Nomadic Ecology: Foldable Habitat Prototype for Weak Regions

Integrating folding geometry, ecological technology, and mobility in extreme landscapes.

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Examiner: Jonas Lundberg
Supervisor: Jonas Lundberg & Kengo Skorick

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Architecture and Urban Design

Chalmers University of Technology
Chalmers School of Architecture +
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You can find the full project at this link.

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Abstract

This study proposes a design strategy named "Foldscape Habitat" and explores the architectural application potential of folding structures in fragile ecological environments through the prototype of a "Foldable Tiny House." Against the backdrop of sensitive areas such as permafrost regions, the research focuses on addressing constrained construction conditions and complex terrains. It investigates how folded geometry can achieve reversible construction, structural stability, and scalable settlement-style spatial organization, thereby offering an alternative to traditional high-intervention construction methods.

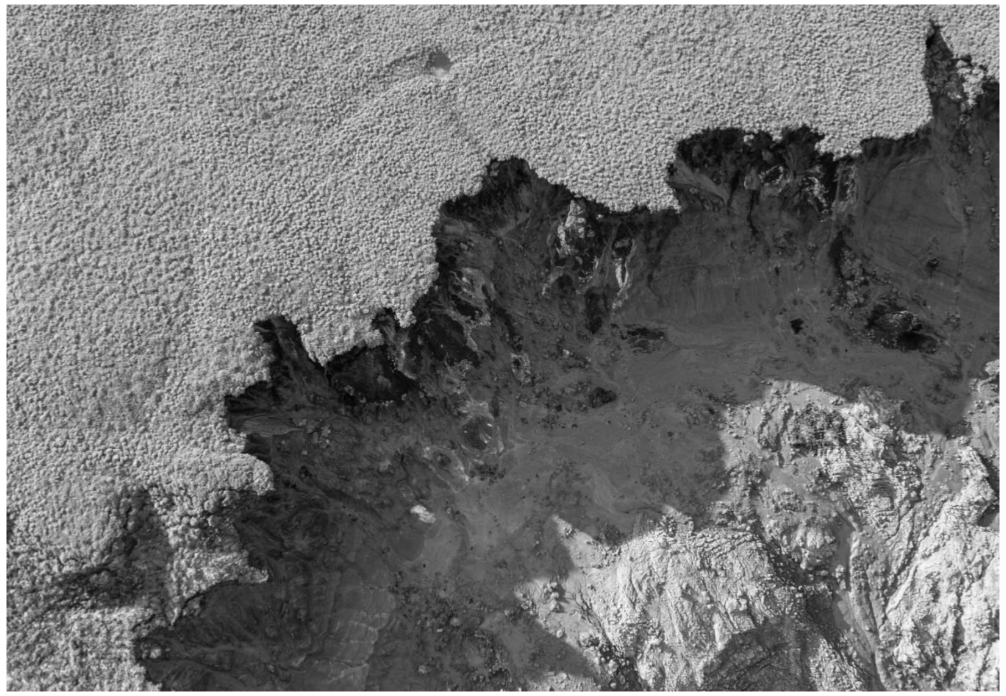
The study employs a design-driven experimental methodology (research-by-design), conducting systematic research on the geometric logic, deployment mechanisms, and spatial organization of folding structures(Liu, Terakawa, Lin, & Komori, 2025). First, based on the theory of folding with material thickness, architectural-scale folding unit models are constructed. Parametric modeling is used to analyze the effects of different folding angles, connection methods, and deployment paths on structural behavior. Subsequently, through physical models and digital simulation experiments, the study focuses on testing the stability of the folding structures in their deployed state, including self-supporting capacity, load-bearing stability, and methods of ground contact and adaptation.

At the scale of the individual prototype, the research further explores the possibility of extending foldable architecture to the community scale. Through combination experiments with modular units, it analyzes how different aggregation strategies perform in terms of assembly efficiency, spatial continuity, and structural collaboration, in order to test the feasibility of using folding structures to form temporary or semi-permanent settlements in scenarios that require rapid deployment and repeated use.

In the expected outcomes of the experiments, the folding structure is intended to maintain a compact folded state while also achieving a stable and controllable spatial expansion. Through standardized connection nodes and modular combination methods, the system is expected to support the coordinated construction of multiple units. By reducing construction steps and minimizing site disturbance, it can also provide a clear structural and spatial logic for flexible layouts at the community scale.

Key Word: Foldable Architecture; Light-Touch Intevention; Research Station Habitat; Extreme Climate Adaptation.

Index



Figue 1.Permafrost thawing and collapse.Dialogue Earth.

Background & Problem Description

Global warming is increasingly reshaping human habitats and amplifying risks in environmentally fragile regions. According to the World Meteorological Organization, the global mean near-surface temperature in 2024 was about 1.55 °C (±0.13 °C) above the 1850–1900 average, and 2025 remained about 1.44 °C (±0.13 °C) above the same baseline; the period 2015–2025 also represents the 11 warmest years on record. Meanwhile, global mean sea level continues to rise and accelerate: the rise rate during 2015–2024 was about 4.7 mm/yr, more than double the early satellite-era rate (1993–2002, about 2.1 mm/yr), with 2024 reaching a record high in the satellite record. Land systems are under comparable stress, with UN information noting that up to 40% of the world's land is degraded, affecting billions of people and worsening vulnerability to drought.

In permafrost zones, high plateaus, drylands, and islands, these global signals interact with local disturbances, making ecosystems and ground conditions highly sensitive. Permafrost alone underlies roughly 23 million km²—about 25% of exposed land in the Northern Hemisphere—and is already experiencing widespread warming and active-layer thickening (with decadal warming rates reaching up to ~1 °C per decade in cold high-latitude and high-elevation settings). Permafrost soils also store a massive carbon pool (~1460–1600 PgC), and thaw-driven greenhouse gas release can create additional long-term warming feedbacks.
Conventional "fixed and heavy" construction methods can exacerbate these risks by causing persistent surface disturbance and thermal imbalance. Engineering guidance notes that buildings and foundations can thaw underlying permafrost, and piles—without mitigation—may transfer sufficient heat to significantly alter the ground thermal profile, leading to settlement or frost heave; surface vegetation disturbance further reduces insulation and promotes summer thaw. Infrastructure can also disrupt drainage and induce ponding, which is linked to deeper thaw and ground instability. In high-altitude ecosystems, surface recovery can take decades; for example, studies along the Qinghai–Tibet Engineering Corridor report recovery times of 20–30 years for alpine grasslands and 45–60 years for alpine meadows after severe disturbance.

At the same time, demand for temporary habitation and flexible infrastructure in fragile regions is rising, driven by seasonal polar research operations and expanding eco-tourism. Antarctica hosts roughly 80 research stations with a strongly seasonal population (on the order of 4,000 in summer and ~1,000 in winter). IAATO statistics show that Antarctic vessel tourism grew from roughly 37,000 visitors in 2013–14 to about 122,000 in 2023–24, remaining near 118,000 in 2024–25. Under these combined environmental and societal pressures, "light-touch" architectural approaches—emphasizing modularity, mobility, renewable energy self-sufficiency, and recyclability—are increasingly relevant, with real-world precedents such as relocatable modular research facilities (Halley VI) and zero-emission polar station practices (Princess Elisabeth Antarctica).

Aim

This study focuses on the "Foldable Tiny House," a foldable housing prototype that combines folding technology, lightweight constructions, and self-sustaining ecological systems. By integrating folding geometries (such as Miura-ori and Hoberman folding mechanisms) with modular construction processes, this system can reduce volume during transit, deploy into stable places on-site, and be quickly removed after use, therefore meeting the goal of "Zero-trace Architecture."

It focuses on frozen and other sensitive landscapes, looking into how folding buildings might reduce foundation destruction, how energy systems can enable off-grid operation, and how the building lifetime can fit with ecological cycles. This project aims to create a light-touch, foldable habitat prototype (Foldscape Habitat) suitable for extreme environments and ecologically sensitive regions, offering an innovative form of "transportable, flexible, and disappearing" architecture for future sustainable construction.

Main Questions

How can a foldable modular architectural system support the rapid deployment of adaptable and low-impact community-scale habitats in fragile environments?

Sub-questions

How can an individual foldable unit achieve compact transformation, structural stability, and spatial usability through its folding logic?

How can multiple foldable units be aggregated into a coherent community system through modular connections and spatial organization strategies?

How can such a foldable community system respond to environmental, logistical, and functional demands in a specific fragile site?

Figue 2. Project relevance to SDG 11 and SDG 13.

Sustainable Development

Considering the combined dangers of climate change and human activity's growing influence on globally ecologically delicate regions (such as deserts, plateaus, and permafrost), architects must rethink the meaning and extent of "architectural intervention." With "Light-touch Intervention" and "Reversibility" as its fundamental ideas, Foldable Habitat is specifically suggested in this context with the goal of minimizing disruption and maximizing adaptation within natural systems.

When a foldable structure and a self-sustaining energy system are combined, carbon emissions from construction and transportation are decreased, leading to minimal energy use over the building's lifetime and causing the least amount of environmental disturbance. Additionally, the structure's transient and transportable design enables a "Zero-trace" presence in environmentally sensitive locations, guaranteeing that the environment may quickly recover following use and establishing a cyclical relationship of "sustainable–reversible–regenerative."

Foldable Habitat meets UN Sustainable Development Goals (SDGs) 11 (Sustainable Cities and Communities) and 13 (Climate Action) from the point of view of sustainable development in general. It also shows a reconsideration of how people will live in the future: architecture doesn't have to be static; it may be a unit that can move, fold, and breathe. This is an effort to find a new equilibrium between ecology and architecture, going from construction to symbiosis, from expansion to equilibrium.

Project

The project, Foldscape Habitat, applies the research through the design of a deployable and self-sufficient foldable dwelling system situated in permafrost and other fragile ecological regions. By designing a deployable and self-sufficient foldable house system that can be placed in permafrost and other delicate ecological areas, the Foldable Habitat project puts the research to use. These areas require architectural solutions that minimize ground disturbance and enable quick, changeable deployment because of their unstable ground, limited accessibility, and high ecological sensitivity.

The prototype will be created as a foldable, modular unit that can be withdrawn without leaving any lasting effects, assembled with little assistance from the foundation, and transported in a small package. The project will investigate how foldable geometry, lightweight construction, and integrated energy systems may work together to create a workable architectural model for low-impact living through material prototyping and site simulations.

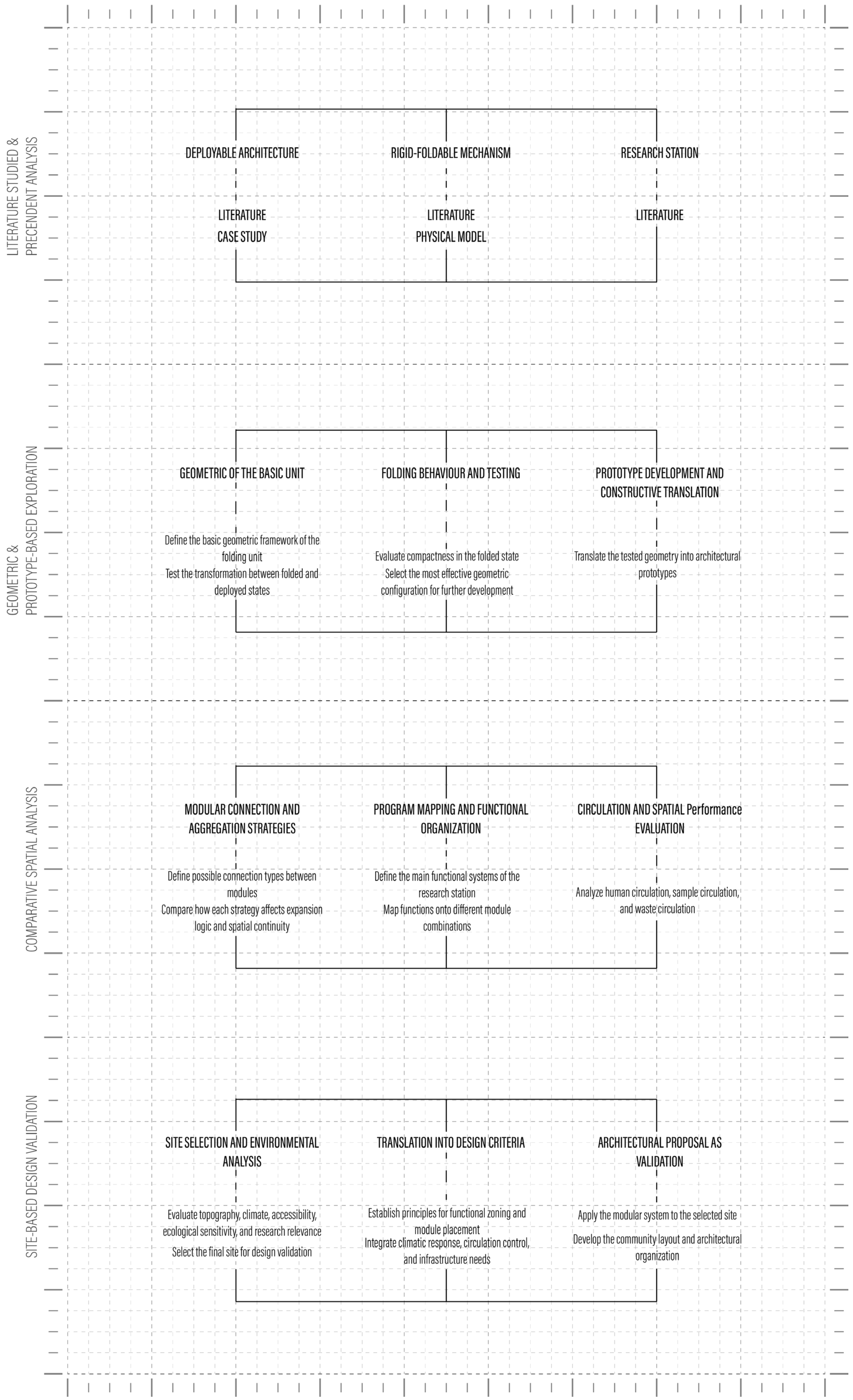
A critical reconsideration of architecture's relationship to the environment, from construction to coexistence, is what inspired this project. The project aims to create a new paradigm of "zero-trace architecture," where occupancy becomes transient, adaptive, and ecologically reversible, by combining deployable engineering principles (Liu et al., 2025) into an architectural setting.

Delimitations

At the technical and structural levels, folding systems still face challenges in terms of structural complexity and material reliability. The fatigue life of the folding joints, stability under extreme climatic conditions, and the integration efficiency of the equipment system all require further verification. Furthermore, the high manufacturing cost of lightweight, high-performance materials limits the economic feasibility and scalable application of the system.

From an ecological and environmental perspective, although the research emphasizes the principles of "light intervention" and "zero trace," the transportation, installation, and use of the structure may still impact the fragile ecosystem. Since most projects are currently still in the prototype stage, the lack of long-term operational data and life cycle assessments (LCAs) after dismantling makes it difficult to comprehensively assess their actual environmental impact.

Regarding research methods and theoretical frameworks, although this study attempts to integrate interdisciplinary approaches such as architecture, ecology, and folding geometry, there is currently no unified interdisciplinary assessment standard. Simultaneously, the energy system scheme has not yet been experimentally implemented with specific feasible solutions. The current verification process lacks actual deployment and long-term monitoring data, making it difficult to comprehensively assess the performance of the design under natural conditions.



Methods & Tools

This study adopts a design-oriented methodological framework to explore the potential of foldable architectural systems in fragile ecological environments. Through literature studies, precedent analysis, geometric and prototype-based exploration, comparative spatial analysis, and site-based design validation, the research develops step by step from theoretical understanding to design testing.

