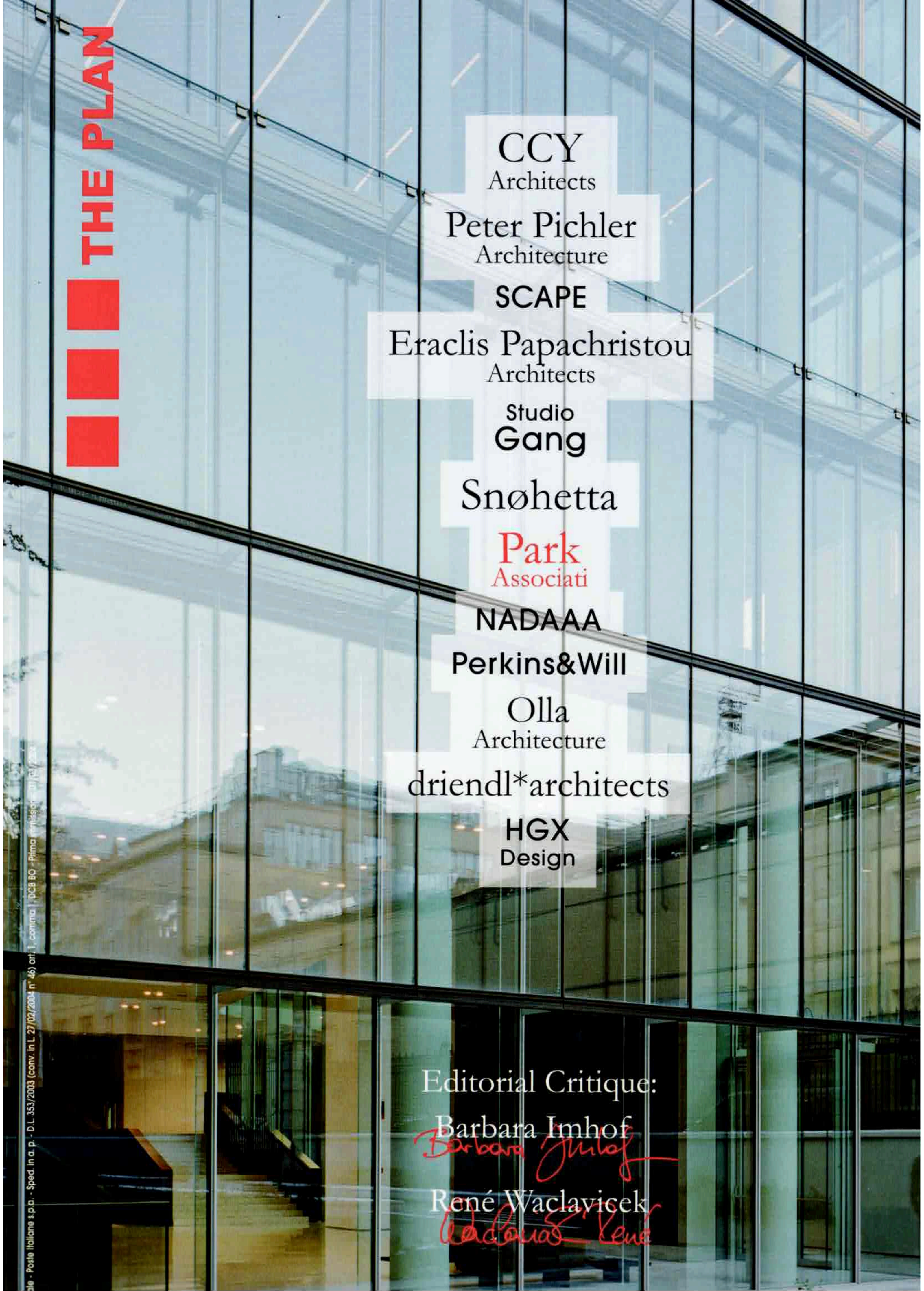

# THE PLAN

CCY Architects

Peter Pichler Architecture

SCAPE

Eraclis Papachristou Architects

Studio Gang

Snøhetta

Park Associati

NADAAA

Perkins&Will

Olla Architecture

driendl*architects

HGX Design

Editorial Critique:

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# BUILDING BEYOND EARTH: THE CHALLENGE OF SPACE ARCHITECTS


1

1. SHEE (Self-deployable Habitat for Extreme Environments), design for human life on the Moon and Mars, SHEE Consortium, 2015
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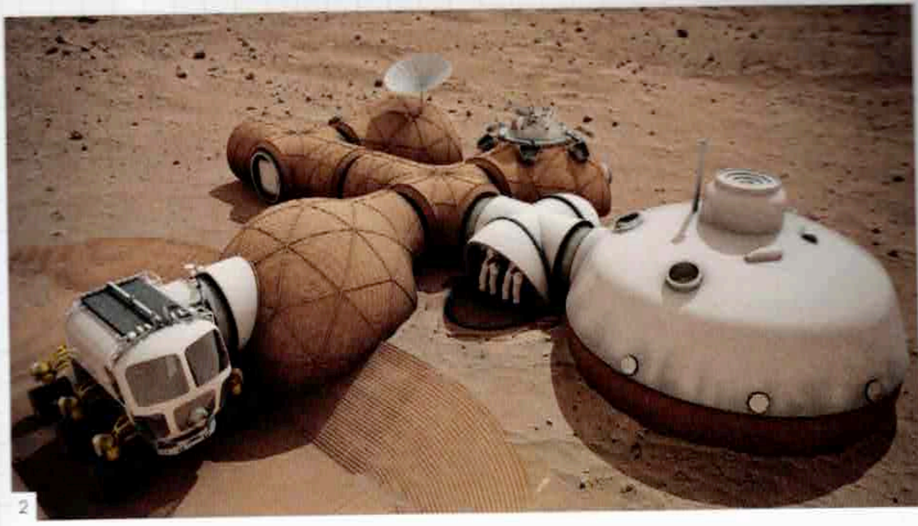
## Liquifer

A space architect and design researcher, she is co-founder and managing partner of Liquifer. She worked at NASA Johnson Space Center and is currently working at the International Habitat module of the Gateway lunar space station. In 2024, she was elected as Associate Fellow of the American Institute of Aeronautics and Astronautics. She is professor of Integrative Design – Extremes at the University of Innsbruck.

**Barbara Imhof**

He started his career working in design and construction planning for terrestrial buildings; since 2019, he is co-managing director of Liquifer. His space architecture projects focus on living in limited and transformable spaces and deal with resource-efficient systems in extreme environments. He applies his skills to interdisciplinary research, design projects and complex geometries, including parametrics.

**René Waclavicek**



**2.** Lava Hive, a modular Mars habitat 3D-printed using a novel construction technique called "lava-casting", Liquifer, 2015 **3.** Space Home Mock-Up, design and implementation for human life in zero gravity, Liquifer Space Systems with Comex and Sabelt, 2021 © ESA **4.** RegoLight, building 3D-printed infrastructure from lunar soil (regolith) using the Sun as the only source of energy, RegoLight Consortium, 2018

## Space Exploration and Life in Space

Space exploration is one of the greatest challenges for science and technology. It drives people beyond the boundaries of Earth and into the vast unknown. From the pioneering efforts of the Apollo missions to the realization of the International Space Station (ISS) and the ambitious plans for Martian settlements, our ambitions to travel into space are more present today than ever before. But the further we venture into space, the more urgent the need to create sustainably habitable habitats becomes.

A new operational field of architecture is emerging. In the future, it will become an essential component of human activities in space. Space architecture is defined as "the theory and practice of designing and constructing inhabited environments in space".[1] It is a discipline anchored in a web of scientific and engineering disciplines in the service of space exploration and settlement. Due to the stringent requirements for accommodation in extreme environments, the design of a habitat is heavily dominated by systems engineers compared to other fields of architecture.

