LIVING INHABITATION SYSTEMS FOR BUILDINGS ON AND OFF THE PLANET

Molly Hogle*, molly.hogle@liquifer.com
Barbara Imhof*, Barbara.imhof@liquifer.com
Waltraut Hoheneder*, waltraut.hoheneder@liquifer.com

*LIQUIFER Systems Group, Obere Donaustraße 97-99/1/62, 1020 Vienna, Austria

ABSTRACT

For centuries, humankind aimed in creating habitats that possessed a kind of dominion over local climatic conditions. Over time, large-scale infrastructures were conceived and constructed to deliver a constant supply of resources; electricity, gas and water to buildings, and take away copious amounts of human- and building-generated waste. The effects these human behaviours have on the global-scale, have led scientists to name the current geological period, as the 'Anthropocene' era.

As many professions look to deal with the challenges presented by rapidly changing ecosystems across the globe, and the dwindling amount of resources, a growing number of architects actively seek new ways of building, that will support a sustainable future in an Ecocene era.

Many architectural designers are breaking the mold and teaming with experts from diverse expertise. Architecture increasingly looks to counteract these destructive human forces, by bringing, back into the living domain of humans, biology and biological systems. By re-introducing 'life' into the built environment, it can be used to replace existing (hard) infrastructures, performing, in a malleable way, through naturally occurring metabolic activities, essential building services, including waste removal, the provision of electricity, biofuel, oxygen and clean water.

This paper discusses four case studies that address the problem of limited resources, encountered both on earth and the extended operational architectural field of outer space. A framework for discussion is being established looking at materials and systems. The replacement of industrially processed materials, by living organisms to perform similar functions is explained, as are the systems that govern these living material processes.

Projects, Living Architecture (LIAR), a bioreactor building brick (1); Water Walls, modular structures for life-support (2), MEDUSA, integrated life-support and habitat for lunar applications (3), and GrAB, biolab experiments for growing a building (4), serve as case studies for the review of *materials* and *systems* in contemporary architecture.

1 INTRODUCTION

The current geological age, named the Anthropocene, considers our current ecological conditions worldwide to be the result of accumulated human activity and behavior. Climatic changes have altered local environmental conditions across the planet. We can observe a rise in carbon dioxide levels through intensive industrialization and water resources become increasingly scarce, with phosphate resides in grey water difficult to treat. The challenges we face here on earth, are simultaneously reflected in our efforts to conquer the next horizon of inhabiting space and other planetary bodies.

As architects, we seek new ways of building, and of designing, that challenge the existing building paradigm, stemming from our earliest ancestors. Current building practices and the designs and architects that propagate them, produce 'life'-less, and static designs for a day and age that has since past. As architects, we aim to instigate change, as if our current era was not the Anthropocene era, but that of the Ecocene. (Built to Grow, 2016, p. 11) An era, where all the actors, participants, citizens of the planet, actively make, and bring into effect, bring back into effect, a dominance of ecology, of nature into our lives.

The architectural concepts highlighted in this paper aim in creating architectures and environmental systems that will support a sustainable future in an Ecocene era.

Four case studies highlight, the growing desire in the field of architecture and building, to incorporate more diversified 'biology' into our building systems. Biological processes and metabolisms are harnessed to perform 'tasks' which would otherwise be performed by energy-demanding, active and mechanical systems.

- Living Architecture (LIAR) is a building component that functions as a bioreactor. It uses building waste as a fuel source and in return produces clean water and electricity.
- Water Walls is an architectural framework for providing life-support in closed-system habitats. Solution-filled, polyethylene cells are activated to perform tasks such as the processing of grey and black water, and removal of CO_2 from the habitat air.
- MEDUSA is an architectural concept, that integrates life-support into the outer skin of an autonomous habitat for living on the lunar or Martian surface.
- GrAB pursues the architectural vision of growing a building, by conducting a series of biolab experiments.

2 FRAMEWORK FOR THE CASE STUDY INVESTIGATION

One possible way for understanding this complex and growing fascination and effort in combining architecture and biology, is through common themes that penetrate each of these projects.