Literature Studies & Precendent Analysis

Literature Studies and Precedent Analysis are mainly used to build the theoretical foundation and problem framework of this research. By reviewing studies on deployable architecture, rigid-foldable mechanisms, modular architecture, reversible construction, and the spatial requirements of research stations, the study first identifies the potential value of foldable architecture in lightweight construction, rapid deployment, low site disturbance, and repeated use. At the same time, literature on building in cold regions, polar environments, and other ecologically sensitive areas is examined in order to better understand the common problems faced by conventional research stations, such as long construction periods, strong dependence on transportation, environmental disturbance, and difficult maintenance.

In the precedent analysis, the study selects relevant examples of foldable architecture, modular habitat systems, temporary deployable buildings, and research living facilities. By comparing their structural logic, spatial organization, connection strategies, deployment methods, and environmental responses, the study extracts design principles that are useful for this project. Rather than using precedents only as formal references, this research focuses more on how these systems operate. This includes how foldable units move between compact and expanded states, how modules connect to form more complex groupings, and how architecture responds to extreme climates and special functional needs.

Geometric & Prototype-based Exploration

Geometric and Prototype-based Exploration is the key step that connects theoretical analysis with design generation in this research. Its main purpose is to investigate the structural logic, movement mechanism, and spatial potential of the basic folding unit through geometric modelling and prototype development. The study first examines the geometric relationships within the unit, including the organization of folding lines, the hinged relations between panels, the volume change between folded and deployed states, and the influence of key angle parameters on the folding process. Through repeated digital modelling and testing, the research aims to identify which geometric configuration can keep a compact folded state while also allowing a stable and controllable spatial expansion.

At the prototype level, the geometric study is further translated into design prototypes that can be observed, compared, and evaluated. These prototypes are used to assess folding efficiency, deployment stability, spatial usability, and construction feasibility. Digital models, together with necessary physical models, serve as research tools that move the folding mechanism beyond abstract diagrams and turn it into an architectural prototype with scale, operation logic, and spatial meaning.

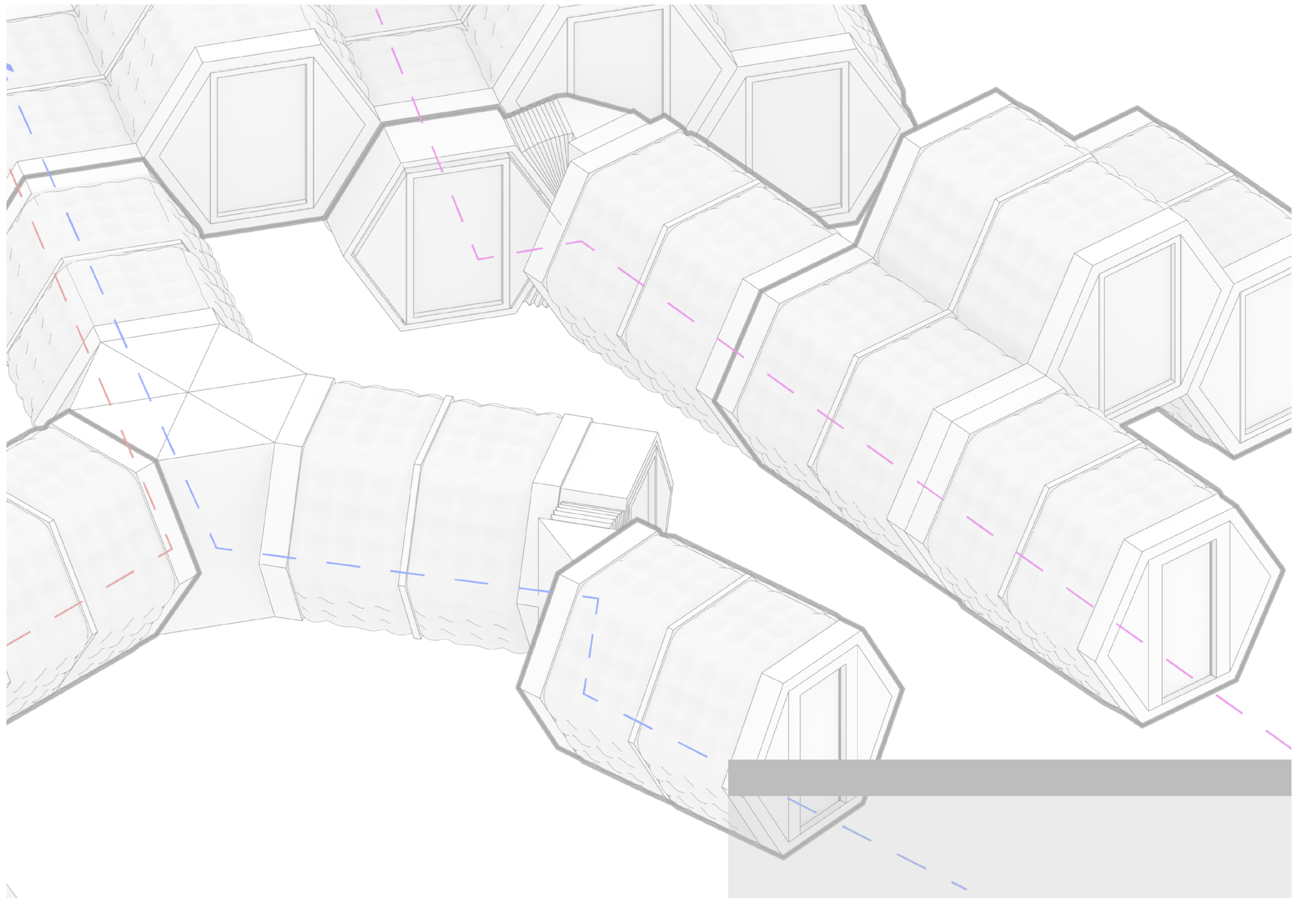
Comparative Spatial Analysis

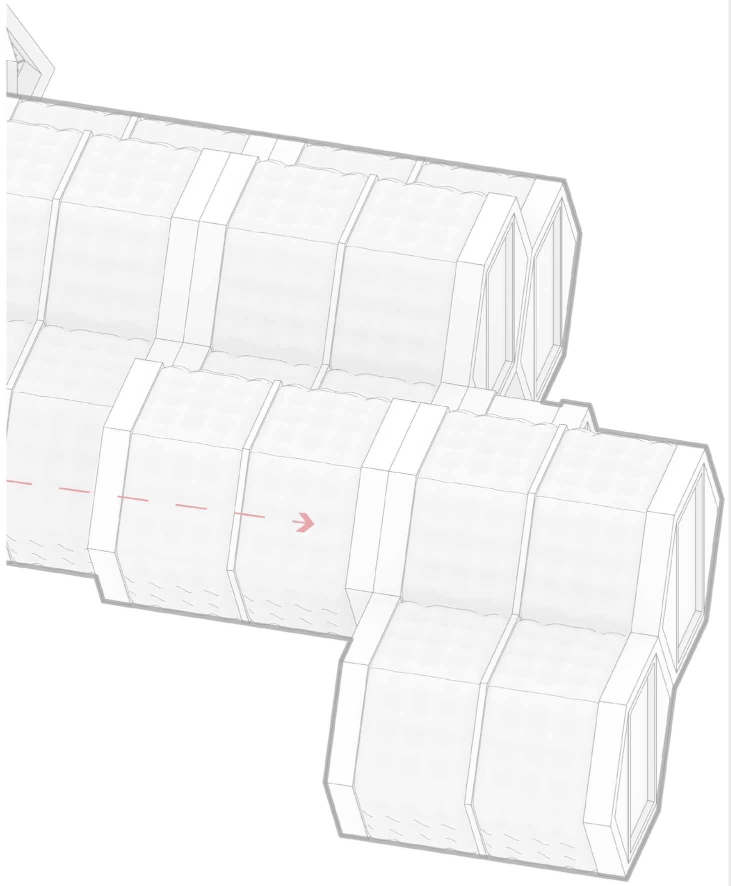
Comparative Spatial Analysis is mainly used to evaluate the spatial organization capacity and system performance that emerge when the folding unit develops from a single prototype into multi-unit combinations. At this stage, the study does not directly move into a specific site. Instead, it first tests different aggregation strategies on a more abstract system level, such as linear connections, angled connections, hub-based connections, and clustered combinations. By comparing these different modes, the study analyzes their differences in construction efficiency, spatial continuity, clarity of functional zoning, structural cooperation, and future flexibility for expansion. In this way, it becomes possible to understand which modular relationships are more suitable for supporting the spatial needs of small- and medium-scale research stations. The main focus of this stage is therefore system performance: not only how modules are connected, but also how these connections affect use, circulation, and spatial hierarchy.

At the same time, the functional requirements of research stations are introduced into the aggregation study. Through program mapping, bubble diagrams, and circulation studies, the research examines how different space types can be organized within a foldable modular system, with particular attention to the relationships between living, working, experimental, and logistical zones. In the context of research stations, human circulation, sample circulation, and waste circulation often become critical constraints. For this reason, modular combinations must not only be formally connectable, but must also respond to the actual operational logic of scientific activities in spatial terms.

Site-based Design Validation

Site-based Design Validation is the final stage of the research, in which the folding logic, modular system, and spatial strategies developed in earlier phases are placed within a specific environmental context in order to test their practical architectural adaptability. The study first compares candidate sites from multiple aspects, including topographic conditions, climate characteristics, accessibility, ecological sensitivity, and relevance to research activities, in order to evaluate their potential as validation sites. After selecting the final site, further analysis is carried out on wind, snow, temperature, ground conditions, views, logistics, and protected boundaries. These objective conditions are then translated into clear design criteria. In this way, the site is not treated simply as a background for the project, but as an active factor that reshapes architectural layout, modular organization, and spatial strategy.



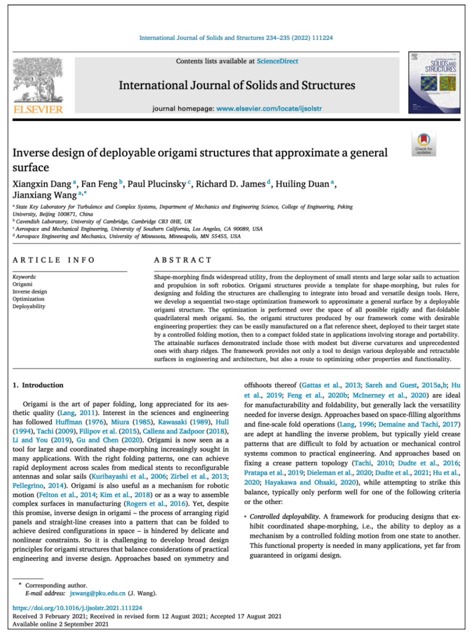


01

Literature Studies & Precendent Analysis

Theory

Folding Techniques: This book presents a wide range of folding techniques and clearly explains how to construct these forms by hand, using step-by-step diagrams and geometric breakdowns. It enables readers to understand both the principles and the practical methods behind creating diverse folded structures.



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Inverse design of deployable origami structures that approximate a general surface

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ABSTRACT

Shape-morphing finds widespread utility, from the deployment of small stents and large solar sails to actuation and propulsion in soft robotics. Origami structures provide a template for shape-morphing, but rules for designing and folding the structures are challenging to integrate into broad and versatile design tools. Here, we develop a sequential two-stage optimization framework to approximate a general surface by a deployable origami structure. The optimization is performed over the space of all possible rigidly and flat-foldable quadrilateral mesh origami. So, the origami structures produced by our framework come with desirable engineering properties: they can be easily manufactured on a flat reference sheet, deployed to their target state by a controlled folding motion, then to a compact folded state in applications involving storage and portability. The attainable surfaces demonstrated include those with modest but diverse curvatures and unprecedented ones with sharp ridges. The framework provides not only a tool to design various deployable and retractable surfaces in engineering and architecture, but also a route to optimizing other properties and functionality.

1. Introduction

Origami is the art of paper folding, long appreciated for its aesthetic quality (Lang, 2011). Interest in the sciences and engineering has followed Huffman (1976), Miura (1985), Kawasaki (1989), Hull (1994), Tachi (2009), Filipov et al. (2015), Callens and Zadpoor (2018), Li and You (2019), Gu and Chen (2020). Origami is now seen as a tool for large and coordinated shape-morphing increasingly sought in many applications. With the right folding patterns, one can achieve rapid deployment across scales from medical stents to reconfigurable antennas and solar sails (Kuribayashi et al., 2006; Zirbel et al., 2013; Pellegrino, 2014). Origami is also useful as a mechanism for robotic motion (Felton et al., 2014; Kim et al., 2018) or as a way to assemble complex surfaces in manufacturing (Rogers et al., 2016). Yet, despite this promise, inverse design in origami – the process of arranging rigid panels and straight-line creases into a pattern that can be folded to achieve desired configurations in space – is hindered by delicate and nonlinear constraints. So it is challenging to develop broad design principles for origami structures that balance considerations of practical engineering and inverse design. Approaches based on symmetry and offshoots thereof (Gattas et al., 2013; Sareh and Guest, 2015a,b; Hu et al., 2019; Feng et al., 2020b; McInerney et al., 2020) are ideal for manufacturability and foldability, but generally lack the versatility needed for inverse design. Approaches based on space-filling algorithms and fine-scale fold operations (Lang, 1996; Demaine and Tachi, 2017) are adept at handling the inverse problem, but typically yield crease patterns that are difficult to fold by actuation or mechanical control systems common to practical engineering. And approaches based on fixing a crease pattern topology (Tachi, 2010; Dudte et al., 2016; Pratapa et al., 2019; Dieleman et al., 2020; Dudte et al., 2021; Hu et al., 2020; Hayakawa and Ohsaki, 2020), while attempting to strike this balance, typically only perform well for one of the following criteria or the other:

- *Controlled deployability.* A framework for producing designs that exhibit coordinated shape-morphing, i.e., the ability to deploy as a mechanism by a controlled folding motion from one state to another. This functional property is needed in many applications, yet far from guaranteed in origami design.

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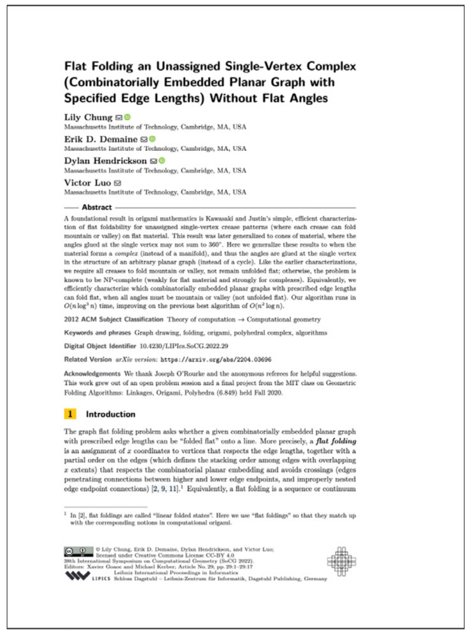
Rigid Origami Theory: The geometry of the Origami pattern - the kinematic relationship between the fold line and the panel; study the fold angle, fold compatibility (flat foldability, developability), folding path, etc. during folding and unfolding. For example, the fold of a rigid panel only moves along the fold line and does not deform the panel surface.

Relevance:
Folding Techniques for Designers provides a systematic overview of folding methods and step-by-step construction techniques, offering direct design insights for foldable Tiny Houses. Its analysis of crease types, folding paths, and geometric behavior helps translate architectural walls, roofs, and volumetric modules into controllable foldable systems suitable for compact storage and rapid deployment.

