitrogen and phosphorus are found in high concentrations in waste streams, coming from agricultural run-off and from waste streams from human habitation, particularly from human excreta. Human waste is one of the largest suppliers of the nutrients and contributes around 80% of the nitrogen found in waste streams and about 60% of the phosphorus (Kirchmann, 1995).

Today, the problem of nitrogen and phosphate nutrients getting 'stuck' in the system falls to the responsibility of wastewater treatment facilities (WWTFs). Currently, however, many "at the source" methods of extracting nutrients from nutrient-rich waste streams are being developed, and serve as viable alternatives to losing these supplies to WWTFs. At the source methods also reduce the costs associated with wastewater treatment in large, centralized systems, saving on both energy and chemical use (Kirchmann, 1995; Larsen 1996).

The blackwater fraction of household wastewaters contains 90% of the overall nitrogen and 90% of the overall phosphorus (Jönsson, 2005) that is discharged from a household (Spångberg, 2014). The urine fraction of blackwater, excluding also the flush water, contains around 80% of the overall nitrogen supply found in the blackwater and 60% that of the phosphorus supply. (Nitrogen takes mainly the form of ammonium in urine.) The composition of urine, therefore, is similar to that which is desired for the fertilization of plants (Heinonen-Tanski, 2005).

Maurer has concluded that the best way of obtaining the urine fraction, of human excreta, is achieved through struvite precipitation and ammonia stripping, and by toilets that are specially designed for separating urine from fecal matter and toilet paper (Maurer, 2006).

Further treatment of the urine is required based on needs and requirements and includes Hygienization, volume reduction, stabilization, P-recovery (Phosphorus), N-recovery (Nitrogen), nutrient removal, and the handling of micropollutants (Maurer, 2006). No single treatment can achieve all criteria, and almost all are still in developmental stages; not yet available in the open market (Maurer, 2006).

Nitrogen

Nitrogen exists naturally in the atmosphere, as a highly stable and nonreactive gas (N_2). When adding nitrogen into synthetic fertilizers, N_2 is removed from the atmosphere and is fixed to the medium in a reactive form (including ammonia, nitrate, and amino acids).

Nitrogen is a valuable resource for plant growth at the location of growth, but the remainder that is not utilized by the plant can get lost in environmental cycles. Reactive nitrogen enters the environmental cycle as NH_4^+ in wastewater causing pollution of waterways and coastal zones and into the air as N_2O causing deterioration of the ozone layer and global warming.

The study led by Rockström (2009) declares that currently 121 million TPY (tonnes per year) of nonreactive N_2 is removed from the atmosphere for human use. Rockström proposes to curtail this amount to 35 million TPY to come back into a 'safe operating space.'

Nitrogen can be recovered through processes both localized (e.g., individual building) and centralized (e.g., WWTF). These processes include: ion-exchange and adsorption-based processes, bioelectrochemical systems (such as microbial fuel cells (MFCs)), air stripping, and membrane separation.

Phosphorus

Phosphorus is a nonrenewable resource found in, and extracted from, igneous and sedimentary rock. Phosphorus is one of the major plant nutrients in the soil and is used in food production throughout the world. Further, a deficiency in phosphorus can have a broad range of negative effects on human health of mind and body.

Significant cost and energy consumption is associated with the extraction and transportation of phosphorus and its conversion into synthetic fertilizer.

Phosphorus found in waste streams, even in concentrations as low as 0.02 mg/L, can have detrimental impact when freely discharged into rivers, lakes, and oceans, causing eutrophication, anoxic events, and mass extinction of aquatic life (Rockström, 2009).

Different methods of recovering phosphorus from household waste include physical filtration and membrane processes, chemical precipitation, acid hydrolysis, physical−chemical adsorption, and ion-exchange and biological assimilation through constructed wetlands.

International and regional standards are increasingly imposed on wastewater treatment plants, regarding nitrogen and phosphorus removal (Rockström, 2009). Biological nitrification and denitrification and chemical precipitation are the most common processes used today to remove nitrogen and phosphorus, respectively. Both processes cannot achieve recovery of nitrogen and phosphorus.