2.1 Material considerations

Material considerations are the first theme, and can be understood as the replacement of traditional infrastructures by actual biological mass and their respective metabolisms. Biological materials are products of their immediate environments, receiving all essential resources at the location of their growth; whereas, material systems in architecture largely consist of products that have undergone levels of industrial processing, requiring an abundance of time and energy. (Built to Grow, 2016, p. 36f)

In addition, a shift in the material paradigm is evident in energy source inputs, whereas traditional buildings are still heavily reliant on fossil fuels for generating heat and electricity, and the Ecocene approach looks to recycle waste produced by a building and its inhabitants for fuel.

2.2 Systems Approach

The second theme looks at the growing tendencies in architecture to use a 'systems approach' to designing building processes, which aim to 'enliven' the systems, through scientific principles, and sometimes biological life, to make the systems and therefore the building, an integral part of an 'ecosystem.' The systems approach, becomes evident in these examples, in that each of the projects aim to create an interactive architecture, one that is responding to its local environment, both by taking resources from the environment and giving back resources as well.

Case studies address the problem of limited resources, and offer strategies on how to improve a building's input/output ratio, through coming closer to a closed-loop system, where power, water, air, and food can be produced from building and inhabitant waste. The case studies aim to implement material and systems approaches to architectural design strategies, to assist in a revolutionary transformation of building in relation to its environment.

3 ARCHITECTURAL SOLUTIONS FOR EVERYDAY PROBLEMS USING BIOLOGY

3.1 Case Study 1 - LIVING ARCHITECTURE (LIAR)

The ongoing project, Living Architecture (LIAR) designs and develops a building component prototype, using living systems to metabolize building waste in order to produce electricity, O_2, and water.

LIAR is an EU-funded, FET-OPEN project, with partners from Newcastle University, University of the West England in Bristol, Spanish National Research Council (CSIC), LIQUIFER Systems Group, Explora Biotech, University of Trento, specialized in the fields of Architecture, Planning, Programmable Materials, Robotics, Computing, Engineering, Biology, Biotechnology, Microbiology and Synthetic Biology.

The Living Architecture model aims to create a living architectural component, able to respond to its local environment; it has built-in flexibility and adaptability, as all living organisms do.

The LIAR solution is to build a 'living architecture' that integrates biological processes into the built environment and to 'program' them to perform 'ecological' tasks. Applications for the prototype component, for use within the urban context, are for installation in domestic, public (schools, hospitals) and office environments. An architectural model is created, acting in complete contrast to that of conventional models for buildings, which are inert, complex and difficult to adapt, esp. in regard to services, technology, ventilation.

3.1.1 Description of the Concept

LIAR is a 3-in-1 bioreactor for producing power, oxygen, and for purifying water. It uses three fundamental principles in combination;

- photobioreactors (Chen et al., 2011)
- microbial fuel cells (MFC) (Logan et al., 2006)
- synthetic microbial consortia (SMC)

An architectural 'brick' is designed and prototyped to house the systems and the interactions between them. An enormous amount of cooperation between scientists and architects is required to coordinate the design specifications, thus guiding the brick's formal configuration and end design. On-going communication via workshops in respective laboratory environments, and presentations are used to convey the key features of the biological systems that are used, that will directly impact the design of the living brick.

The architectural process is therefore iterative, based on continuous feedback between consortium partners.

3.1.2 Specific aim

Hybrid Photobioreactor-Microbial Fuel Cell

The goal is to create a selectively-programmable bioreactor capable of extracting valuable resources from building waste. During operation it will polish wastewater, and produce useable biomass, fertilizer and electrical power. The self-learning, self-governing system, using the 'intelligence' of living systems, will adapt to local conditions.

The most important principal underlying the whole project is the Microbial Fuel Cell (MFC).

> The **Microbial Fuel Cell** is an electrochemical device that converts the chemical energy of organic feedstock into electricity, through the metabolic processes of microorganisms, acting as biocatalysts. (Logan et al., 2006)
>
> Microbial Fuel Cells 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 protons. The electrons travel via an external circuit and the protons flow through the PEM, to recombine

at the cathode. As the protons and electrons recombine, they react with oxygen (used as an oxidizing agent), to produce water.

The MFC produces electricity using microorganisms to breakdown waste and produces clean water when provided a source of oxygen.

At this point, there are two points of activity where additional measures can be taken to improve the system.

The first is to have control over the metabolic processes that occur in the anode, knowing exactly what the feedstock is and what bacteria or microbial consortium (*two or more bacterial communities living symbiotically*) can best process the feedstock (building waste).