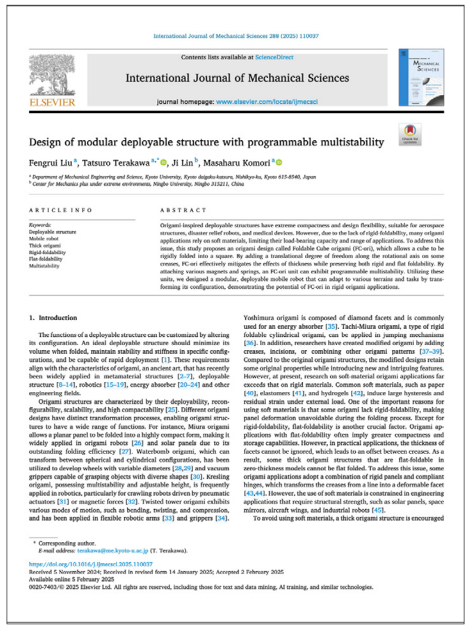
Relevance:
Rigid Origami Theory provides the geometric and kinematic principles that allow foldable structures to transform without panel deformation, relying solely on hinge rotations. For foldable Tiny Houses, this enables walls, roofs, and volumetric modules to follow controlled folding paths and single-degree-of-freedom motion while maintaining structural strength. As a result, the house can be compactly folded for transport and reliably expanded for habitation.


Flat Folding an Unassigned Single-Vertex Complex (Combinatorially Embedded Planar Graph with Specified Edge Lengths) Without Flat Angles

Lily Chung
Erik D. Demaine
Dylan Hendrickson
Victor Luo

Maekawa's theorem: Ensure that all folds form a continuous, alternating chain of mountain and valley folds to keep the structure continuous and symmetrical while folding. If the folds do not form a continuous, valley-like pattern or are random, they will twist or lock. This principle enables the synchronization of the origami's general movement and is an important factor for deciding whether a complicated folded structure may be entirely flattened.

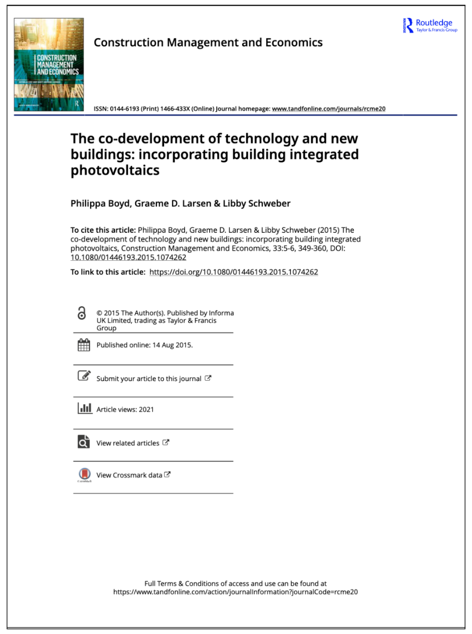
Relevance:
Maekawa's theorem, as one of the fundamental conditions for flat-foldability in zero-thickness origami, ensures that a folding vertex can achieve smooth, single-degree-of-freedom deployment and contraction. For foldable Tiny Houses, any collapsible wall, roof, or volumetric module must theoretically satisfy such flat-foldability constraints to achieve reliable, interference-free rigid folding at the architectural scale.


International Journal of Mechanical Sciences

Design of modular deployable structure with programmable multistability

Thick Body Folding: This paper presents a method for rigidly folding a cube with finite thickness into a compact configuration. Building upon classical zero-thickness origami theory, the study further investigates how thick-panel elements can be folded without deformation by introducing strategies such as sliding crease mechanisms. These techniques address geometric interference caused by material thickness, demonstrating how foldable systems can be scaled up for architectural applications. Only by resolving the challenges associated with thickness can deployable structures achieve true rigid-foldability and flat-foldability at the building scale.

Relevance:
With appropriate crease arrangements and segmentations, the same principles can inform foldable transformations in more complex architectural volumes, enabling Tiny House designs to incorporate deployable structures beyond simple cubic forms.


Construction Management and Economics

The co-development of technology and new buildings: incorporating building integrated photovoltaics

Philippa Boyd, Graeme D. Larsen & Libby Schweber

BIPV: As an integrated form of building envelope and energy production system, BIPV enables the foldable habitat unit to operate independently in an off-grid state, reducing reliance on external energy sources. Through the combination of flexible photovoltaic films and folding geometry, Foldscape Habitat achieves a deep integration of architectural form and energy system functionality, demonstrating a self-sustaining architectural paradigm where technological innovation converges with ecological design.

Relevance:
Incorporating Building-Integrated Photovoltaics (BIPV) into a mobile tiny house enables the structure to generate its own energy without compromising its architectural form or spatial expression. By relying on clean and renewable energy, the building significantly reduces its environmental impact during operation, enhancing both ecological sensitivity and overall sustainability.


Lecture Notes in Mechanical Engineering

Salvatore Gerbino · Antonio Lanzotti · Massimo Martorelli · Ramón Mirálbes Buil · Caterina Rizzi · Lionel Roucoules *Editors*

Advances on Mechanics, Design Engineering and Manufacturing IV

Proceedings of the International Joint Conference on Mechanics, Design Engineering & Advanced Manufacturing, JCM 2022, June 1–3, 2022, Ischia, Italy

LCA: This theory evaluates a building's energy consumption and carbon emissions throughout its entire life cycle—from material extraction, manufacturing, and transportation, to construction, use, and demolition/recycling—revealing the ecological advantages of lightweight, reversible, and modular construction methods.

Relevance:
Life Cycle Assessment (LCA) provides a scientific and systematic framework for evaluating the environmental impacts of a building throughout its entire life cycle. Rather than focusing solely on the operational phase, LCA encompasses all stages including material production, construction, transportation, operation, maintenance, and end-of-life processes such as demolition and recycling. This holistic perspective allows for a more accurate understanding of the building's total environmental footprint.

Reference Project

Figue 3. Lunark habitat prototype deployed in a polar environment.

Thick Habitat:
The LUNARK habitat is an example of what happens when the architect steps back and allows the extreme environment on the Moon and the high arctic to mold a habitat around two human beings. Inspired by the patterns seen in a budding leaf as it unfolds, we created an origami habitat which unfolds from a tight bud to a large ovoid shape with a rigid carbon fibre shell. It's exterior is tough as a tank while its interior is a cozy home with a sense of Nordic "hygge".A black glossy shell made of carbon fiber makes out the main exterior of the habitat. The carbon fiber structure is sandwich panels with a foam core for extra insulation. Carbon fiber is ideal because it's lightweight - which is crucial for transport and unfolding - yet strong. The panels are connected by a white foldable composite rubber. The main load bearing structure is an aluminium frame.

Relevance:
The design of the LUNARK Habitat centers on a lightweight, foldable, and rapidly deployable living module for extreme environments. Its use of geometric folding, hinged joints, and flexible skins to achieve a transformation from a compact transportable volume to a full-scale habitat closely aligns with the logic of foldable Tiny House research. LUNARK demonstrates how thick panels can be folded, how deployment footprints can be minimized, and how essential systems can be integrated along fold lines, while still maintaining structural stability, insulation performance, and modular interior organization.

Figue 4. Example of a mobile and deployable small-scale living unit.

WALKING HOUSE:
WALKING HOUSE is a modular dwelling system that enables persons to live a peaceful nomadic life, moving slowly through the landscape or cityscape with minimal impact on the environment. It collects energy from its surroundings using solar cells and small windmills. There is a system for collecting rain water and a system for solar heated hot water. A small greenhouse unit can be added to the basic living module, to provide a substantial part of the food needed by the Inhabitants. A composting toilet system allows sewage produced by the inhabitants to be disposed of. A small wood burning stove could be added to provide CO2 neutral heating.

Relevance:
The Walking House by N55 offers valuable relevance, particularly in how it integrates autonomous energy systems and interfaces with the ground in a low-impact manner. Through the combination of wind power, solar panels, and rainwater harvesting, the project achieves a fully off-grid mode of living, which directly informs strategies for BIPV and multi-source energy integration in foldable Tiny House design. In addition, the Walking House uses adjustable mechanical legs that maintain minimal point-contact with the terrain, reducing disturbance to the landscape and establishing a model of low-impact, nomadic architecture. These principles are highly relevant for deployable foldable tiny houses intended for ecologically fragile environments.

Figue 5. Interior access of a modular sleeping unit.

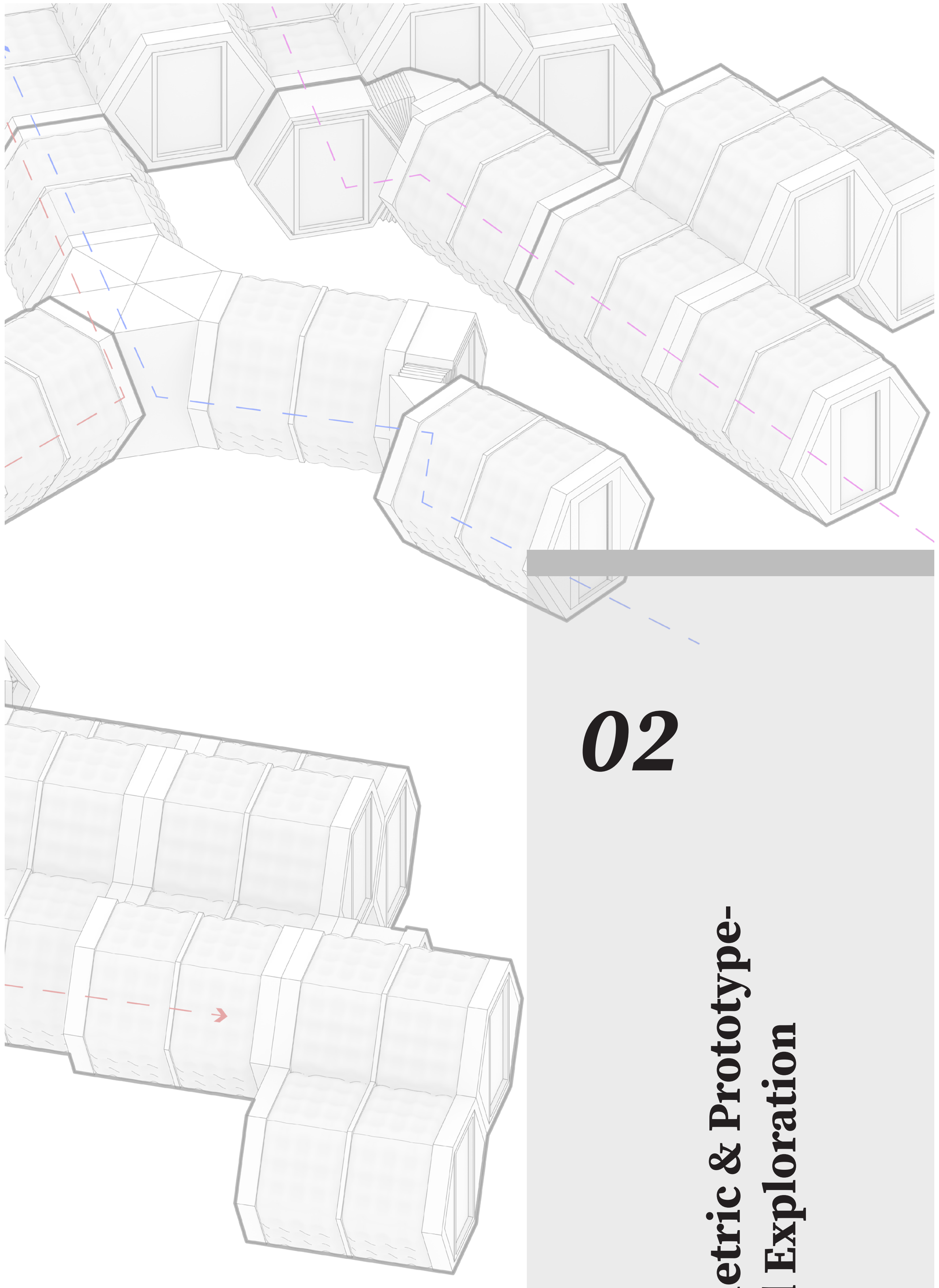
B-and-Bee Camping Concept:
This modular honeycomb of wooden cells by a team of Belgian designers could provide a solution for people avoiding music festivals because they don't like sleeping in tents. Lockers, lights and a power supply are also included in the larch wood-clad cells, which can be stacked four high in a diagonal line to accommodate 50 revellers on 100 square metres of ground.

Relevance:
The B-and-Bee stackable sleep cells demonstrate how a single standardized module can be efficiently aggregated—both vertically and horizontally—to form a temporary communal structure. This directly informs how foldable and mobile tiny-house units in your project can be organized into modular research outposts in extreme environments. The project shows that compact, self-contained units can combine to create a larger functional community while maintaining flexibility, independence, and rapid deployability. This unit-to-community logic offers an important reference for constructing temporary scientific stations in harsh climates using foldable, mobile modules.

Figue 6. Example of flexible interior organization in a compact living space.

Folly House:
The sprawling 4500 sq ft house offered a wide range of possibilities to respond to the brief. Our approach was to create an open plan home where every functionality of the home was compacted into multi-functional or mobile objects. The remaining space was left untouched, activated only when these objects unfolded, rotated or pivoted open. The living room consisted of two such objects, a multi-functional carved wooden topography and a fold-out wooden cube. The continuity of space was paramount in the design of both objects. This created an 'exteriority' within the interior space. The overall experience of the house transformed from 'living in rooms' to 'living amongst objects'. Since the nature of each object is different, the house remains unpredictable and new relationships between everyday home objects are constantly discovered. Chance and unpredictability create follies.

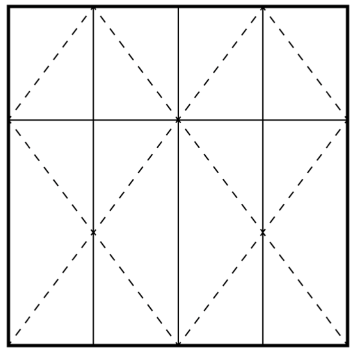
Relevance:
The Folly House project demonstrates how a complete set of living functions—sleeping, storage, working, and basic utilities—can be highly condensed into a compact volume. This directly informs the living-module consolidation strategy for a foldable Tiny House operating within extreme spatial constraints. Additionally, the project's modular and system-integrated approach offers valuable reference for energy and utility module integration, showing how power, ventilation, and water systems can be efficiently organized within a small-scale, self-sufficient dwelling unit.



02

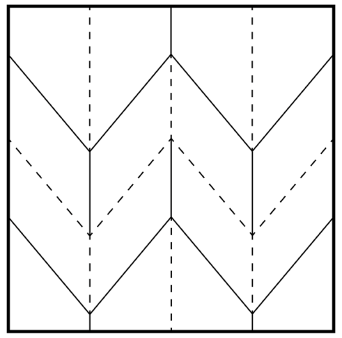
Geometric & Prototype-based Exploration

Basic Crease Learning



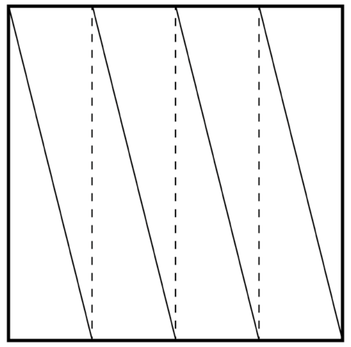
Square Diagonal Fold

The Yoshimura pattern, consisting of a square grid formed by intersecting diagonals, offers multi-directional folding capability and high structural rigidity. Its geometric stability and isotropic properties make it widely applicable to foldable shelter systems and lightweight shell designs.