SELECTIVELY PROGRAMMABLE APPS (LIVING ARCHITECTURE)

The Living Architecture project (Living Architecture, 2016) builds an apparatus that structurally integrates biological processes into the built environment and programs them to perform tasks essential to waste management. The design has built-in flexibility and adaptability and can be programmed to do different tasks. Tasks are largely defined by initial inputs to the system. Each waste product type (e.g., urine, gray water) has a general set of attributes that is characterized and then manipulated by and through carefully designed biological processes.

Living Architecture, a system of three, collaboratively working bioreactors, is developed as a single (local) architectural solution with the potential to disrupt the established system of centralized providers of energy (electricity, fuel, etc.) and water and could eliminate the need for centrally controlled and operated WWTFs. Using **photobioreactors**, **microbial fuel cells** (MFCs), and **synthetic microbial consortia** (SMC) in a single setup, the project demonstrates the transformation potential of turning household waste (gray water and urine) into valuable resources by providing (through recovery) nutrients useful to agricultural production.

Examples of biological processes being built-in to the physical environment as programmable applications for performing desired tasks can be illustrated by the Pee-Power Toilet, Glastonbury festival in 2015, and the BIQ building.

The Pee-Power Toilet is an energy-independent system developed on campus of the University of the West of England (UWE), developed by UWE with funding from Oxfam and the Bill and Melinda Gates Foundation. The work aims to provide safety in remote toilets by providing lighting and a sanitary and effective way of treating human waste in areas where centralized waste collection services are not available. At International refugee camps, the Pee-Power toilet is conceived to provide sanitary facilities that can be lighted autonomously, for safety concerns, by the urine itself. The project was presented at the Glastonbury festival in 2015, which used specially designed urinals to collect urine from male users and feed it to built-in MFCs. In total, the Glastonbury prototype used 432 cells to generate on average 300 mW of power, enough to illuminate the interiors of the urinals (Ieropoulos, 2016).

Arup, in collaboration with Splitterwerk architects, built the first publicly accessible algae facade for the BIQ House, which served as a form of micro-agriculture. Energy savings were made within the building through the solar-thermal effect of algae biomass (Steadman, 2013). A business model was created and based on comparing output to input, always using algae and biomass production (6 kg of biomass a day). These values were both totally measurable and could be determined easily in a financial way. However, currently the 6 kilos is not being sold in a commercial way (Wurm, 2017).

Microbial fuel cells

The most important principal underlying the Living Architecture project is the MFC. MFCs (Bennetto, 1984) are electrochemical devices that convert the chemical energy of organic feedstock into electricity, via the metabolic processes of microorganisms, which act as biocatalysts. MFCs are increasing their commercial traction within the wastewater treatment industry, particularly at utility scale (Nastro, 2014), as well as significant interest in microbial electrolysis, microbial desalination, and microbial reverse osmosis (Fig. 21.1).

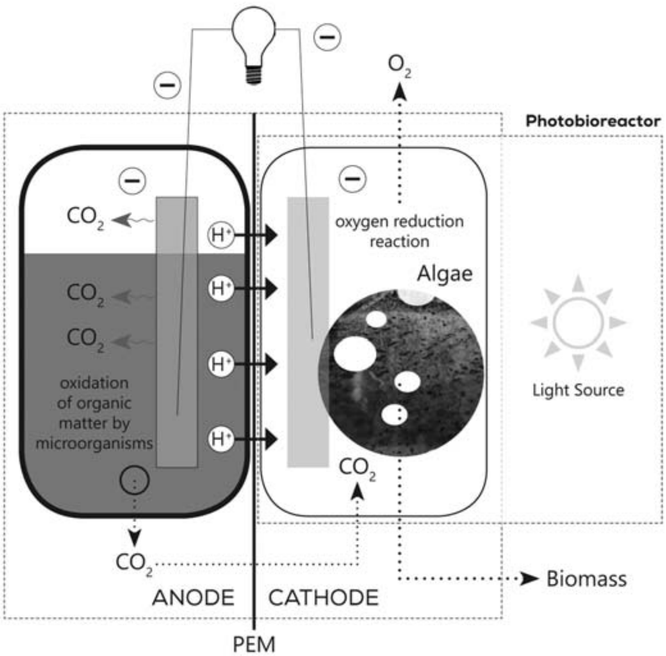
The electricity generated from the MFC can directly support the parasitic load of the system (pumping, mixing, heating, sensors for condition monitoring, etc.) with the expectation that surplus power will be diverted to meet the demand of the building in which it is installed.