In the project LIAR, biologists and microbiologists map these processes to help define the best '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. In the cathode, communities are designed, largely, to support the growth of algae. In this way, the cathode can simultaneously function as a 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 et al., 2011)

A photobioreactor is therefore incorporated into the cathode of the MFC, using algae as a photosynthesizing agent to producing oxygen.

To have better control of these natural processes, the LIAR team develops synthetic biology parts, which can fill in and replace naturally occurring bacterium, for better performance.

Synthetic Biology is the design and construction of new biological parts, devices, and systems, and the re-design of existing, natural biological systems for useful purposes.

The LIAR brick incorporates all of these systems into a single, Hybrid Photobioreactor-Microbial Fuel Cell.

Architects are currently developing the optimal shape-form for a LIAR brick, respecting spatial adjacencies and interfaces of the different scientific principles and biological consortia. The primary vision of the project is a free-standing partition composed of modular bioreactor units (the LIAR brick), for immediate use and integration into modern spaces with traditional utilities.

Architectural scenarios are developed within the project to transfer the LIAR brick technology from building, to the urban context. Therefore, suggesting a much wider impact on local ecologies and urban sustainability.

Design concepts are developed in an iterative process - continuously adjusting scenarios for use at both the building and city scale, as well as the actual brick design. The materiality of system components is forefront in importance. The material systems of the Living Architecture brick are both biological, as well as traditionally, architectural.

The biological material, shall only be shortly mentioned, in that through its use in the system, it shall replace the function of, for instance, at the municipal scale, a waste treatment facility. Biological life and its natural processes, brought directly into a building, could potentially *replace* municipal infrastructure, services and the required labor and energy needs for processing the waste.

The materiality of the architectural brick however, is defined by the creative forces of humankind. In close collaboration between architect designer and microbial fuel cell researchers, specifications are being identified for the exact material content of the LIAR brick, to maximize efficiency and durability of the system.

Ceramics are being explored, for their Electrical conductivity, Luminosity and Porosity / texture known conductive property and strength in compression. A vast number of ceramic models have been fabricated and tested to measure the effect different surface characteristics, shapes, surface areas, and clay characteristic has on the functioning of the overall brick. The LIAR brick is in current development; the project will end in March 2019.

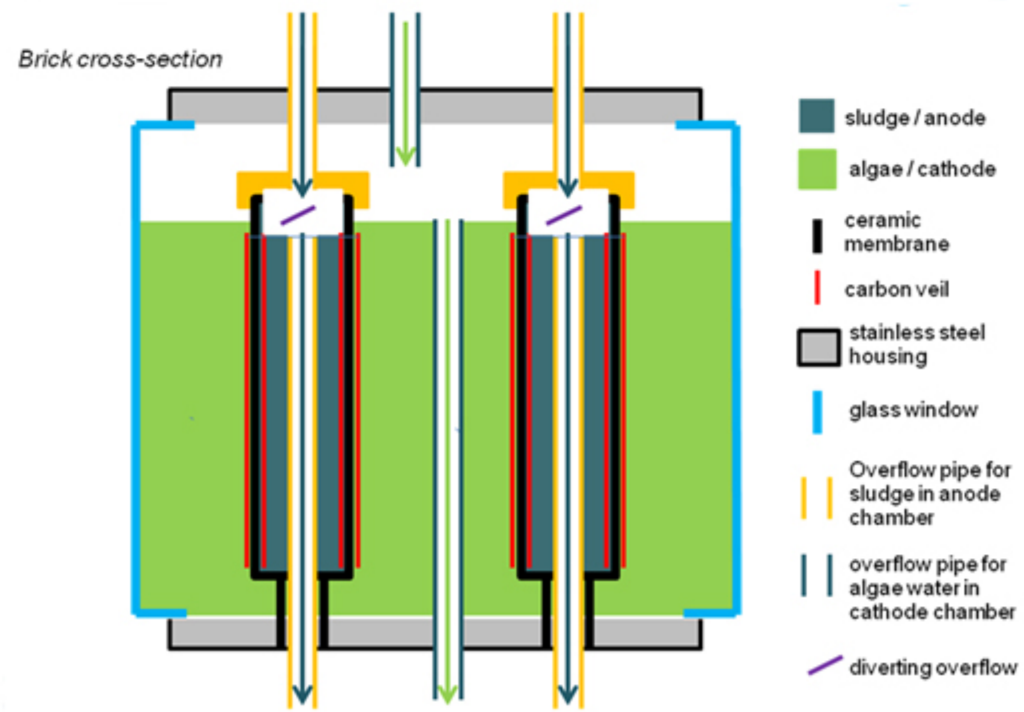

Fig.1a concept design for the Living Architecture interlocking building element step 1 (including the Microbial Fuel Cell, excluding the Synthetic Biology Consortia), credit: LIQUIFER Systems Group, 2017