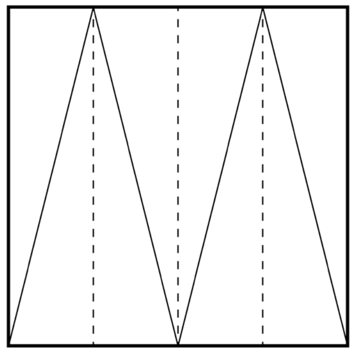
Miura Fold

The typical single-degree-of-freedom folding system composed of continuous rhombus units achieves efficient compression and deployment through alternating mountain and valley folds. Its geometric continuity maintains overall surface smoothness during motion, combining lightweight properties with mechanical stability.



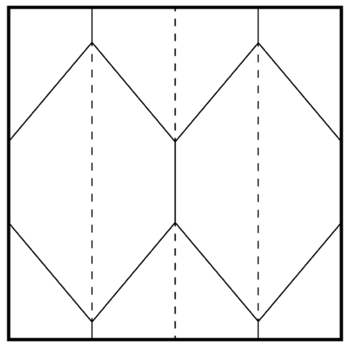
Oblique Zigzag Fold

The diagonal folding pattern, characterized by diagonal creases, can generate continuous curved surfaces or wave-like configurations through angular variations, exhibiting high morphological adaptability and spatial flexibility. This pattern is suitable for adaptive facades, dynamic envelopes, and responsive structural systems.



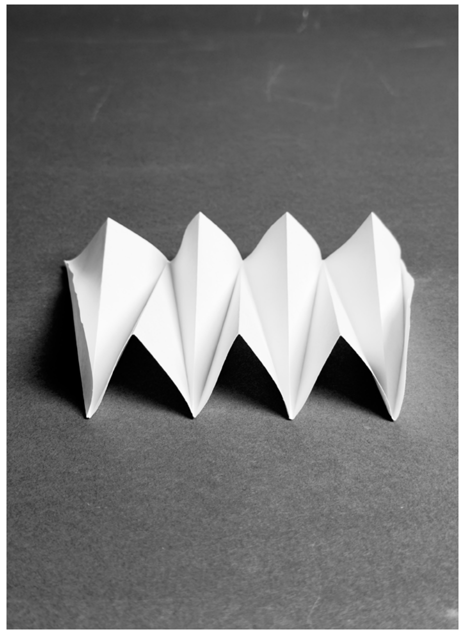
Triangulated Pleat Fold

The folding mechanism consists of regular zigzag creases, forming a unidirectional linear folding path that offers structural simplicity and manufacturing convenience. With high stiffness along the crease direction, it is suitable for rapidly deployable and reusable components such as temporary walls, sunshades, and lightweight roofing systems.



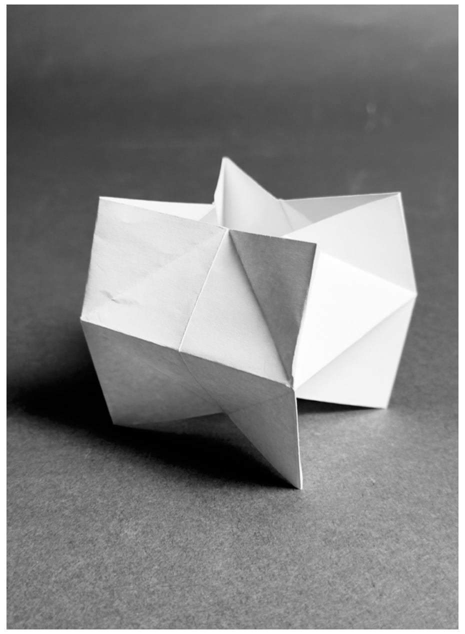
Diamond Fold

The diamond-symmetric folding pattern consists of mirrored upper and lower units, featuring balanced folding paths and strong motion reversibility while maintaining high surface flatness when deployed. This configuration demonstrates stability in both mechanical and geometric aspects, making it widely applicable in repeatedly deployable roof systems and reversible structural units.



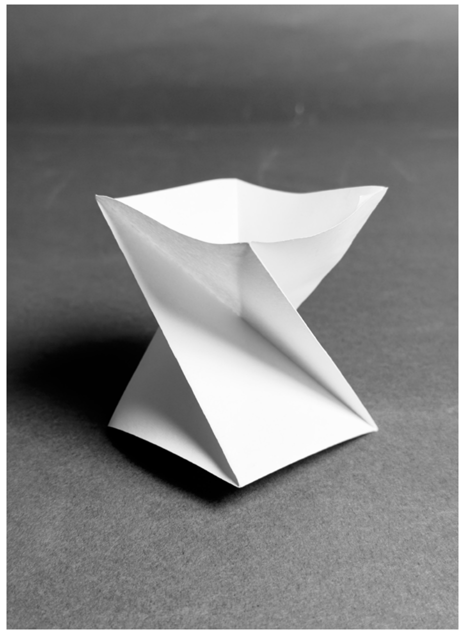
Basic V-pleats
Based on the original V-pleat, a linear array is developed to create a continuous and rhythmic spatial effect in the folded structure. Its form unfolds along a single direction, making it suitable for constructing rollable or retractable surface systems.

Reflected
This form achieves bidirectional spatial movement through symmetrical folding and reverse rotation, resulting in a shell-like curved structure. Its geometric characteristics enable a high compression ratio in the folded state, while exhibiting a dynamic morphology that combines flexibility and fluidity when deployed.



Box+Fold Motifs
This form integrates both "box folding" and "surface folding" logics, achieving stable support for a dual-layer structure through intersecting creases across surfaces and edges. Its geometric characteristics demonstrate the coexistence of rigidity and flexibility, enabling both compressibility and load-bearing capacity.

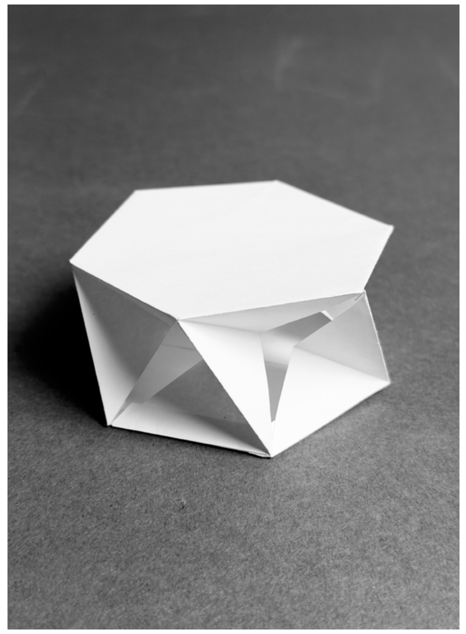
Hexagon+Folded Motifs_1
Based on a hexagonal unit, this structure forms a vertically stacked body through staggered folding. Its cross-section remains balanced throughout the folding process and can be fully compressed, though its perimeter cannot be completely flattened when deployed.



Box Spirals_1
The structure is generated by twisting and folding a square base, creating a subtly rotating volumetric transformation. Its spatial expression combines both regularity and asymmetry, exhibiting noticeable directional torque during the folding motion.

Box Spirals_2
Building upon the previous type, this design incorporates volumetric contraction and angular variation, resulting in a form with enhanced vertical dynamism. The structural center of gravity shifts upward, creating more complex overlapping relationships that demonstrate the dual coupling of "form-mechanics" in folding systems.

Hexagon+Miura-ori
This pattern integrates Miura-ori folding logic with a hexagonal layout, forming a multi-directional folding system capable of longitudinal compression and lateral expansion. Its motion trajectory remains smooth throughout deployment, enabling the formation of continuous surfaces or cylindrical structures when fully expanded.



Hexagon+Folded Motifs_2
This folding pattern takes the hexagon as its base form and creates multi-level spatial relationships through internal diagonal creases. The structure remains highly compact in the folded state, while forming stable spatial boundaries when deployed. Its geometric characteristics demonstrate potential for "internal folding" applications.

Basic Folding Structure

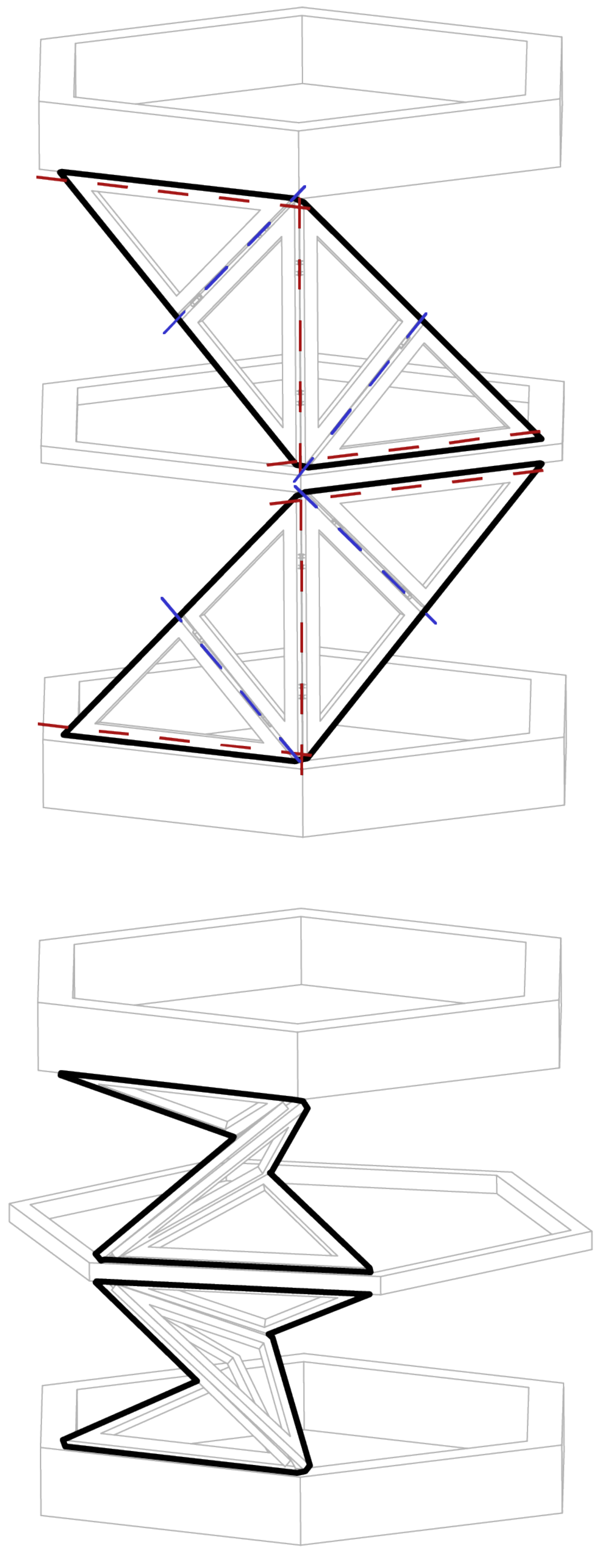
The basic folding unit designed in this study belongs to the category of rigid-foldable mechanisms. Its deformation is driven primarily by hinge movements, meaning each panel remains rigid and experiences no elastic material deformation during the folding process. This rigid-foldability allows the structure to follow a controllable motion path with high repeatability under geometric constraints, making it ideal for deployable structures and shape-shifting systems.

The design of this unit is partly inspired by the research of Fengrui Liu et al. on "modular deployable structures with programmable multistability." Their study demonstrates that by designing specific folding parameters and adding controllable energy elements to the folding unit, it is possible to achieve multi-stable behavior and self-locking capabilities.

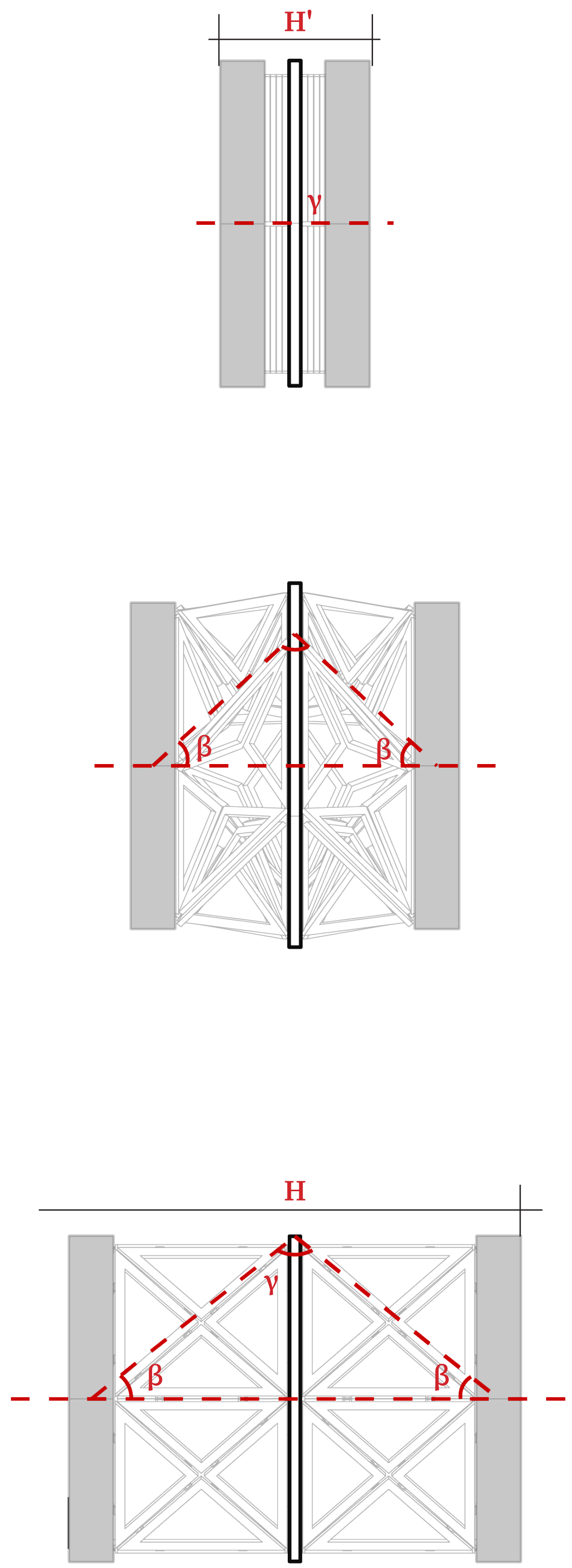
Basic folding components

As shown in the figure, the basic folding mechanism is composed of triangular units: the overall structure consists of symmetrical rigid triangular links on both sides and a central driving hinge. In the deployed state, the folding sub-units are positioned at each corner and maintain axial symmetry. When the angle of the central hinge changes, the entire unit contracts or expands horizontally.

Each sub-unit features distinct valley folds (blue) and mountain folds (red). This process exhibits single-degree-of-freedom (1-DOF) kinematics across all axes. Consequently, the structure achieves continuous folding and unfolding by adjusting only one control parameter (the folding angle), eliminating the need for complex driving mechanisms.



Figue 7 . Crease display diagram.



Figue 8 . Module space unfolded horizontal diagram.

High Compression Ratio

o describe this geometric motion, three points that align in a straight line when the unit is folded are connected to define two key parameters: folding angle β and folding angle γ.In the initial state, γ = 180° and β = 0°. As β increases (approaching 40°), the horizontal span of the module expands while γ decreases, bringing the structure toward a fully deployed state. Conversely, when β decreases, the horizontal span contracts and γ increases back toward 180°, returning the structure to its folded state. This angle-geometry relationship characterizes the folding path and provides a basis for quantifying the compression ratio and geometric efficiency.