MFCs consist of two compartments, the anode and the cathode, separated by a Proton Exchange Membrane (PEM). In the anode chamber, bacteria (microorganisms) anaerobically oxidize organic feedstock and in the process release electrons and cations such as protons. The electrons travel via an external circuit and cations flow through the PEM to the cathode. The cathode is engineered to maximize the oxygen–reduction potential of the system.

Algae are incorporated in the cathode to generate generous supplies of oxygen. This increase in oxygen increases the oxygen–reduction potential for attracting electrons. A separate photobioreactor grows the algae which are then supplied to the cathode, where the oxygen is depleted. There is not significant algae growth occurring at the cathode. If the cathode wall chamber is transparent, then the algae will photosynthesize to supply the cathode with sufficient O_2.

The system can be improved by having control over the metabolic processes that occur in the anode, knowing exactly what the feedstock is and what bacteria or microbial consortia (two or more bacterial communities living symbiotically) can best process the semisolid feedstock.

For the PEM, a variety of tailored ceramic materials have been explored for their electrical conductivity, luminosity, porosity, texture, and strength in compression and are fabricated as containment vessels for the anode chambers of the MFC, as well as for the labor modules of SMC.



■ **FIGURE 21.1** Functional diagram of a Microbial Fuel Cell, *credit: Living Architecture Consortium, 2016*

In the project Living Architecture, biologists and microbiologists map these processes to help define the best applications ('apps') for performing different tasks or building services. By selectively manipulating consortia performance, building systems with high efficiency can be maintained and different types of waste can be processed locally. These programmed communities can be used in both the anode and cathode.

SMC-based bioreactor

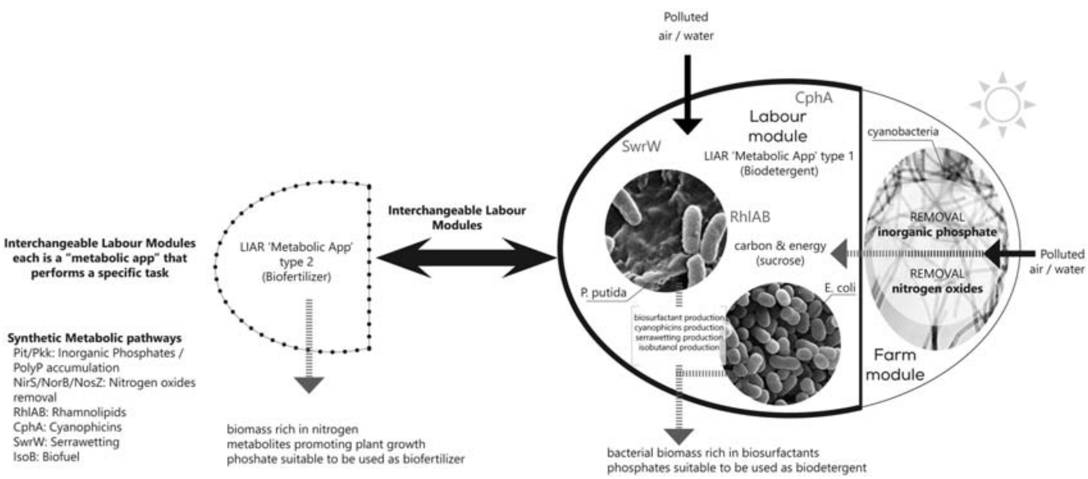
Synthetic Biology is the design and construction of new biological parts, devices, and systems, and the redesign of existing, natural biological systems for useful purposes. Through Synthetic Biology, entirely new organisms can be constructed through DNA modification. This change at the organisms' molecular level creates a new organism, capable of performing specific tasks that are desired. Consortia of these newly constructed organisms, as well as well-known preexisting organisms, can be combined, providing a community of workhorses able to perform many complex and unrelated biological tasks. Biological Consortia become a critical design item in Living Architecture. Living organisms are introduced into the system to take over otherwise large engineering projects. Biological processes are used to do naturally, what mechanical systems do artificially (Fig. 21.2).