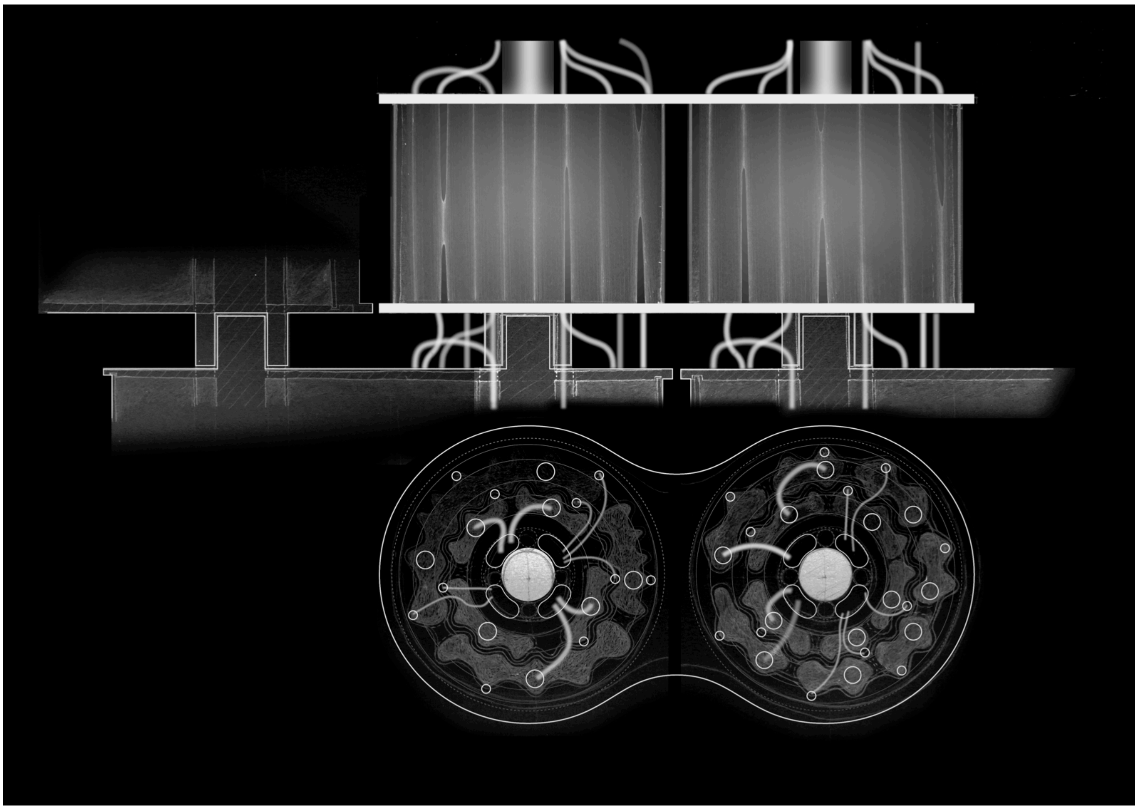

Fig.1b concept design for the Living Architecture building element step 1 (including the #microbial Fuel Cell, excluding the Synthetic Biology Consortia), credit: Simone Ferracina, 2017

3.2 Case Study 2 - WATER WALLS

Living Architecture can be understood as an architectural attempt to create *micro-sized ecologies* in order to perform building services. Water Walls represent an architectural solution for chemically engineering life support systems for use in space. Architectural 'cells' are designed to perform specific functions within a closed-loop system. Designed by Michael Flynn, as Principal Investigator and chief engineer, Marc M. Cohen, founder of Astrotecture, and Architect Renée L. Matossian, Water Walls provide astronauts an endless supply of air and water, critical to survival.