To evaluate the folding performance of the prototype, the characteristic axial dimension is defined as H (representing the axial length between the end frames or the effective length between center rings). Accordingly, the compression ratio λ is defined as:

$$\lambda = H(\text{deployed})/H'(\text{folded})$$

Our measurements show that this prototype achieves a compression ratio of λ = 3.2. This indicates significant geometric compactness and high volume efficiency in the folded state. Such a high ratio effectively reduces the footprint during transport and storage, enhancing the logistical adaptability of the deployable system.

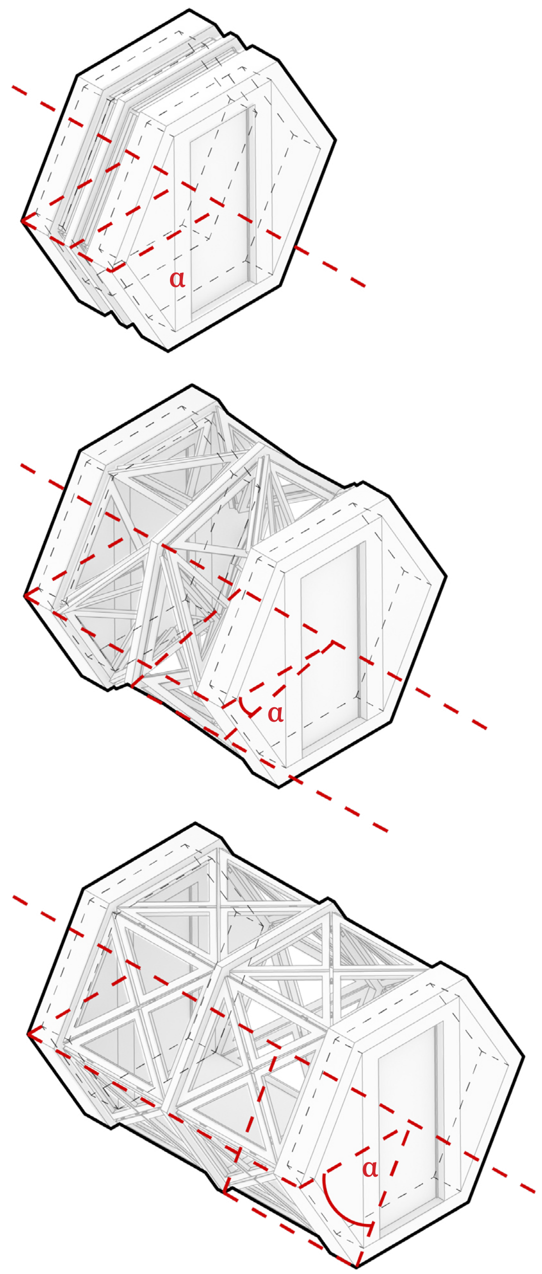
Multistable Self-locking

While rigid-foldable mechanisms typically follow a clear motion path, specific configurations—combined with the effective use of gravity—can create local potential energy minima at certain folding angles. This multistability provides the structure with self-locking capabilities, allowing it to maintain a specific shape without continuous driving force and improving post-deployment stability.

When an external disturbance moves the structure away from its stable state, the system tends to return to the nearby minimum point. Conversely, crossing a potential barrier (energy peak) triggers a configuration switch. This framework aligns with the concept proposed by Liu et al. regarding "programmable stable points via geometry and energy elements," explaining the "staged pausing" and "self-maintenance" observed during the unfolding process.
The figure illustrates the typical motion sequence of the base unit from fully folded to semi-deployed and finally fully deployed. To analyze the folding path and geometric transitions, we connected the center points of the end and middle units and tracked the rotation angle α of the hexagonal ring.

Fully Folded State: The relative rotation angle α between the central hexagonal ring and the ends is 0°.
Deployment Process: As the constraints are released and the sides are pulled apart, α gradually increases from 0° to 60°.

By strategically adding counterweights to the central ring to ensure the center of gravity (CoG) offset matches the rotation direction, gravity can serve as an assistive force for deployment. When the CoG is eccentric relative to the rotation axis, gravity generates a torque that provides forward momentum within a specific angular range. Near the target configuration, the coupling of geometric constraints and potential energy minima creates a "self-stabilizing" effect, securing the structure in its intended deployed state.



Figue 9 . Module rotation angle analysis during deployment.

Other Function Integration

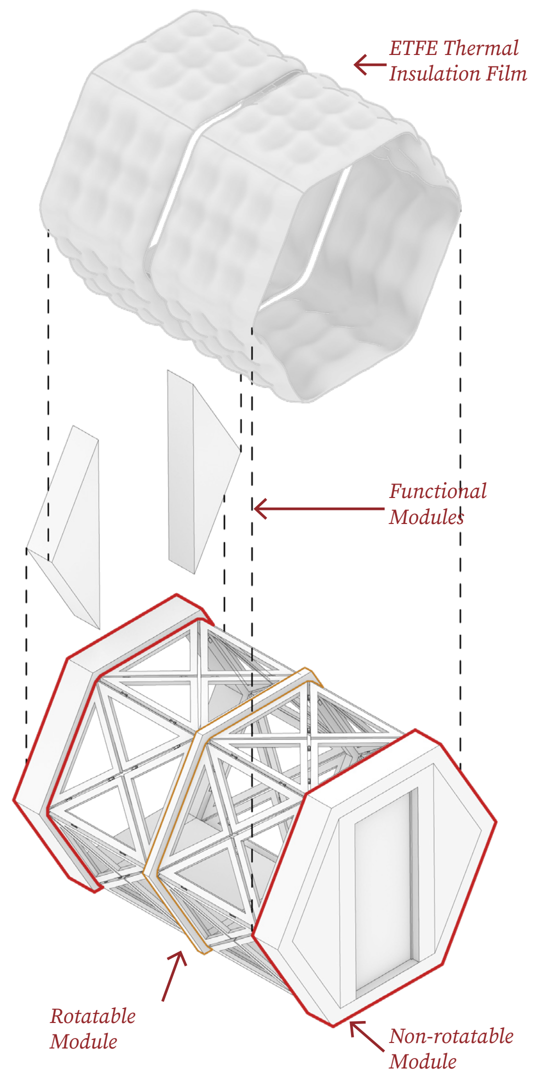
In this study, the folding unit is defined not merely as a "kinematic component" for geometric deformation, but as a building-integrated platform capable of hosting multiple systems. Beyond its core folding function, the unit offers high scalability for enclosures, thermal management, and equipment mounting, creating a tight coupling between deployment efficiency and functional performance.

Enclosure and Thermal Systems

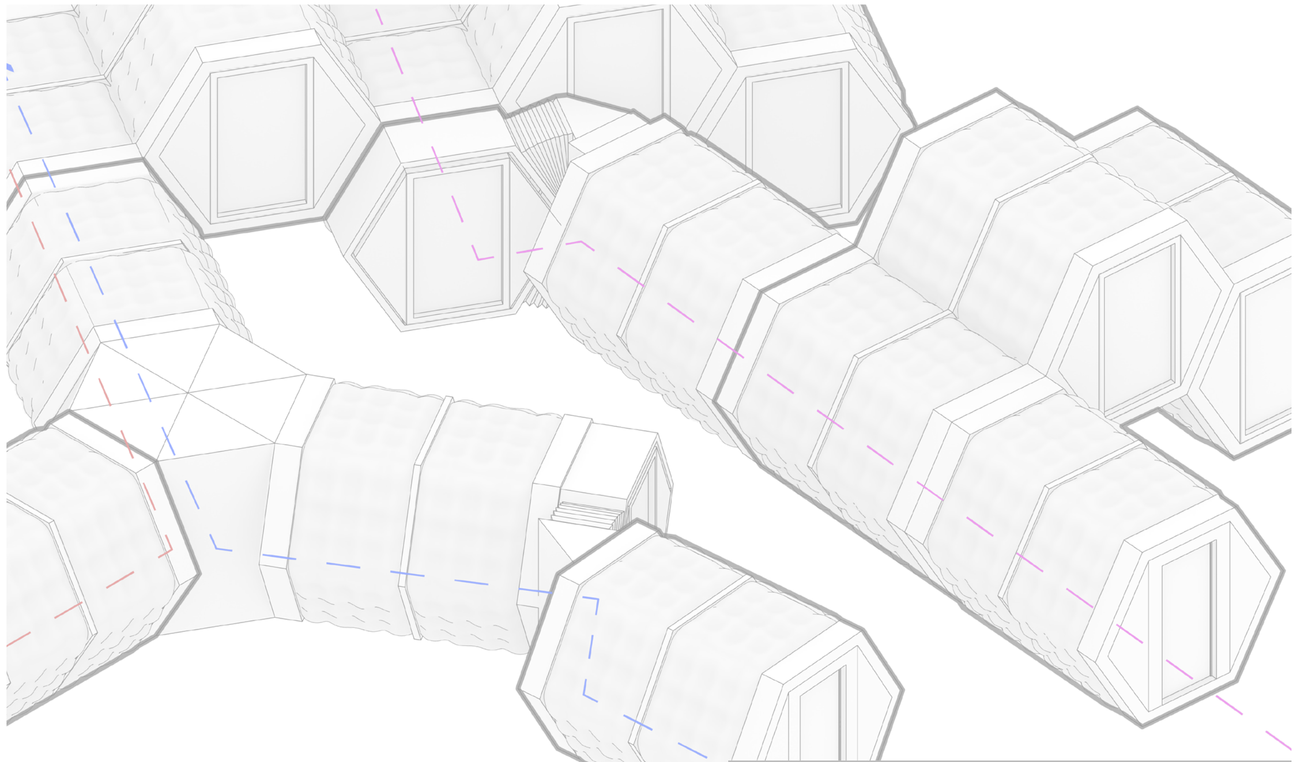
The exterior of the unit integrates an insulation layer using ETFE (Ethylene Tetrafluoroethylene) as the primary material. ETFE is lightweight, foldable, and weather-resistant, making it ideal for the requirements of deployable structures.
Folded State: The membrane retracts along with the structural geometry to achieve efficient compression and minimize transport volume.
Deployed State: Once expanded, the system inflates to form stable air cushions, switching from a "compressible form" to a "working form."
This air cushion layer not only increases thermal resistance and wind stability but also reduces condensation risks and improves indoor thermal comfort, achieving a synergistic design of kinematics and thermal performance.

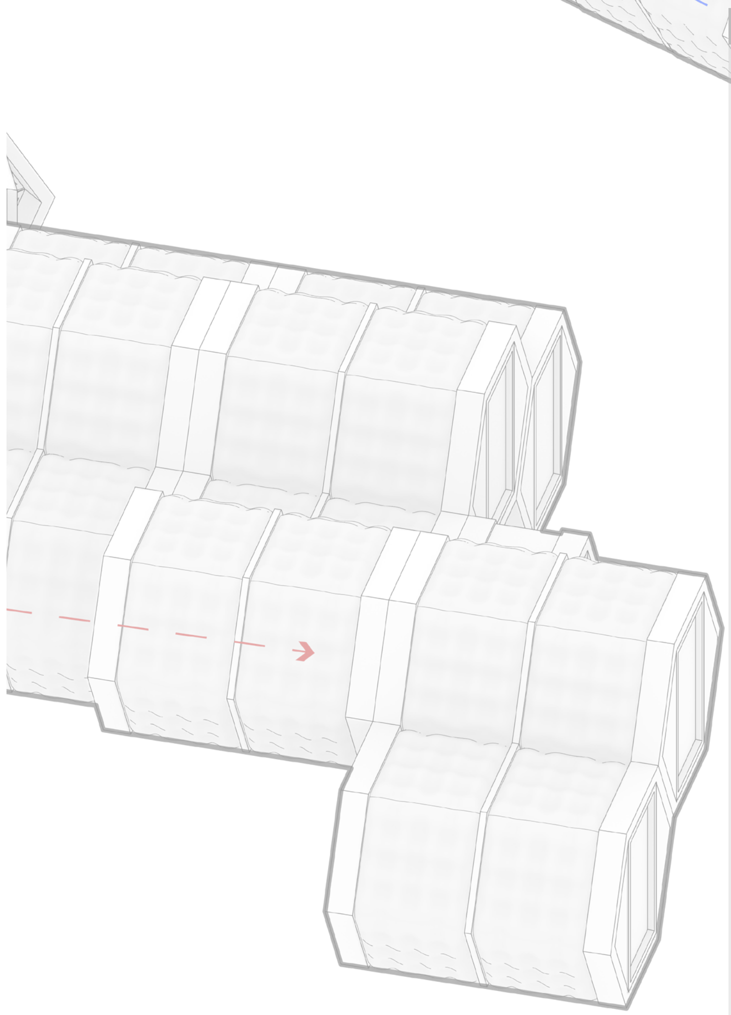
Functional Modularity and Interface Strategy

A single base unit consists of three hexagonal modules. The end modules (marked in red) are non-rotating components that serve as standardized functional interfaces. These nodes are designed for "plug-and-play" components, such as:
Entrance/doorway modules.
Inter-unit connection and transition segments.
Inflation/valve control and energy storage modules.
By concentrating systems that require stable connections in these non-rotating zones, the interference of folding movements on wiring and sealing is significantly reduced, improving overall system reliability and maintenance accessibility.



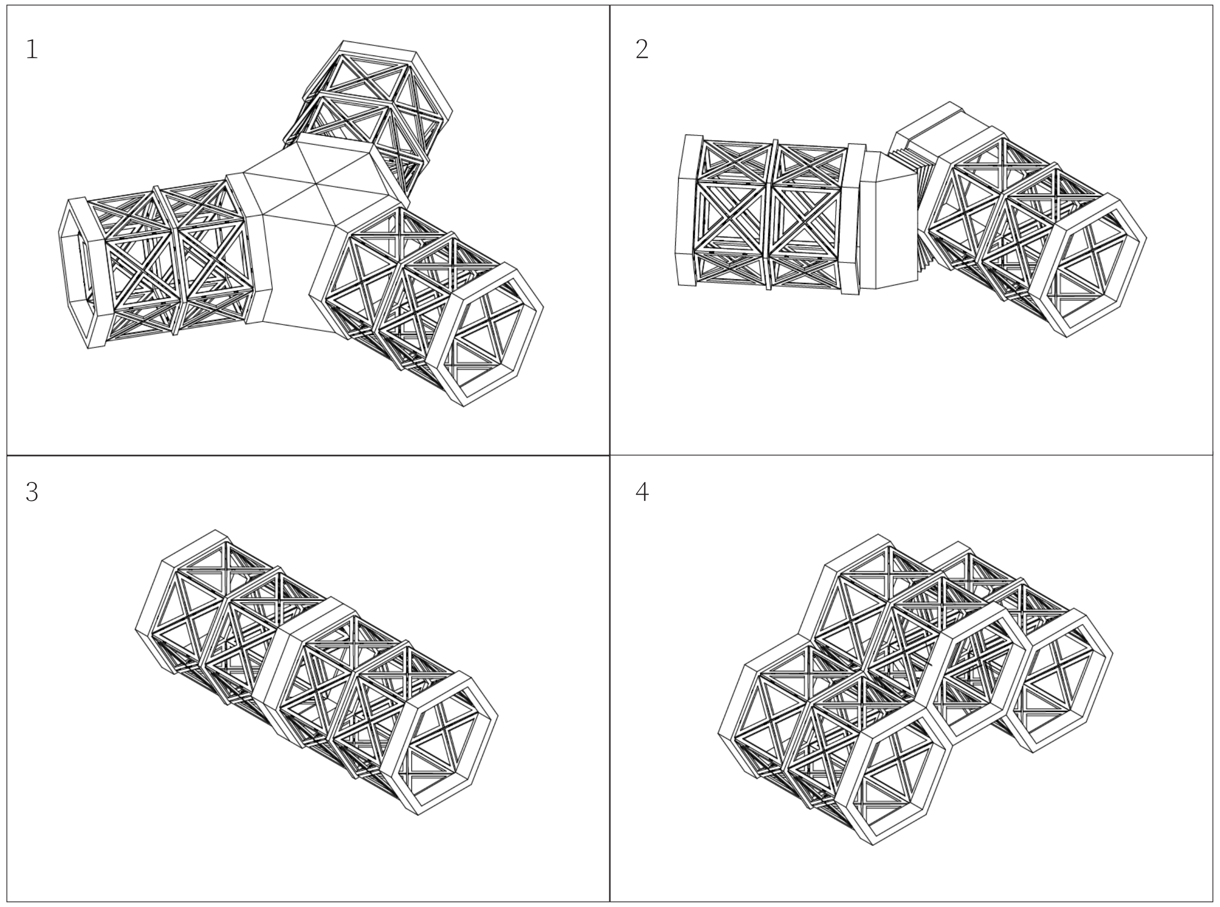
Figue 10 . Exploded view of basic unit.