Firstly, a functioning technical biosphere must be built, which severely restricts the freedom to design interior layouts and configurations. Therefore, the architect's role in planning a space habitat is not a leading one, but one that assists in meeting this scientific and engineering challenge. The design of habitable environments that enable life in zero gravity, on the Moon and on Mars is therefore always a multidisciplinary endeavour.

In general, space exploration represents extraordinary co-operative initiatives that unite nations on a supranational level. Examples include the ISS space program, the Gateway program of a space station to orbit the Moon and various other international space exploration programs.

## Who is the Space Architect?

When planning and designing for the space environment, it is crucial to understand its specific design requirements. A solid architectural education is the foundation. The technical requirements associated with the extreme conditions make the design of space habitats a challenging task. How are life support systems constructed, how do orbital mechanics work to get from one place to another, and why are there no beds, no chairs and many other familiar pieces of furniture in zero gravity? Space architects deal with these and similar questions when they approach the planning of a habitable space base. Space architecture is based on a foundation of knowledge from various other fields, including space systems design, physiology, psychology and sustainability strategies. Additional education through space-related courses and work in the field is mandatory to be successful in the field of space architecture.

Due to the scarcity of resources, design strategies must be applied to conserve them. These design approaches include, for example, the reuse of spatial hardware, the use of 3D printing for efficient and autonomous construction and in-situ resource utilization (ISRU). Understanding natural models, such as terrestrial biospheres, is a prerequisite for the development of closed-loop systems in which air, water and waste are immediately recycled. Due to the shortage of space, strategies such as multifunctional rooms, transforming room elements, or folding furniture are becoming essential design tools. In principle, a personal space for each crew member, a so-called crew quarter, is important to provide a private retreat. Circadian lights that mimic a day-night cycle and a greenhouse where plants contribute to the general cycle of matter and can be harvested for fresh food consumption are beneficial for the crew's well-being during long missions.

## Designing for Human Life in Zero Gravity

The microgravity environment of space requires a rethink of traditional architectural norms. Living on an orbital station means living without gravity. It is a life in constant motion and we need to stabilize our bodies to perform certain tasks. It is living and moving in a truly three-dimensional space where we can access every corner of the volume without being tied to the x and y axes of a horizontal plane. Orientation is more difficult as there is no order of above and below, and sometimes we simply refer to the "below" as where our feet are. Fixation aids that support us when carrying out experiments, eating, sleeping or watching films are important to keep the body in one position. To minimize the muscle atrophy and loss of bone density caused by weightlessness, two hours of special physical training every day are essential.

It is also important to consider noise reduction on space stations. The constant humming of life support systems can lead to sleep

4

disturbances and stress among astronauts. Therefore, measures must be taken to reduce noise so that loud fans and other mechanical devices do not interfere with astronauts' work and negatively affect their health.

**Design for Human Life on the Moon and Mars**

Building settlements on the Moon and Mars pose unprecedented challenges. These celestial bodies have no breathing atmosphere and no protective magnetosphere, which exposes the inhabitants to dangerous radiation and extreme temperature fluctuations. Space architects are working on the development of habitable structures that can protect their inhabitants from radiation. For example, designs for lunar habitats could include the use of existing materials such as regolith and natural formations such as lava tunnels for radiation protection. On Mars, proposals are also being considered for habitats that are partially or fully underground for radiation protection or covered with 3D-printed regolith.

In addition, the development of bioregenerative life support systems that regenerate water and oxygen and utilize plants for oxygen and food production is a crucial element for survival on the Moon and Mars. Such systems mimic Earth's closed ecosystems and convert waste products into essential resources.

The goal of enabling human life in space poses a challenge to conventional terrestrial construction methods that were once based on the assumption of unlimited resource availability. It is critical to develop and implement new approaches, as the basic resources essential for human survival are not easily accessible in space and the cost of transporting matter into space is exorbitant. Current strategies include practices such as reuse and recycling, in-situ resource utilization, 3D printing of hardware and the establishment of closed-loop systems.