The basic SMC design is comprised of two separate modules: (1) a cyanobacterial-based "farm module" exposed to a light source and (2) a bacterial-heterotrophic-based "labor module" that is interchangeable and accessible from in the interior of the building. *Escherichia coli* and *Pseudomonas putida*, two well-known and widely used biotechnological workhorses, are included and maintained in the labor module through engineering synthetic cross-feeding relationships.

The farm module supplies easily metabolized carbon to the labor module, sustainably feeding the labor module which is further programmed to perform the desirable biotechnological functions.

Specific targeted functions include the cleaning of gray water and polluted air by removing inorganic phosphate (Pi) and nitrogen oxides (NOxs), respectively. Additionally, the labor module is genetically programmed for producing high value-added substances: products such as biofertilizers and biodetergents. Four main functions are being identified:

1. **Phosphate** "cleaning" **biobricks**: removed Pi in the form of Polyphosphate is accumulated in bacterial biomass which can be further used as biofertilizer (Pi is a well-known limiting nutrient for plants).
2. **The NOx-removal-biobrick**: the current SMC will be engineered for efficient removal of NOx from air producing molecular nitrogen (N_2). N_2



■ **FIGURE 21.2** Functional diagram of a Synthetic Microbial Consortia Bioreactor, *credit: Living Architecture Consortium, 2016* is an innocuous gas and can be used as nitrogen source by specific microorganism strains contributing this way to complete the nitrogen cycle.

3. **Biodetergents**: *Pseudomonas putida* will be engineered to efficiently produce biosurfactants such as rhamnolipids, which can be used as sustainable biodetergents.
4. **Serrawettin synthetase (SwrW)** in the labor module means producing the biosurfactant Serrawettin W1, which has additionally plant growth promoter properties thus enhancing the production of biofertilizer and biodetergents of the whole SMC.

Microbial consortia and the mapping of the complex interactions that occur among the different species within the consortia serve as the base knowledge of the Living Architecture project. Based on the knowledge obtained during the experiments of open and closed wild-type systems, more controllable and genetically tractable microbial consortia can be synthetically designed.

The Living Architecture team uses the online open platform Doulix (2017) for designing synthetic biology constructs choosing among standard biological parts and synthesize them using the assembling technology of individual choice.

Photobioreactor

A photobioreactor is a closed system using microorganisms to generate oxygen and biomass from light, and carbon dioxide through the biological process of photosynthesis (Chen, 2011). The Living Architecture photobioreactor is supplied with nutrients for the algae, light, and CO_2; and the outputs are O_2 and biomass.

A photobioreactor can therefore be incorporated to the overall system as a separate reactor, connected to the MFC and SMC, using algae as a photosynthesizing agent to produce oxygen. It is sized to provide a sufficient amount of O_2 to the MFC for continuous operation.