03

Comparative Spatial Analysis



Figue 11 . Basic unit connection method.

Geometric Connection Method

Radial Hub Joint [1]

The Radial Hub Joint is a connectivity method centered around a hexagonal columnar node that radiates outward in multiple directions. By utilizing a stable geometric pivot, this joint organizes various functional modules under a single core structure, creating a cohesive spatial arrangement. This method enables multi-directional expansion within a limited footprint and establishes a clear spatial hierarchy. It allows for differentiated prioritization within the layout, effectively segregating functional areas while ensuring relative independence and accessibility for each unit.

Linear Extension Joint [3]

The Linear Extension Joint is a connectivity method that unfolds continuously along a single axis. Through the serialized assembly of repetitive units in one direction, it establishes a distinct spatial backbone and a continuous flow of movement. This approach emphasizes directionality and order, making it ideal for spatial organizations requiring clear functional workflows or hierarchical zoning, such as laboratory circulation or logistics corridors. Linear extension joints are highly scalable, allowing for modular expansion based on demand while maintaining the stability of structural logic and spatial order.

Angled Buffer Joint [2]

The Angled Buffer Joint facilitates spatial transition and environmental adaptation through angular shifts. By introducing an angled relationship between two units, this method creates a transitional zone with buffering properties. Its primary function is to respond to topographical variations, climatic conditions, and ecological boundaries. Compared to linear connections, angled joints offer superior adaptability and elasticity; they maintain structural continuity while regulating movement rhythms and spatial hierarchy, serving as a vital strategy for linking disparate functional zones or environmental interfaces.

Vertical Stack Joint [4]

The Vertical Stack Joint is a connectivity method that achieves spatial density and functional layering through vertical superposition. This method couples units vertically, creating a tiered relationship between different functions across different heights. Vertical stacking is particularly suited for scenarios with limited land availability or high-volume requirements—for example, placing utility spaces on lower levels with residential or observation spaces above. This approach not only optimizes land-use efficiency but also establishes a clear load-bearing path, serving as a key strategy for high-density deployment and structural stability.

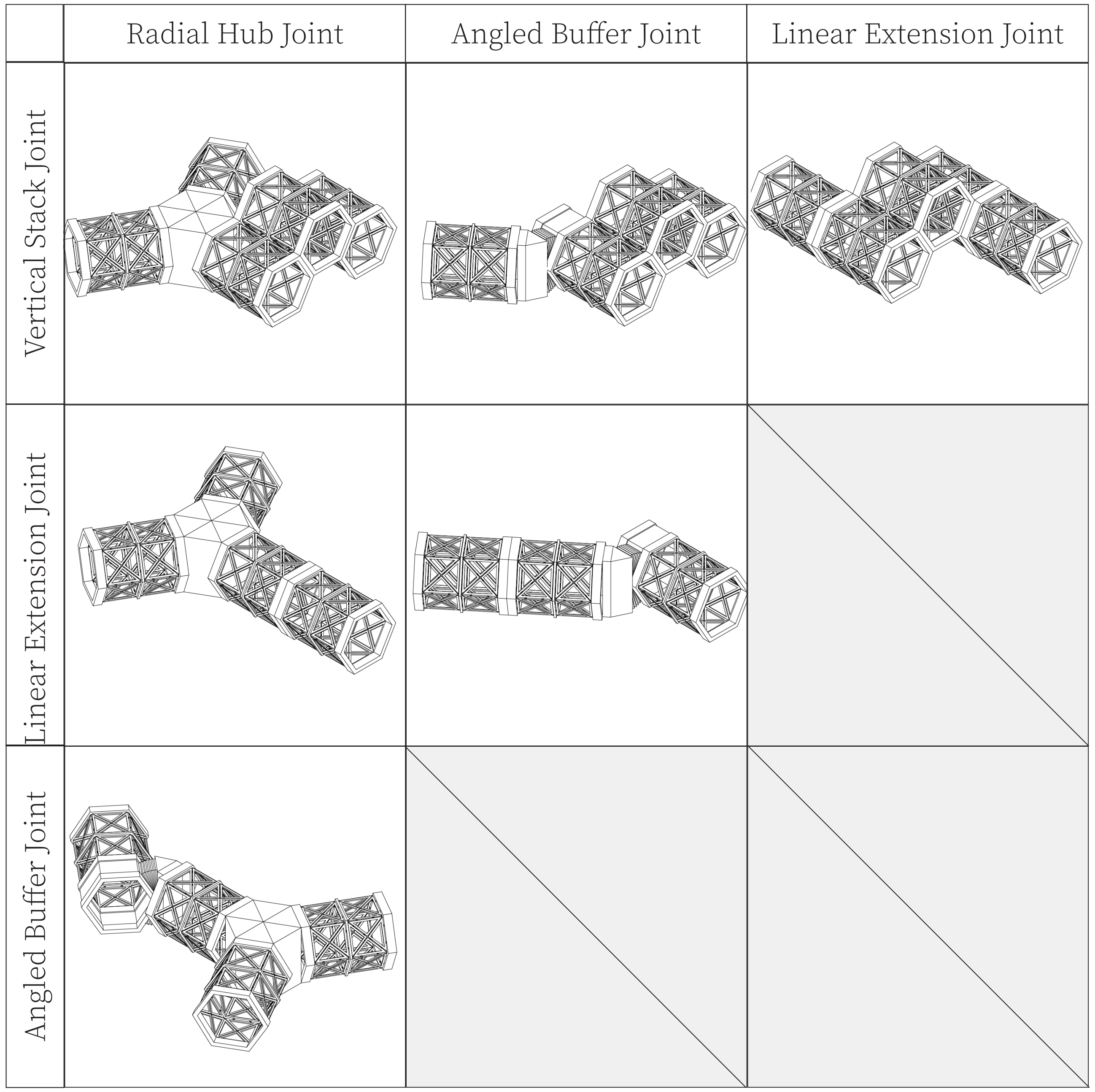


Figure 12 . Connection method combination.

Different Combinations

The pairwise combination of the four fundamental connectivity logics—Radial Hub Joint, Angled Buffer Joint, Linear Extension Joint, and Vertical Stack Joint—yields six composite modes characterized by distinct spatial organizational traits, which essentially represent the cross-dimensional synthesis of four core principles: spatial prioritization, procedural order, environmental adaptability, and spatial density.

Specifically, the integration of the Radial Hub and Angled Buffer establishes a "Hierarchical Core–Ecological Transition" structure that defines central functional hierarchies while softening boundaries through angular transitions, rendering the core space simultaneously cohesive and environmentally responsive.

The combination of the Radial Hub and Linear Extension constitutes a "Core-Driven Axial Order," where the hub anchors spatial hierarchy and centrality as linear units unfold along a primary axis to facilitate clear operational workflows, thus harmonizing social structures with functional sequences.

When the Radial Hub is coupled with the Vertical Stack, it generates a "Three-Dimensional Hierarchical Core" that superimposes vertical stratification onto planar aggregation, further partitioning the core space along the vertical axis to enhance both density and structural articulation.

Furthermore, the synthesis of the Angled Buffer and Linear Extension creates an "Environmentally Adaptive Sequential System," which maintains functional continuity while modulating spatial rhythm through angular shifts, ensuring that axial expansion remains elastic and topographically sensitive rather than rigid.

The pairing of the Angled Buffer and Vertical Stack forms a "Three-Dimensional Adaptive Framework," utilizing the synergy of planar angling and vertical stacking to provide a multi-dimensional response to complex site conditions, thereby enabling spatial regulation across both horizontal and vertical planes.

Finally, the Linear Extension and Vertical Stack together produce a "High-Efficiency Stratified Sequence" that reinforces axial logic with vertical functional zoning, preserving procedural clarity while optimizing spatial density and utilization efficiency. Collectively, these six combinations are not mere morphological overlaps but the dimensional coupling of four fundamental logics, constituting a generative, scalable, and adaptive spatial syntax.

Space Requirements for Research Stations

In extreme and fragile ecosystems—such as high-altitude wetlands, permafrost zones, and alpine lake-river systems—a research station should not be viewed simply as a collection of rooms. Instead, it should be defined as a highly integrated "micro-infrastructure" system that simultaneously supports knowledge production, life support, and small-scale community operations. Existing research on polar facilities shows that remote stations must function as self-sufficient, closed-loop systems encompassing scientific experiments, housing, energy, water treatment, logistics, and mental health support (National Science Foundation, 2012; COMNAP, 2017). Therefore, rather than using a traditional list of "labs, dorms, and canteens," this study adopts a systematic framework that divides spatial needs into five interconnected functional systems: the Scientific System, Habitation System, Technical & Infrastructure System, Logistic & Transition System, and Collective / Psychological System.

Specifically, the Scientific System includes labs, sample storage, and data analysis rooms, emphasizing technical stability such as temperature control and vibration resistance. The Habitation System covers sleeping units and living areas; its design must balance compact layouts with psychological comfort, as the right mix of privacy and social space is vital for residents in "ICE" (Isolated, Confined, and Extreme) environments (Palinkas, 2003). The Technical & Infrastructure System manages power, water, and waste, prioritizing fire safety and easy maintenance. The Logistic & Transition System consists of airlocks and storage platforms, serving as a thermal buffer against harsh external conditions. Finally, the Collective & Psychological System uses shared dining and viewing areas to build social networks and reduce the stress of isolation. Under the "Foldscape Habitat" framework, these five systems are not fixed zones within a single building but are translated into a network of foldable, deployable modules. Through a three-layer logic of "System–Module–Aggregation," functional requirements are turned into structural rules. This allows the architecture to respond to extreme environments while remaining reversible, mobile, and low-impact, providing a sustainable model for infrastructure in fragile regions.

Research Space

- Sample Pre-processing Room
- Cleanroom
- Data Analysis Room
- Data Center
- Observation Tower

Research support spaces are the heart of any scientific station, providing the steady and controlled environment needed for discovery. These areas handle everything from lab experiments and sample processing to data analysis and long-term monitoring. To work effectively, the layout must follow a "research workflow chain"—a seamless path from collecting and processing to analyzing and storing. This requires a smart design that strictly separates clean and dirty zones and keeps traffic paths organized to avoid cross-contamination.

Environmental stability is critical, requiring precise control over temperature, humidity, and air quality, as well as protection against vibrations and electromagnetic interference. Labs often need independent ventilation or negative pressure systems to stay safe, while server and instrument rooms require backup power, dust-proofing, and heavy-duty cooling. Finally, observation areas need wide, clear views but should be structurally isolated from the main station to remain quiet and stable for sensitive equipment.

Living System Space

- Sleeping Unit
- Dining Space
- Bathroom
- Medical / First Aid Space

Living support spaces are the backbone for researchers staying long-term. Their main goal is to keep everyone healthy and on a normal schedule, creating a "micro-living ecosystem" that can withstand extreme environments. Within a small footprint, these spaces must balance privacy with social areas, allowing individuals to recharge while keeping the team connected.

High standards for warmth, soundproofing, and hygiene are essential here. Sleeping quarters need to be quiet, dark, and well-insulated. Dining and common areas should feel open and catch as much light as possible. Bathrooms and clinics require waterproof, anti-bacterial materials and their own waste systems, while storage needs to stay dry and at a steady temperature. Ultimately, these spaces are all about staying warm, being durable, and feeling comfortable.

Energy and Ecosystem Space

- Energy Pod
- Water Treatment System
- Waste Sorting & Compaction Space
- Mechanical Equipment Room

Energy and ecological systems are the station's life support, built as a sustainable "technical ecosystem" for self-sufficiency. They handle power generation, water recycling, and waste treatment—the essentials for living off-grid. While these systems operate behind the scenes, they are the true foundation of the entire station.

Because they can be noisy and vibrate, these areas require heavy-duty structures and are usually separated from living and research zones. Power units must be fireproof and easy to access for repairs; water and waste systems need to be leak-proof and low-maintenance; and mechanical rooms require plenty of ventilation to stay cool. Ultimately, the focus here is on easy access, system backups (redundancy), and top-tier safety.

Communication Space

- Airlock Entrance
- Meeting / Remote Communication Space

Communication and exchange spaces act as the station's gateway to the outside world. They handle the flow of people moving in and out and serve as a hub for academic sharing and remote teamwork. In extreme environments, this area is more than just a room—it's both a protective shield and a lifeline for information and resources.

The entrance requires an airlock and a buffer zone to control temperature swings and prevent contamination. For remote meetings, the space needs rock-solid communication systems, great acoustics, and backup power. While these areas don't need to be huge, they must be perfectly airtight and highly technical, with clear paths to keep everyone safe and organized.

Community and Psychological Support Space

- Meditation Space
- Viewing Space
- Public Interaction Space

Community and psychological support spaces are vital for keeping a team healthy and stable during long stays. In isolated, high-pressure environments, these areas act as an emotional buffer and a place to recharge. They are more than just functional rooms—they are symbolic spaces that help people reconnect with nature, each other, and themselves.

These spaces prioritize natural light, wide views, and comfortable materials. An open feel and plenty of sunlight are essential to prevent the "boxed-in" feeling of a research station, while quiet and private zones help reduce stress. By using warm textures and slightly larger room scales, these areas provide a much-needed "breathing space" for mental well-being.

Assumptions on the Size of the Research Station Space

This chapter aims to construct an operational methodology for organizing the spatial functions of research stations, translating abstract functional classifications into a quantifiable, testable, and scalable design framework. The study takes three representative scenarios as analytical benchmarks—small-scale (10 people / 1,000 m²), medium-scale (30 people / 2,800 m²), and large-scale (80 people / 8,400 m²). Through a systematic decomposition of personnel structure, research intensity, logistical complexity, and shared public ratios, a generalized area allocation framework is established, encompassing the research core system, living support system, logistical support system, and shared public space. On this basis, standardized module lists and flexible area ranges are further developed, enabling proportional scalability and structural isomorphism across different station sizes rather than simple linear enlargement. This approach provides predictable spatial interfaces for future multidisciplinary integration and phased expansion.

At the level of spatial organization, the proposal introduces a longitudinal structural framework defined as "Front – Core – Back." The "front" zone accommodates external communication and transitional functions, including entrance airlocks and meeting or remote communication spaces. The "core" concentrates on primary research functions, organizing laboratories, data analysis, and observation systems within graded clean and safety zones. The "back" consolidates energy systems, water treatment, storage, and mechanical equipment into a low-interference operational band. In addition to this main axis, a relatively independent living wing is positioned laterally, forming a spatial configuration described as "three-part main axis + side living unit." This structure reinforces hierarchical functional zoning while ensuring strict physical separation among living activities, research operations, and logistical circulation through controlled interfaces and spatial distancing, effectively mitigating contamination risks and safety hazards caused by intersecting flows.