Research into construction methods using lunar and Martian regolith as building materials is therefore extremely interesting for space architects. Sintering, a process of melting the surface of local sand particles – known as regolith – to form solid structures, shows promising results for the construction of robust structures that only require the Sun as an energy source and sand as a basic building material. The sintering of building materials and the realization of habitable structures are carried out using 3D printing machines. Construction outside the Earth requires autonomous processes independent of humans. Robust automated 3D printing technology will be crucial for the construction of human settlements beyond the Earth's atmosphere. 3D printing complex and heavy structures using local resources not only minimizes costs, but also contributes to the development of a sustainable human presence in space.

**The Role of 3D Printing in the Construction of Planetary Outposts**

The 3D printing technology has a major impact on space construction techniques. Space architects are working with materials scientists and space engineers to further develop this technology to create resource-efficient, customized structures using local materials. NASA's efforts to further develop and demonstrate the potential of 3D printing for space habitats are noteworthy. For example, their Centennial Challenges include the development of 3D printed habitats and demonstrators using robotic arms that extrude a mixture of regolith simulants and binder materials to create architectural structural elements. In recent years, three stages of these challenges have been carried out, which has now led to the realization of the 3D printed Mars Dune Alpha habitat for simulation purposes by the company ICON in Houston, Texas.

**Designing for Earth by Living in Space**

Transferring the know-how of space architecture to Earth requires a profound change in our idea of the cities of the future. Since 2010, the concept of the "City as Spaceship" has emerged from the joint work of Susmita Mohanty, Sue Fairburn, and Barbara Imhof including guest contributors. The concept challenges us to redesign urban environments by looking at them through the lens of a self-sufficient spaceship. This concept emphasizes the critical aspects of housing and resource limitations and challenges planners to consider strategies such as recycling, closed-loop systems and complete self-sufficiency in terms of energy and food production. If we consider cities as self-contained ecosystems similar to a spaceship, we prioritize efficiency in the use of space. Just as in spatial habitats, where every inch of space is carefully considered and utilized, future cities must optimize space and focus on compact designs without compromising the quality of living.

5

6

Furthermore, the concept of the City as Spaceship emphasizes the importance of resource recycling. Similar to life support systems in space stations, future cities will need closed-loop systems for waste management and resource utilization. Waste should be seen as a valuable resource, with robust recycling and waste-to-energy systems integrated into the urban infrastructure. This approach minimizes waste generation and maximizes resource efficiency, contributing to a sustainable and circular economy.

Achieving complete self-sufficiency in terms of energy and food is becoming a primary goal of future construction. Cities can make extensive use of renewable energy sources by incorporating solar energy, wind power and other sustainable energy technologies. Urban vertical farming and hydroponic systems can be integrated into urban landscapes to ensure local food production and reduce dependence on external sources. Such approaches in design increase sustainability and resilience. Under the premise of City as Spaceship, design principles for future urban agglomerations can serve as a guide to resilient, sustainable and therefore livable cities.

**Our Vision for the Future**

In our shared vision of the future, we are at the forefront of pushing the boundaries of human existence. We are interested in advancing the knowledge that will allow us as humanity to think and travel beyond the horizon of Earth. Our endeavors involve both entering uncharted territories within our solar system and advancing innovative strategies for sustainable life on Earth. Our combined efforts in architecture, engineering, science and technology development aim to improve life, satisfy our thirst for exploration and push the boundaries of knowledge. By engaging in this broad field of research, we also recognize the *continuum* of Earth and space, in which our home planet, as a spaceship travelling through space, is a part of a larger system.

*The use of "we" reflects our two decades of experience in establishing the interdisciplinary Liquifer space architecture practice. With locations in Vienna and Bremen, the office is spearheaded by Barbara Imhof, René Waclavicek, and Waltraut Hoheneder.*

7


**5.** Paver – Paving the road for large area sintering of regolith, Paver Consortium, 2022 **6,7.** Eden ISS, ground demonstration of plant cultivation technologies and operation in space for safe food production on-board the International Space Station, Eden ISS Consortium, 2019