Architects work with experts in life support and astrobiology in designing a structural matrix to accommodate solution-filled, 'cells,' each capable of chemically processing waste to produce valuable, life-sustaining resources. The architecture provides an alternative to purely mechanical life support systems that repetitively fail on long-term missions to space, and acts as the consummate integrative discipline, that coordinates civil, electrical, mechanical and structural parameters in creating smart design.

Cells are conceived and developed to perform the following functions benefitting a crew and habitat in outer space:

- process grey water (urine and wash water), transforming it into potable water
- process black water (solid waste), transforming it into fertilizer and CaCO3 (gypsum - a usable building material)
- remove CO_2 from the air and replenish O_2 levels
- control temperature and humidity
- grow food
- provide radiation protection

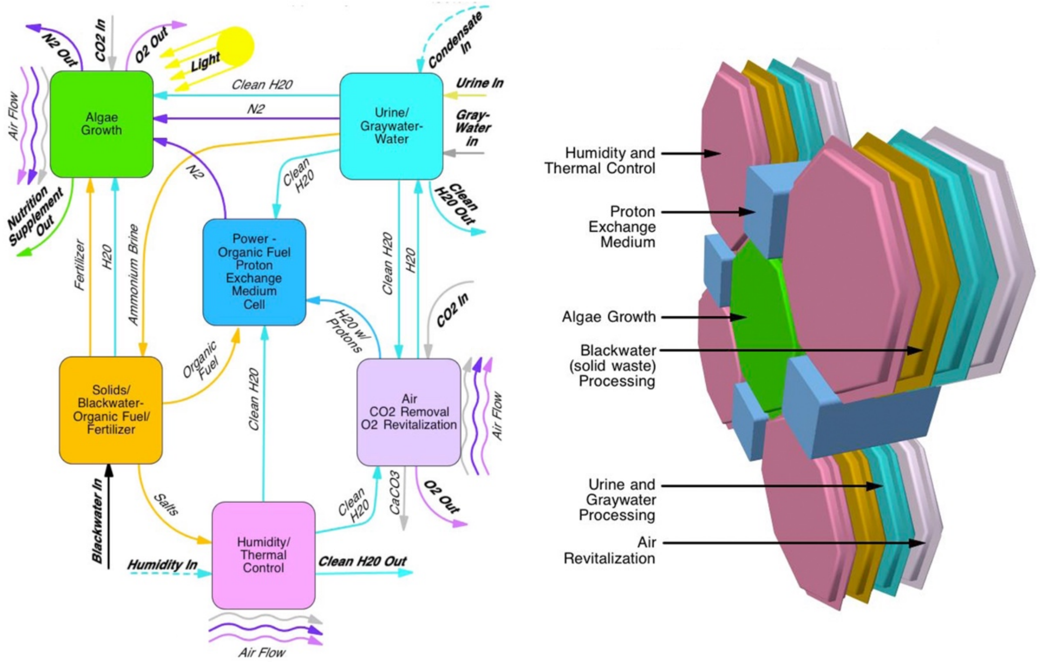

Fig. 2 System concept drawing of the Water Walls concept, credit: Marc Cohen, 2012

3.2.1 Description of the Concept

Water Walls, develops an *architecture* which enables a series of events, where cells are staged to perform processes that are triggered by the functions of the cells proceeding it. Modular cell units, made of polyethylene, are aligned in four layers (dimension 10x50x50cm) and are connected to create a functional flow matrix. Before the cells can be used, they are primed with water and starter ion solutions in low earth orbit.

3.2.2 Specific aim

Each modular unit (cell) is connected to one or more other module units by a semi-permeable, '*forward osmosis'* (FO) membrane. Working with the natural process of 'forward osmosis,' Water Walls uses the 'osmotic potential' between two fluids of differing solute/solvent concentrations to move the solvent from a less concentrated solution to the cell space of a more concentrated solution. The FO membrane separating the different cells, allows solvent to pass through, but not solute.

As effluent is fed from one bag to another, chemical processes are triggered, maintained, or turned off. Each bag is 'activated' through exposure to essential resources, present in the immediate environment that they are expected to maintain (e.g. space habitat, including, surface air flow, and light) and from the solvent received from other cells (offering O_2, N_2, water and algae nutritional supplement).

When the concentration of solvent content equalizes between the cells, the next event in the series will be triggered, by opening the valve between the next progressive function in the series. Water Walls is mostly a passive system; the only active elements in the design are the valves and small pumps. The valves control the interfacing between cells, and the small pumps are used to transporting habitat waste to the location of treatment (taking place inside the different cells, e.g. waste water).