In terms of circulation strategy, the design employs both bubble diagrams and flow-line simulations to disaggregate and overlay personnel flow, sample flow, material flow, and waste flow. This layered analysis ensures separation or controlled intersection at critical nodes. Research circulation emphasizes clean–dirty segregation and unidirectional progression to prevent backflow; living circulation forms an independent loop to minimize disturbance to laboratory zones; logistical circulation is primarily organized along a peripheral ring to guarantee continuity and operational safety. Through this systematic modeling of circulation, the bubble diagram evolves beyond a mere representation of functional adjacency, becoming a visual instrument for expressing safety hierarchies and efficiency pathways.

Regarding spatial configuration, the study prioritizes single-story layouts whenever site conditions permit. A single-level arrangement shortens the transfer paths of experimental samples and observational data, reduces vibration and electromagnetic interference from vertical transportation systems, and minimizes the spatial loss associated with vertical fire compartments and service shafts, thereby improving spatial efficiency. When a fully single-story layout is not feasible, zoning by levels and structural separation are employed to control interference boundaries and maintain the stability of core laboratory environments. This principle of "single-story priority with stratified zoning as a secondary strategy" allows the building to balance operational efficiency with practical constraints.

Module	Number of People	Use Frequency Assumptions	Suggested Area (m²)	Area Percentage	Expected Number of Units
Airlock & Entrence	8	Daily	20	2. 41%	1
Office/Research Workspace	10	6–10 Hours Daily	70	8. 43%	5
Meetings	10	2–5 Times Per Week	35	4. 22%	3
Laboratory	4	4–8 Hours Daily	100	12. 05%	7
Sample Receiving and Processing	3	Depending on the Sampling Batch	45	5. 42%	3
Sample Storage/Cold storage	1	Daily Short-term + 24-Hour Continuous Operation	35	4. 22%	3
Experimental Support/Decontamination and Waste	2	Daily	35	4. 22%	3
Living Area (Kitchen/Dining Area/Rest Area)	10	Daily	90	10. 84%	6
Dormitory	10	Nighttime Permanent Residence	90	10. 84%	6
Toilet/Shower	3	Daily	30	3. 61%	2
Logistics/Unloading & General Warehousing	2	Weekly	55	6. 63%	4
Vehicle/Equipment Maintenance	2	Weekly	70	8. 43%	5
Safety and Emergency	2	Duty + Event Triggering	20	2. 41%	1
Sustainable Systems (Energy/Water Treatment)	1	Daily Inspection	45	5. 42%	3
Equipment/Computer Room	1	Daily Inspection	90	10. 84%	6

Small-scale Research Station

Scale: 10 permanent residents (typically composed of 6–7 researchers and 2–3 technical/logistics/driver-maintenance personnel, with possible seasonal rotation).

Operational Characteristics: Field sampling and short-cycle sample processing coexist. The logistical "base-load cost" is relatively high, as power generation, water treatment, maintenance, and storage functions account for a larger proportional share in small-scale stations. This aligns with the operational requirements of field observation research stations, which must be equipped with supporting facilities such as on-site power plants, water treatment units, and storage spaces for daily and technical supplies.

Module	Number of People	Use Frequency Assumptions	Suggested Area (m²)	Area Percentage	Expected Number of Units
Airlock & Entrence	15	Daily	30	1. 35%	2
Office/Research Workspace	25	6–10 Hours Daily	200	8. 99%	14
Meetings	30	2–5 Times Per Week	100	4. 49%	7
Laboratory	10	4–8 Hours Daily	300	13. 48%	21
Sample Receiving and Processing	6	Depending on the Sampling Batch	100	4. 49%	7
Sample Storage/Cold storage	2	Daily Short-term + 24-Hour Continuous Operation	100	4. 49%	7
Experimental Support/Decontamination and Waste	4	Daily	110	4. 94%	8
Living Area (Kitchen/Dining Area/Rest Area)	30	Daily	240	10. 79%	17
Dormitory	30	Nighttime Permanent Residence	260	11. 69%	19
Toilet/Shower	10	Daily	90	4. 04%	6
Logistics/Unloading & General Warehousing	8	Weekly	150	6. 74%	11
Vehicle/Equipment Maintenance	4	Weekly	160	7. 19%	11
Safety and Emergency	3	Duty + Event Triggering	45	2. 02%	3
Sustainable Systems (Energy/Water Treatment)	2	Daily Inspection	120	5. 39%	9
Equipment/Computer Room	3	Daily Inspection	220	9. 89%	16

Medium-scale Research Station

Scale: 30 permanent residents (with clearer division of roles among research, technical, and logistics staff).

Operational Characteristics: Sample processing and laboratory activities become routine and institutionalized. Demand for academic and office space increases. Unloading, storage, and vehicle maintenance can be organized into a more clearly defined back-of-house service chain. According to research building design standards, office areas may be arranged either independently or in mixed configurations; however, mixed layouts must prevent mutual interference and implement appropriate contamination control measures. Also, efficient connectivity among research spaces is emphasized.

Module	Number of People	Use Frequency Assumptions	Suggested Area (m²)	Area Percentage	Expected Number of Units
Airlock & Entrence	30	Daily	50	2. 25%	4
Office/Research Workspace	60	6–10 Hours Daily	550	24. 72%	39
Meetings	60	2–5 Times Per Week	350	15. 73%	25
Laboratory	25	4–8 Hours Daily	1000	44. 94%	71
Sample Receiving and Processing	12	Depending on the Sampling Batch	350	15. 73%	25
Sample Storage/Cold storage	3	Daily Short-term + 24-Hour Continuous Operation	250	11. 24%	18
Experimental Support/Decontamination and Waste	10	Daily	300	13. 48%	21
Living Area (Kitchen/Dining Area/Rest Area)	80	Daily	700	31. 46%	50
Dormitory	80	Nighttime Permanent Residence	900	40. 45%	64
Toilet/Shower	25	Daily	250	11. 24%	18
Logistics/Unloading & General Warehousing	15	Weekly	450	20. 22%	32
Vehicle/Equipment Maintenance	8	Weekly	400	17. 98%	29
Safety and Emergency	6	Duty + Event Triggering	120	5. 39%	9
Sustainable Systems (Energy/Water Treatment)	5	Daily Inspection	400	17. 98%	29
Equipment/Computer Room	8	Daily Inspection	700	31. 46%	50

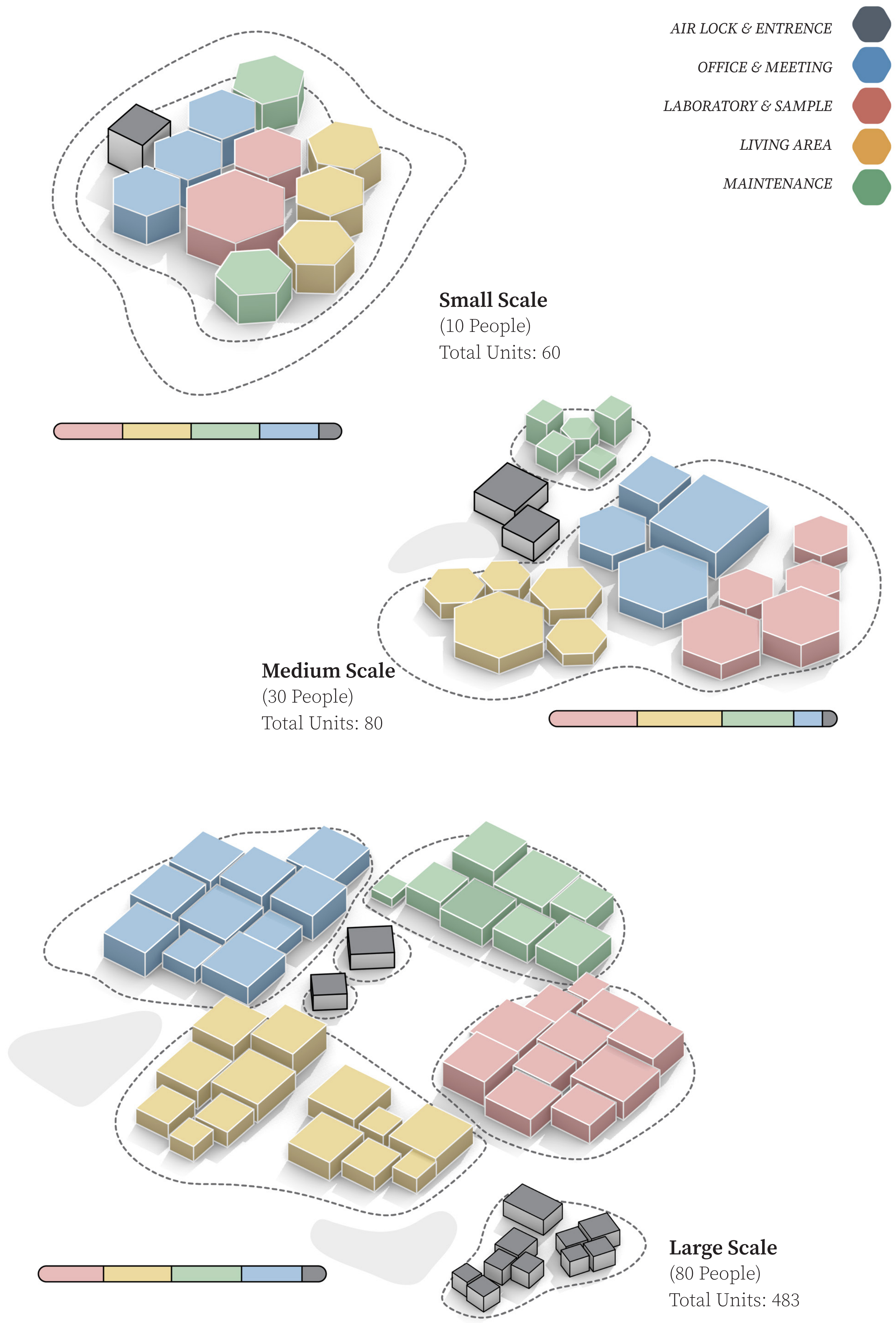
Large-scale Research Station

Scale: 80 permanent residents (with a higher degree of specialization across research teams, technical platforms, logistics, and security personnel).

Operational Characteristics: Research functions are more likely to adopt a combined configuration of “general laboratory areas + specialized laboratory/instrument platforms” (for example, dedicated spaces requiring cleanroom conditions, constant temperature and humidity control, vibration isolation, etc.). Greater emphasis is placed on the stability and reliability of both the sample chain and the data chain throughout the research process.

Comparison of the Three

By comparing the spatial assumptions for small-, medium-, and large-scale research stations, it can be seen that as the number of residents and the intensity of research activities increase, the suggested area and expected number of units for each functional module also grow accordingly. At the same time, the overall spatial composition remains highly consistent across all three scales. First, spaces related to experimentation, living, and daily work support always form the main body of the research station. Among them, the Laboratory, Office/Research Workspace, Living Area, and Dormitory occupy relatively large proportions in all three cases, showing that, regardless of scale, the core of a research station is always organized around the three basic needs of research, work, and living. Second, supporting spaces such as sample receiving, cold storage, decontamination and waste handling, equipment rooms, and energy and water treatment remain consistently present in all three scales, even though they serve fewer users directly. This suggests that these spaces do not change only in proportion to the number of occupants, but are also shaped by the continuity of research activities, environmental control requirements, and the operational logic of infrastructure systems. Third, in terms of development across scales, the small research station places more emphasis on the compact integration of basic living and essential research functions; the medium-scale station begins to show clearer functional differentiation; and the large-scale station further strengthens laboratories, logistics, storage, and equipment maintenance, reflecting a higher degree of specialization and systemization. Overall, the three sets of data indicate that the spatial organization of research stations is based on a relatively stable functional framework, including entrance buffering, research and office space, experimental processing, living support, logistics, and infrastructure systems. The main differences between the three scales lie not in changes to the spatial types themselves, but in the expansion of area, the increase in unit numbers, and the greater degree of functional differentiation within each system.



Figue 13 . Spatial Type Proportion Analysis Chart.