■ ARCHITECTURE

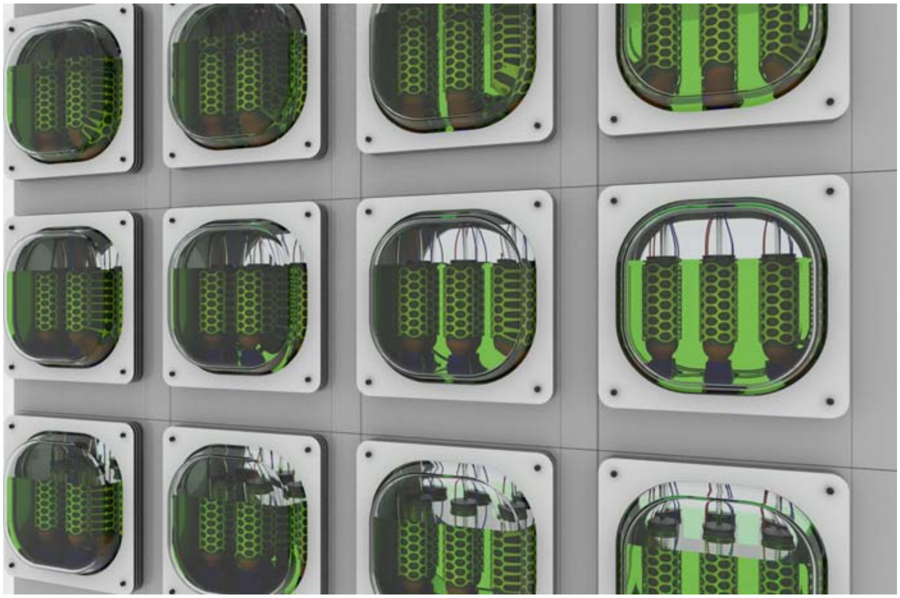
The Living Architecture building element is a set of modular bioreactor units (MFC, SMC, photobioreactor) combined into one hybrid system. It is planned for immediate use and integration into modern spaces with traditional utilities. This hybrid system is in effect, a complex managed microcosm (or microecology) wherein a defined set of factors (e.g., illuminance, temperature, pH, etc.) are continuously regulated to create and maintain the desired environmental conditions that support the biotic (living) system outcomes.

The project tackles common concerns from an architectural scale, one based in building a solution, brick by brick, that connects with and to its user, not only visually, but also spatially.

A free-standing partition composed of modular bioreactor units was demonstrated in May 2019 (visualization example (Fig. 21.3), breadboard model (Figs. 21.4 and 21.5)). With further development of the system, beyond the scope of the current project, the Living Architecture interior partition wall can shift to the exterior envelope of the building, decreasing the system's reliance on external energy sources of light, allowing the system to become more passive using the sunlight to power the photosynthesis process activating the entire system.

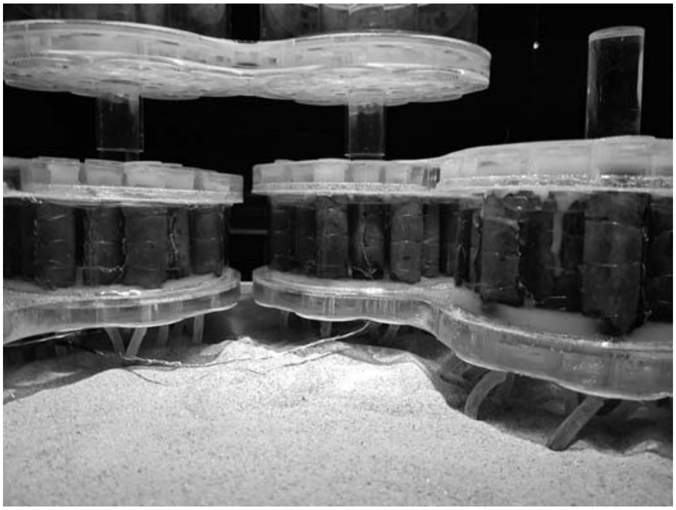
Building a bioreactor architecture will proceed incrementally, first based on MFC arrays and testing different feedstocks, then building an integrated MFC/photobioreactor system as illustrated in Fig. 21.1, which will comprise of nine MFC-based bricks, a photobioreactor, and a settlement tank. Relative dimensions and optimization of feedstock are being determined experimentally, and as different set-ups and prototypes are built, they will be fitted with the required actuators and sensors.

In the brick, small MFC units will be connected to MFC stacks to make power generation more efficient, and miniaturization and multiplication will



■ **FIGURE 21.3** First test prototype 1 visualization for a microbial fuel cell, vertically and horizontally stacked, displayed as modular building element. It can be extended with an algae bioreactor and an SMC. *Credit: Living architecture consortium, visualization: LIQUIFER Systems Group, 2017.*

■ **FIGURE 21.4** First test prototype 1 for a microbial fuel cell, vertically and horizontally stackable modular building element. *Credit: Living architecture consortium, photo: LIQUIFER Systems Group, 2017.*



■ **FIGURE 21.5** First test prototype 2 for a microbial fuel cell, indirect stackable modular building element. *Credit: Living Architecture Consortium, photo: Simone Ferracina, University of Newcastle (2017).*

be used as scale-up method. Recent prototype design approaches foresee the immersion of several small MFC anode chambers in a single larger cathode chamber. The MFC cathode chamber represents the multifunctional brick component, serving simultaneously as cathode, photobioreactor, and SMC farm module.