Water Walls provides massive redundancy and the potential for replacement of the different cells. The system is regenerative and functions as a closed-loop system.

3.3 Case Study 3 - MEDUSA

MEDUSA—from subsea to Moon and Mars, is an architectural proposal for an autonomous lunar habitat based on the mission timeline outlined by International Space Exploration Coordination Group (ISECG) in 2012.

MEDUSA was developed for the International Competition in Architecture of the Jacques Rougerie Foundation in 2012. The aim of MEDUSA was to develop an autonomous habitat, with some features of life support, in preparation of human space exploration on the lunar and Martian surface.

3.3.1 Description of the Concept

The project was developed as a subsea lunar-analogue, with an end vision of applying its basic concepts to an actual habitat on the moon and Mars.

The MEDUSA design aimed for a solution that could be used in both (subsea and space) applications, ending up with a double-layered membrane design, that could be fixed to a central structural framework.

3.3.2 Specific aim

On the moon, the double-layered membrane could be used as an inflatable structure; easily transported to space due to its low volume to weight ratio. The double-layered membrane is conceived to inflate around any type of landing vehicle, which otherwise becomes obsolete upon landing. The landing vehicle can be utilized as the central core of the habitat, and a sub-structure made from components stored inside the lander during transport, can be deployed to provide space for working, living and life-support elements, as well as any additional structural support for the inflated skin of the habitat.

In its subsea application, the double-layered membrane, is re-programmed to support bioreactor algae walls, used to provide nutrition supplement, oxygen, purified water and capable of processing waste; therefore, providing some elements of life support. Rather than a payload on a lander, the subsea model is centered on a classic diving bell.

The double-layered membrane, is sectioned into compartments that can perform different functions. In the subsea application, the different compartments are filled with water to offer structural integrity to the submerged habitat, acting as 'buoys,' able to counteract the downward pressure of the water above. The compartments are further programmed to provide biological services. Using algae, carbon dioxide can be transformed into oxygen, through photosynthesis, and nutrient supplementation is provided. The water-filled compartments will also protect astronauts against ionizing radiation, as water is a good shielding element for solar energetic particles. The varying shades of green, expressed by the algae compartments also support the psychological well-being of the inhabitants.

Medusa was designed for undergoing testing and validation in an underwater environment. Design parameters therefore reflect both the ultimate goal (extra-terrestrial planetary surface) and the analogue underwater environment, relevant for its reduced gravity.

Fig. 3 Overall architectural concept for MEDUSA, visualization: LIQUIFER Systems Group

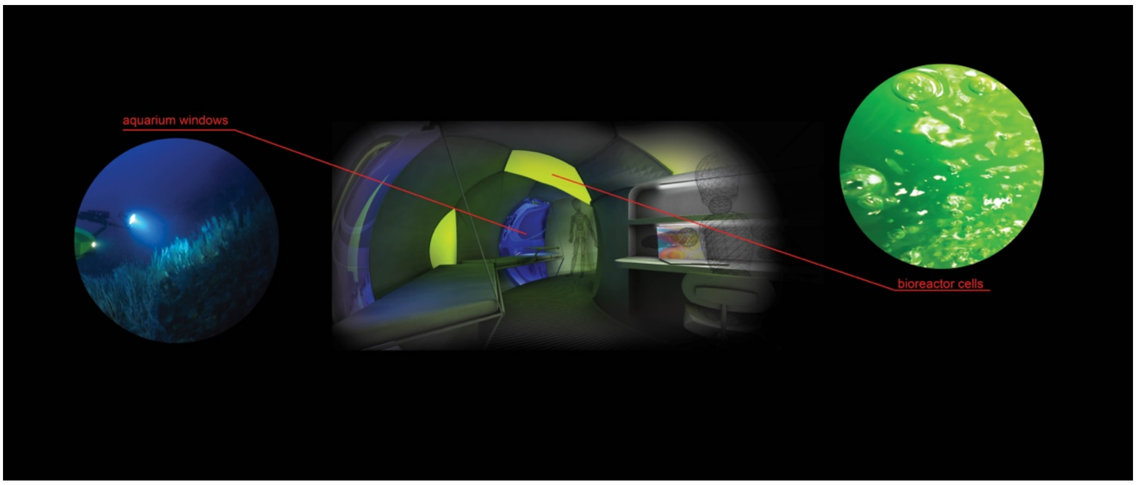

Fig. 4 Concept drawing of the photobioreactor cell of the MEDUSA envelope, credit: LIQUIFER Systems Group

3.4 Case Study 4 - Growing As Building (GrAB)

GrAB, Growing As Building (2013- 16), was an arts-based research project, funded by FWF.