Different SMCs are developed within the project, each programmed to perform a specific task. They are interchangeable and interface with other components of the partition wall for reciprocal benefit.

The Living Architecture modular unit is an array of individual reactors acting in parallel. Each has inputs and outputs, which require a high level of process and control modeling in order to maintain healthy and functional ecologies throughout the system. The reactor outputs will include polished water (the surplus nutrients are cycled back through the system), fertilizer (containing nitrogen, phosphate/polyphosphate, organic matter), recoverable biomass for extractable organic products, for example, next-generation biodegradable detergents, oxygen, and electrical output.

■ SCENARIOS

For development beyond the scope of the actual project, which demonstrated only a single prototype of a bioreactor array, architectural and speculative scenarios were developed to transfer the Living Architecture modular technology from building, to the urban context, expanding its use in larger operational fields, assuming real users and real local environmental parameters.

Three different examples are discussed for use of Living Architecture in the context of: (1) a single housing unit; (2) a building as an autonomous habitat (exemplified by SHEE for use in remote locations on earth and as analogue facility for space habitation); (3) large-scale urban infrastructures with potential to replace traditional WWTFs.

Tables 21.1—21.3 set the main parameters of the three scenarios next to each other for comparison. The scenario descriptions are structured into external and internal factors, and text highlighted in "blue" identifies commonalities between the three scenarios. External factors describe the location context for each scenario type, being either urban, rural, or remote; and are further defined by contextual climate and society. Internal factors discuss aspects of modularity and personalization, and aspects of maintenance which is of high importance in systems involving living organisms. Therefore, while designing Living Architecture systems, the focus must lie in solving questions of who will care for the system (individual, collective, external service) and whether the tenants will be equipped with the tools and knowledge that are required to repair malfunctions of the system. Key parameters for a functional design are, therefore, redundancy, robustness, and high automation of the system.

Table 21.1 Scenario parameters of external and internal factors.

	(1) Housing unit ***Partition wall***	**(2) Building** ***Life-support system***	**(3) City** ***Self-sustainable WWTF***
External factors	Scattered, individual use in **urban (dense) to rural areas**	**Remote areas**	**Ubiquitous use throughout urban area** both private and public
	Integration in existing buildings and integration into new building	**Integration in SHEE**	**Integration into existing constructions, significant component of new building constructions, infrastructural application**s—connectors between buildings, for incorporation into bridges and other public infrastructure
	Temperate climate	**Extreme environments** such as earth poles areas, jungle, deserts, outer space	**Temperate climate**
	Affluent societies	Special groups in **specialized fields of work** and/or remote areas	**Affluent societies**
Internal factors	**Modular system** to define size of partition wall	**Modular system** to be integrated in modular interior of Life Support Systems of SHEE	**Modular system** designed and fabricated as 'building blocks' for constructing large-scale projects
	From one system fits all to **personalized**, specific design all levels acceptable	**Personalized**, specific design to fit into SHEE	**Meets general requirements** for processing all factions of human wastewater
	Individual and collective commitment possible	**Individual commitment** for users to keep system functioning	**Communal commitment required**
	Robust and highly automated, external service to repair	**Robust and highly automated**, high importance of maintaining all components	**Robust and highly automated**, municipal service to repair and maintain
	Aim at redundancy and maintenance free	**Aim at redundancy and maintenance free**	**Aim at redundancy and maintenance free**

Table 21.2 Economic, social, and ecological goals.