It comprised an interdisciplinary team of biologists, architects, ecologists, zoologists, botanists, micro-biologists, and designers from the institutions: University of Applied Arts, Institute of Architecture, Vienna, Austria, Ethiopian Institute of Architecture, Building Construction and City Development, Addis Ababa University, University of Oxford, Department of Zoology, UK , University of Freiburg, Botanic Garden, Plant Biomechanics Group, Germany, and Delft University of Technology, Participatory Systems, Netherlands.

The main focus of GrAB was to explore the multifold intersections of architecture and biology, based on the research group's architectural vision of *growing a building*. The design project utilized D-I-Y laboratory experimentations to explore these intersections.

3.4.1 Description of the Concept

One fruitful trajectory of GrAB biolab experimentations, linked biological processes with the technique of 3D-printing.

A design methodology was developed, utilizing the metabolic activity of living organisms to fuel additive manufacturing processes; which could potentially be used in the future to offset the environmental challenges of building, which require a great deal of fuel resources.

The design uses an algae photobioreactor, using CO_2 and sunlight as input sources and providing as by-products (output), oxygen and biomass. Microbial processing of the biomass produces acetic acid and ethanol, essential to the functioning of the 3D-printer. Calcium carbonate in combination with acetic acid and ethanol is used by the printer as the main building material. In the process of mixing this printer material, CO_2 is released as a by-product. The CO_2 can be fed to the algae community within the photobioreactor, partly closing the loop. The significance of this system is the integration of material input and output. The concept looks to radicalize building technologies to use waste as a form of fuel.

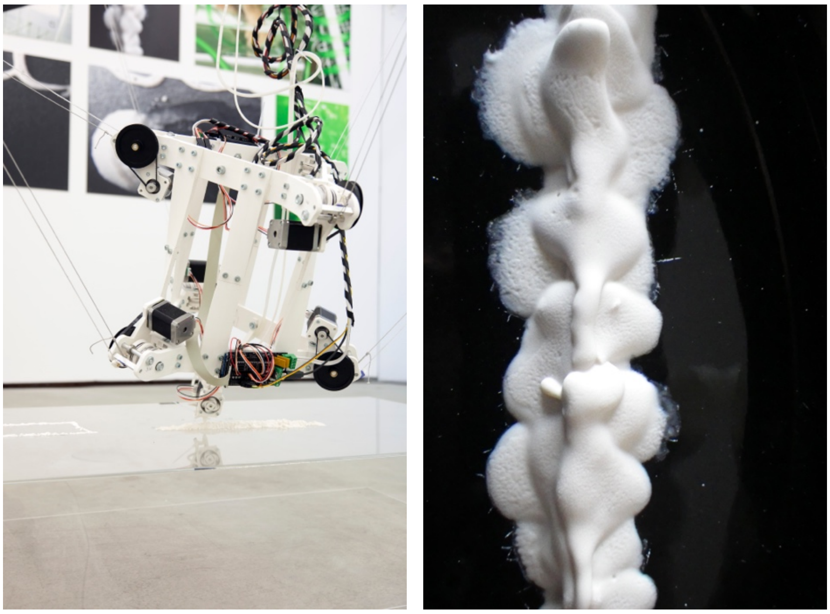

Fig. 5 Left: Mobile 3D printer, credit: Bruno Stubenrauch, right: printer material comprising $CaCO_2$, Acedic Acid and Ethanol, credit: GrAB team