	(1) Housing unit *Partition wall*	(2) Building *Life-support system*	(3) City *Self-sustainable WWTF*
Economic goals/values	**Improve individual and/ or communal economic situation**—Value medium	In remote areas and extreme environments closed-loop systems are **essential and independent of economic goals or values—value high**	**Improve communal economic situation**—Value high
Social goals/values	**Improve social situation of individual user—Value low** **Improve intercommunal social situation—value medium** Helps to **foster awareness of dwindling resources—Value high**	**Does not play a major role due to remoteness**—Value low	**Improve communal social situation—value high** Helps to **foster awareness of dwindling resources—Value high**
Ecological goals/values	**Reduce depletion of local natural resources** **Fosters regional, national, global environmental protection—Value high**	**Reduce depletion of local natural resources** **Fosters regional, national, global environmental protection—Value high**	**Reduce depletion of local natural resources** **Fosters regional, national, global environmental protection—Value high**

Living Architecture is a highly adaptive, programmable, and flexible "building element," with the critical function to receive waste products in order to produce utilizable resources. It provides both the "hardware" and "software" for a functioning system. The hardware is comprised of the containment units of the MFC, SMC, photobioreactor, their physicality, materiality, and interfaces. The software is defined by the synthetic biological parts that are included into the system, constructed to perform specific tasks.

With these parameters defining the hardware and software components of the system, Living Architecture is flexible to be integrated into existing systems (Scenario (1)), can be configured to act as human life-support system (Scenario (2)), and can be fortified and multiplied for use in large-scale infrastructural projects (Scenario (3)).

Table 21.3 Utility and bequest values.

	(1) Housing unit *Partition wall*	(2) Building *Life-support system*	(3) City *Self-sustainable WWTF*
Utility-based values	**Direct use values: Direct use/consumption of goods and services—value high**	**Direct use values: Direct use/consumption of goods and services—value high**	**Direct (and indirect) use values: Direct use/ consumption of goods and services—value high**
Willingness to invest into indirect use values—usually nonconsumptive, indirect benefits	**Bequest values: Satisfaction in preserving natural environments** for future generations—**value potentially high**	**Bequest values:** Relevant in remote areas because external environment **needs to be protected—value potentially high**	**Bequest values:** In long-run, all **waste produced by human metabolic systems** (and other wastewater) are transformed through metabolic activities of synthetic biology parts **into valuable resources—value potentially high**
	Aesthetic values: algae bioreactor offers **attractive and intriguing** green light—**value potentially high**	**Aesthetic values:** algae bioreactor offers **attractive and intriguing** green light—**value potentially high**	**Aesthetic values:** algae bioreactor offers **attractive and intriguing** green light—**value potentially high** can provide secondary services at the urban scale including visual continuity of the city-scape and **orientation markers—value medium**

Scenario (1): Housing unit/Partition wall.

Now. Within scope of project; proof-of-concept May 2019.

Scenario (2): Building/Life-support system.

Near Future. Lots of developments are being made in the realm (/field) of closed-loop systems. In this scenario, we are using **SHEE (Self-deployable Habitat for Extreme Environments)** (see Fig. 21.6), a project built through the Seventh European Framework Programme between 2013 and 2015. SHEE can be used as an extraterrestrial mission/operation base and in extreme terrestrial environments, for example, in arctic or jungle regions where high-tech units are needed. SHEE is a 28 m^2 habitat, fitted with all necessary facilities and life-support systems for two persons (Imhof, 2015). The users living in SHEE with a Living Architecture system must have a basic understanding of its functions and be able to tend it.

■ **FIGURE 21.6** SHEE in the Antarctic, visualization: Ondrej Doule, SPIN, 2015.

Scenario (3): Self-sustainable WWTF.

Long-term aims. In the future, truly sustainable cities must and will actively and sustainably deal with metabolic human waste. Living Architecture, scaled to an urban scale, built, applied, incorporated, paving everything—living bricks, scrubbing valuable waste to produce water, electricity, and valuable nutrients and biomass, will ultimately replace centralized waste treatment facilities detrimental to our environment through its large energy demands and heavy use of chemicals.

Facing climatic challenges, and an ever-growing population, most nations and earth citizens have become aware of the critical environment we now inhabit. How can we "value" renewable energy systems such as the one proposed? In the scenario development three strains of values are considered: economic, social, and environmental.