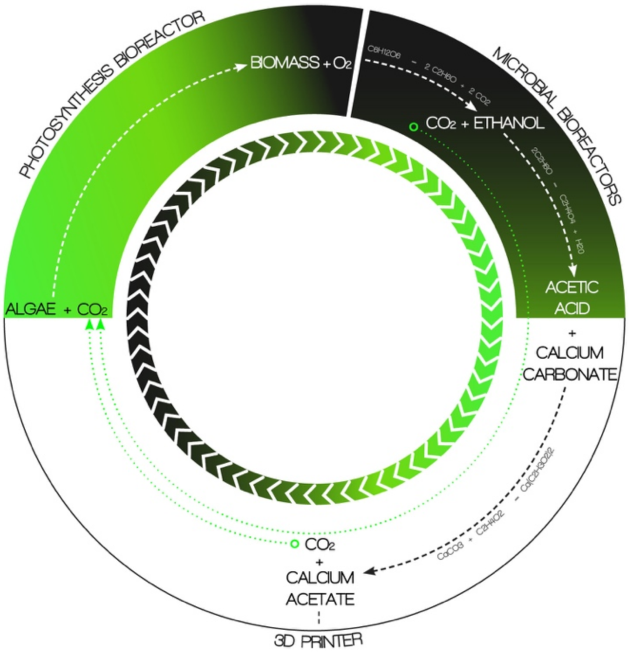

Fig. 5 Systems diagramme for the algae photobioreactor including the printer material in the loop

4 CONCLUSION

A central problem facing architecture, building and future design, is the amount of resources that buildings use. Buildings of industrialized nations today are almost still exclusively dependent on fossil fuels to meet its heating/cooling and electricity needs; and they indiscriminately utilize clean drinking water for all serviceable functions, including the flushing of toilets, cleaning, cooking and bathing.

The outputs of buildings are less attractive, releasing carbon dioxide, as fuel is burned to heat our homes, warm our bath water, cook our meals; and the waste water that is produced, is almost exclusively discarded through tubes and transported to a processing treatment plant, managed locally using local standards.

The solution is to design and build, resilient buildings and systems (self-sufficient buildings, regenerating systems, self-repairing systems) – that have economic use of material resources, energy, and labor demands.

This paper aimed to identify the different means of addressing these issues, by paying particular attention to the material and operational 'systems' that govern smart-forward thinking designs of today. It attempts to provide a framework to help designers in the field of architecture look at design defined by material inputs and outputs and their governing systems (see Table 1).

Table 1: Display of Case study projects within the established framework

Case Studies	'Material' Approach	'Systems' Approach
Living Architecture	Biological metabolisms perform building services, replacing traditional infrastructures (requiring lots of material resources, incl. in-building HVAC and municipal waste treatment facilities and utilities) Ceramics are used as an architectural material to increase the effectiveness of the LIAR bioreactor.	Synthetic biology is used to maximize the effectiveness of a Hybrid Photobioreactor-Microbial Fuel Cell.
Water Walls	Carefully orchestrated, chemically-balanced 'cells' are used in a series to provide life-support to crew members in space missions. Cells are capable of processing (organic) waste to produce clean water, oxygen and food, replacing purely mechanical systems that are currently used in space and prone to malfunction.	Forward osmosis is used to 'bring into life' successive solution-filled cells. As fluid from one cell flows into to another cell, different environmental tasks are performed.

MEDUSA	A single architectural double-membrane is used to both enclose an autonomous habitat and facilitate life-support systems. Algae filled chambers replace mechanical systems to provide oxygen and nutrition supplementation.	Medusa is conceived as a building structure where the life-support bio-reactors make part of the overall system. The double-membrane is filled with a fresh water solution, providing radiation shielding and a counteractive - buoyancy against seawater.
GrAB	Additive manufacturing (building) processes are supported by material inputs produced by an algal photobioreactor. Resources generated on-site by biological metabolisms are used for building.	A semi-closed-loop system is engineered, using algae to fuel building processes.

The outcomes of the discussed projects are varied. LIAR is currently being developed and is scheduled to end in March 2019. It illustrates exciting new advancements in bioreactor technology using consortia of synthetic bacteria. LIAR, recycles building waste, generates electricity, produces clean water and biomass.

The development of Water Walls is still ongoing. First prototypes of algae cells have been developed. The team is currently looking for further resources after the first NASA funding to continue its development.

The Medusa, subsea habitat is still at the conceptual stages of development but offers provocative solutions for life support integration into a habitat's structural enclosure. The water-filled architectural shell, with intermittent modules filled with algae, provides protection from solar radiation, transformation of CO_2 to O_2, and nutrition supplementation.

The 3D-printer developed in the arts-based research project, GrAB, uses by-products produced by photosynthesized algae as building material inputs. Although the printer is only in the developmental phases, it promises a new method of 3D-printing, that uses local resources as printing material.

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