Economic goals or values (see Table 21.3) are difficult to estimate based on the prototype still under development. One can speculate that the Living Architecture prototype will provide individual-user empowerment through the production of off-grid resources such as electricity, clean water, and waste treatment. On a communal level, one could envisage that many Living Architecture systems could stabilize local economies, especially in case of risky local support chains which is less significant in Europe than in other parts of the world. For implementation in remote locations with little or no infrastructure, closed-loop systems solutions are more economic in the long term. Systems which require bringing power and resources to a remote place entail effort and costs. Therefore, economic value is implicit in a more sustainable self-sufficient system. In the urban context, monetary resources spent to build and maintain conventional WWTFs, including their networked infrastructures for channeling waste, centralized facilities, energy needs, personnel costs, and all other related costs, can be diverted instead to the fabrication and maintenance of Living Architecture.

Social values of individual autonomy, networks, safety, health, and status could be improved by using the Living Architecture system. The same applies to the communal level where such a bioreactor array could stabilize local societies and improve communal autonomy and networks. Ecologic values provide reasons for using and for developing these bioreactors: they promote sustainable energy generation, water management, and waste treatment; reduce local natural resources depletion; and foster regional, national, and global environmental protection. Regarding the extreme environment scenario of SHEE, ecologic values are similarly present but much more explicit when living in an environment which is scarce of resources.

The last group of scenario parameters (see Table 21.3) regarding values refers to utility-based values and to indirect benefits such as bequest and aesthetic values. For all scenarios, there is a direct use of the bioreactors which deliver a specific set of services. With all systems, products, and ideas supporting sustainability and resilience of our living environment, we can draw bequest values, satisfaction from preserving a natural environment (for future generations). To imagine the Living Architecture bioreactors as an interior partition wall, as a volume filled with soft, greenish glowing light, a certain aesthetic attractiveness can be drawn. Especially, in a remote and extreme environment where stimuli offered by an exterior landscape are rare, greenish light and water movement inside a confined space can be beneficial to the well-being of the crew, or in large-scale urban applications, can provide continuous and fluid infrastructural works that are not only purposeful, but also intriguing in a visual way.

■ LIVING ARCHITECTURE ENVISIONED TODAY, REALITY TOMORROW

Living Architecture was developed and demonstrated at a small scale, capable of being integrated into existing structures (1). Yet, Scenarios (2) and (3) offer products and services beyond our and the industry's current means. The goal of the architectural scenarios is to further propel the imagination through artistic speculative means. As competencies in these fields increase, modular mass deployment in terrestrial cities, discussed in Scenario (3), could be envisioned, as autonomous habitats for extreme environments in off-grid living as well, discussed in Scenario (2).

Reaching these goals would have a gigantic impact in both developed and emerging nations. The valuable resources that are produced come from the renewable energy source of human consumption and metabolism, placing natural human processes into a partially ‘closed-loop’ system for producing electricity and biomass, for recovering valuable nutrients, for increasing the oxygen level in the atmosphere, and for providing clean water for doing laundry, dishwashing, or flushing toilets.

Living Architecture today creates mini-ecosystems for incorporation into singular architectural entities. Tomorrow, the Living Architecture bioreactor system prototype, matured by foreseeable dramatic advancements in science, technology, synthetic biology, and society, will be transformable into forms and applications that are shaped by the contexts and the people they serve, whose programming of them will be limited only by their ability to imagine their potential.

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URBAN AND REGIONAL AGRICULTURE
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Professor Droege directs the Liechtenstein Institute for Strategic Development, and is President of EUROSOLAR and the General Chairman of the World Council for Renewable Energy. A graduate of the Technical University of Munich and the Massachusetts Institute of Technology he has taught and researched at MIT, held an Endowed Chair in Urban Engineering at Tokyo University's Research Center for Advanced Science and Technology, was the Lend Lease Chair of Urban Design at Sydney University, and both developed and held the Chair for Sustainable Spatial Development at the University of Liechtenstein. He also serves as Conjoint Professor at the School of Architecture and Built Environment, University of Newcastle, Australia. He has published extensively on urban design and renewal, and regional regeneration, energy, and sustainability strategies.

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