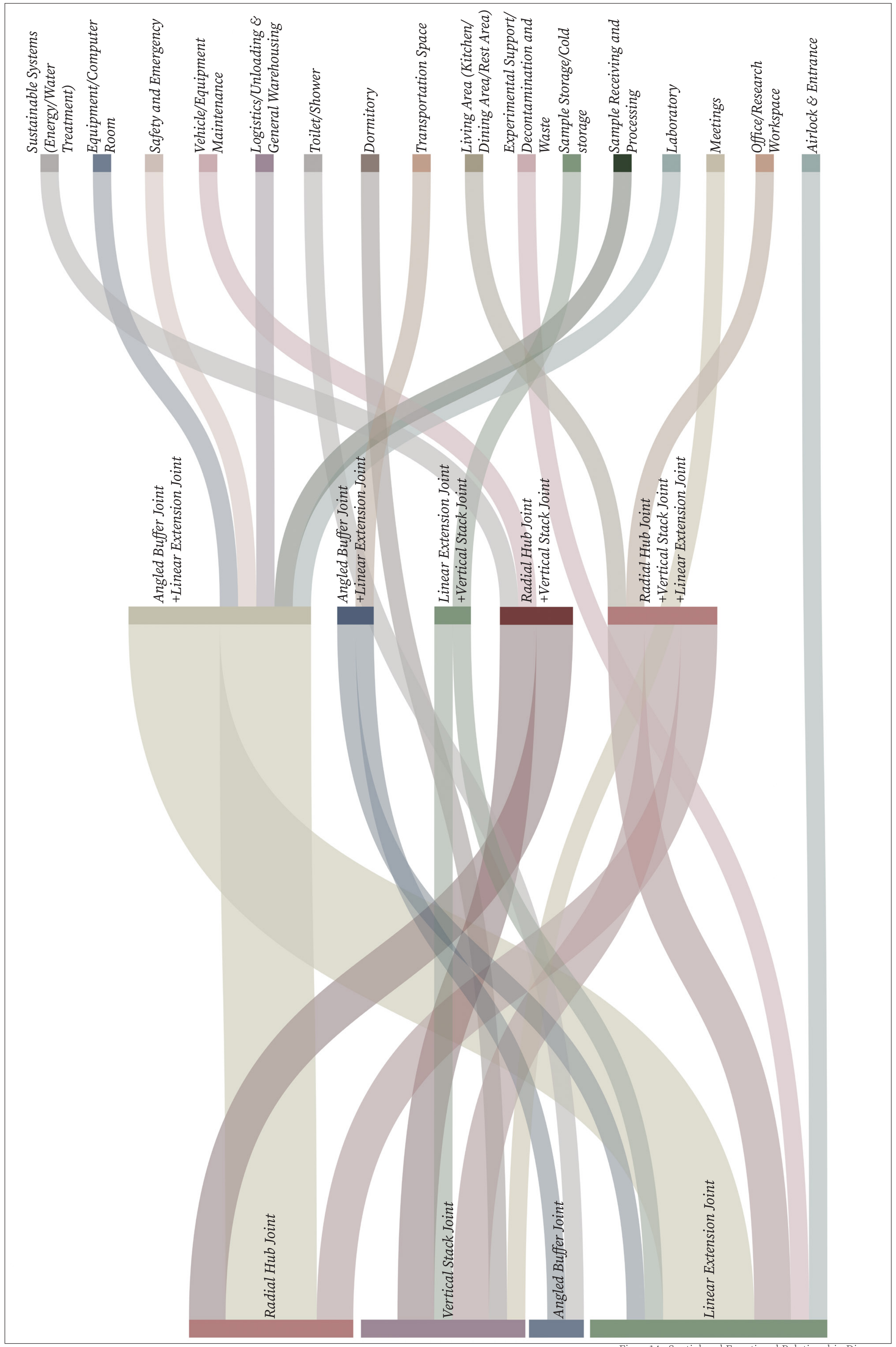


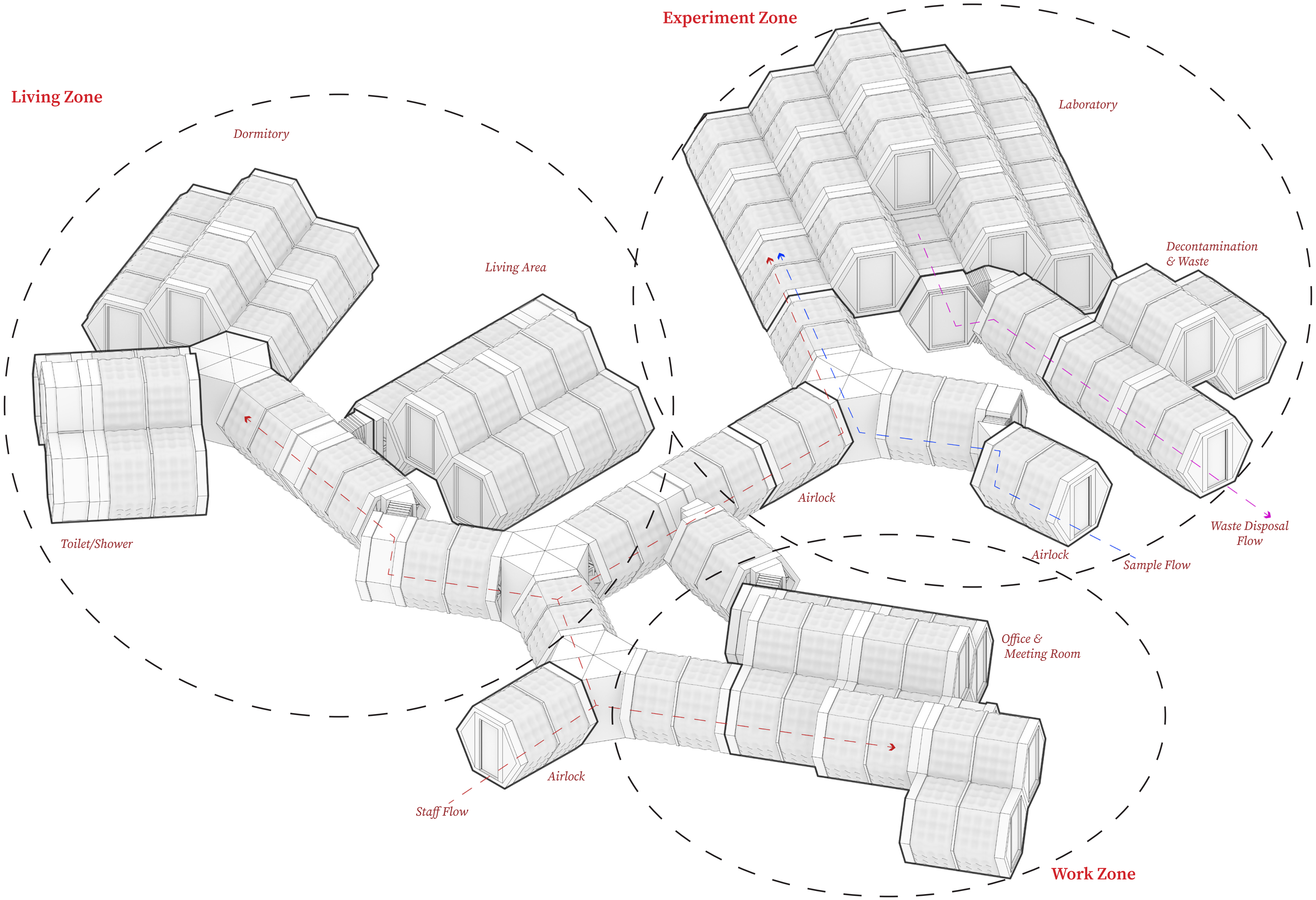
Figure 14 . Spatial and Functional Relationship Diagram.

From Module to Community

The transition from a single module to a complete community is not merely a quantitative accumulation, but a systematic evolution driven by structural logic, functional relationships, and environmental adaptability. In the earlier stages of the research, the module was defined as a fundamental unit with clearly articulated structural boundaries, environmental strategies, and interface logic, capable of operating independently. However, when the scale of inquiry shifts from the individual unit to the collective, the core design question is no longer how a single module performs in isolation, but how multiple modules can form an integrated whole through functional coordination, spatial hierarchy, and resource sharing.

Based on a comparative analysis of research communities of different scales, this study focuses on the small research stations as the primary framework for community construction. This scale avoids the organizational complexity inherent in large-scale base systems, while also moving beyond the isolation of single facilities. Within a limited footprint, it enables the establishment of a clear functional network and spatial order. The small research stations must balance living spaces, research activities, public interaction, energy systems, and ecological infrastructure; therefore, their community structure emphasizes logical interconnections between modules rather than mere expansion in size.

In terms of strategy, different functional categories are mapped onto corresponding module types, and differentiated aggregation methods are employed to construct spatial hierarchies. High-frequency shared functions form central clusters; living and resting units are connected through buffering elements to maintain relative independence; and energy and ecological support systems constitute a peripheral infrastructural layer. Through connective nodes and organized circulation paths, modules establish a networked relationship that transforms the space from a collection of units into a coordinated functional system. In this process, modularity transcends its role as a construction method and becomes a structural framework for organizing social relations, research collaboration, and environmental responsiveness.

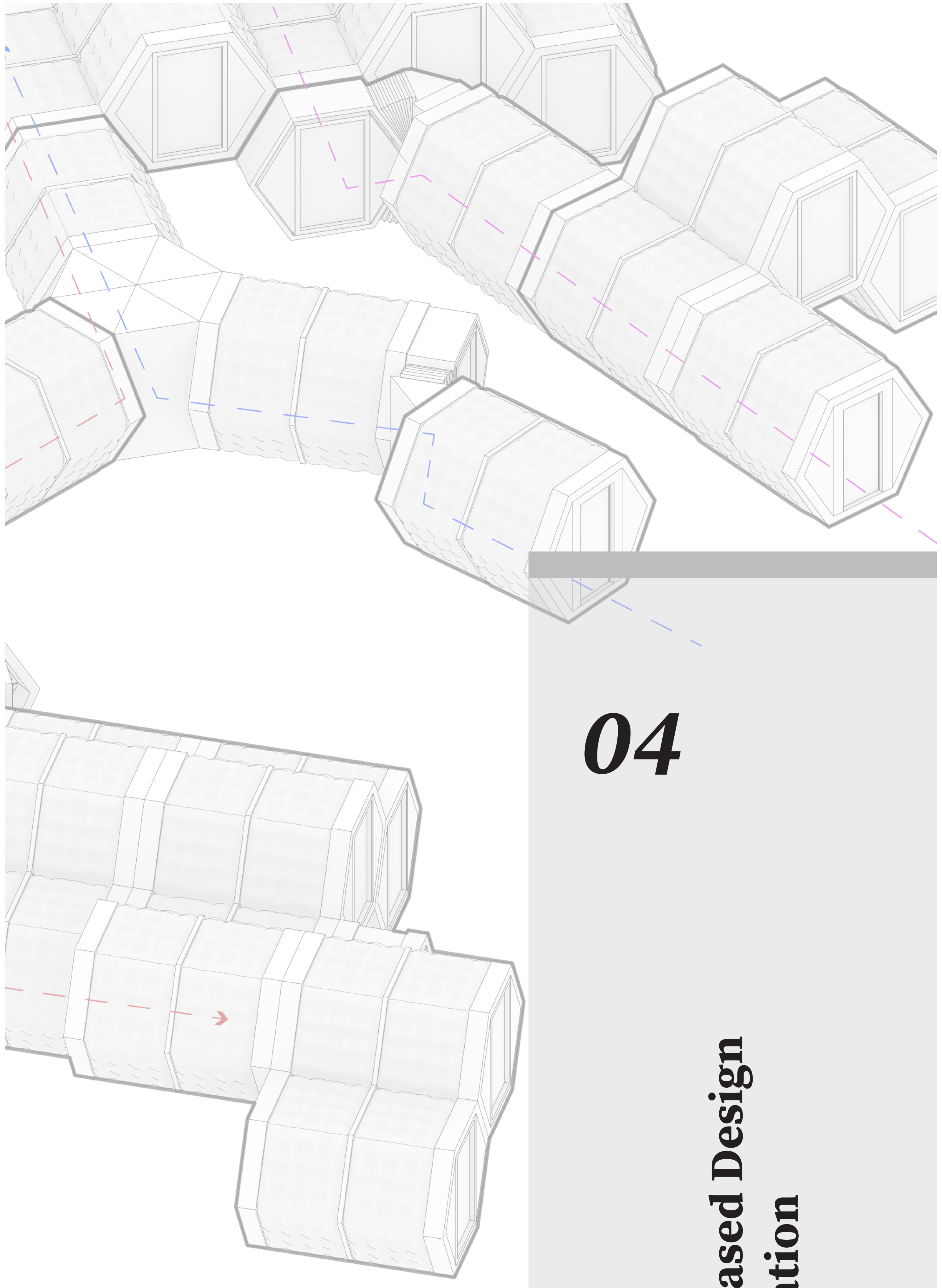


Figue 15 . Space and Flow of Small Research Station.

Small Research Station Space & FLow

From the diagram, the spatial organization of a small research station can be summarized into three clearly defined functional zones: the Work Zone, the Experiment Zone, and the Living Zone. The Work Zone mainly supports daily administration, data processing, and team coordination, including offices and a meeting room. The Living Zone provides essential facilities for long-term stay, such as sleeping units, a dining area, and bathrooms/ showers. The Experiment Zone is used for sample handling and laboratory work, and it also includes areas for contamination control and waste management to reduce the risk of cross-contamination.

Based on this zoning, the operational efficiency of the station is largely shaped by three types of circulation: staff flow, sample flow, and waste disposal flow. Staff circulation should support frequent movement between "living–work–experiment" while avoiding contamination-control areas whenever possible. Sample circulation should allow samples to enter from the sampling entrance and reach pre-treatment and laboratory spaces quickly, with clear transitions between "clean" and "non-clean" conditions at key points. Waste and contaminated material circulation should remain physically and logically separated from both staff and sample routes, forming a closed path from the points of generation to centralized temporary storage and treatment. In this way, safety boundaries and operational boundaries can be established consistently through spatial layout. Overall, the overlap of the three zones and the three circulation systems forms a basic organizational framework that enables both efficient collaboration and effective contamination control within a compact station.



04

Site-based Design Validation

Prototype Alternative Address

Qinghai-Tibet Plateau, China

Known as the "Roof of the World," the Tibetan Plateau sits at an average altitude of over 4,000 meters, characterized by extreme cold, sharp day-night temperature swings, intense UV rays, and vast permafrost. Because its ecosystem is so fragile and sensitive to human activity, traditional heavy construction can easily disrupt the thermal balance and cause the frozen ground to degrade. This makes the region an ideal testing ground for lightweight, low-impact, and reversible architectural prototypes. Specifically, foldable structures can minimize ground disturbance and use elevated systems to reduce heat transfer, while integrated solar power allows for off-grid living. Given the region's importance for climate and ecological research, there is a real demand for mobile research stations and seasonal housing, providing a perfect real-world application for these portable, eco-friendly designs.

Lapland Region, Sweden

Located within the Arctic Circle and spanning northern Finland, Sweden, and Norway, Lapland is defined by long winters, polar nights, and extreme cold. While the population is sparse, the region is active with Arctic research, eco-tourism, and indigenous reindeer herding. Building permanent structures here is tough due to high energy use, short construction windows, and expensive transport. Foldable prototypes offer a smart solution: they can be shipped in modules and deployed quickly, minimizing damage to the fragile tundra. By using high-performance insulation and adjustable shapes, these buildings can adapt to the changing seasons. These reusable, lightweight systems are perfect for Northern Lights viewing, research camps, and low-impact tourism. As a prime example of Europe's high-latitude cold zones, Lapland is the ideal place to test these prototypes within a developed infrastructure.

Western Sichuan Plateau, China

Located on the eastern edge of the Tibetan Plateau, the Western Sichuan Plateau features a mix of high-altitude meadows, deep canyons, and active seismic zones. As the source of the Yangtze and Yellow Rivers, this ecologically fragile area is critical for hydrological research, but its complex terrain means foundations are often unstable. Because heavy construction could trigger a "butterfly effect" that damages the river systems, foldable and mobile architectural prototypes are an ideal solution. These lightweight structures reduce seismic impact and easily adapt to steep, irregular slopes without disturbing the soil. Whether used for post-disaster housing, eco-tourism stops, or research outposts, this region serves as a vital testing ground for how adaptable architecture can perform in a complex natural and social environment.

Antarctic Peninsula

The Antarctic Peninsula is a global hotspot for both climate change and international research. With its extreme cold, fierce winds, and icy terrain, traditional buildings here are energy-intensive and must follow strict international treaties that demand a "leave no trace" approach. This makes the region a perfect match for foldable, mobile architectural prototypes. These lightweight modules can be easily transported by ship or air, drastically reducing onsite construction time and allowing for total removal after a mission. Ultimately, the peninsula serves as the most rigorous testing ground to verify the structural stability, thermal performance, and energy self-sufficiency of these designs under the harshest conditions on Earth.

Current Site Selection Conditions and Problems

In the context of extreme environments, the site selection for research stations and deployable modular architectures is not driven by any single factor; rather, it is the result of a multi-variable coupling of environment, geology, climate, logistics, and policy frameworks.This issue extends beyond mere spatial positioning—it is fundamentally concerned with structural safety, long-term operational stability, and institutional feasibility. Site selection under extreme conditions exhibits distinct multi-scale and multi-system interlaced characteristics, necessitating a systematic analysis across four critical dimensions: natural environment, geological stability,logistics accessibility, and governance frameworks.

Natural Environment

First, natural hazards are the primary limit. Extreme cold, strong winds, heavy snow, and permafrost put huge pressure on building structures and materials. To prevent materials from becoming brittle or losing heat, these environments require high-quality insulation and freeze-resistant designs. At the same time, wind vibrations and ice loads constantly threaten the stability of the structure. In high-altitude or polar regions, temperature swings and freeze-thaw cycles also affect the durability of joints and the efficiency of energy systems. Therefore, site selection must evaluate environmental loads and material needs from the start, rather than trying to fix problems later in the design process.

Furthermore, the combination of isolation and extreme weather significantly increases the cost of maintenance and supplies. This makes every risk more dangerous. Because of this, choosing the right location is actually the first and most important step in controlling risk.

Geological Stability

Second, geological stability determines if the building and its foundation will work. Factors like soil stability, earthquakes, landslides, slopes, and groundwater all affect how the ground supports the building's weight.

In permafrost (frozen ground) areas, the strength of the ground and the risk of "frost heave" (ground swelling) are very important. Research shows that as permafrost melts, the ground can lose 20% to 45% of its strength. This also changes how the building vibrates and reacts to movement, which makes it less safe.

Because of this, picking a site isn't just about looking at the ground today. You must also predict how climate change will melt the permafrost in the future. Even local plants and bacteria can change how the soil holds heat, which indirectly affects stability. In short, geological safety is not a "one-time" check—it is a dynamic process that changes over time.

Logistics Accessibility

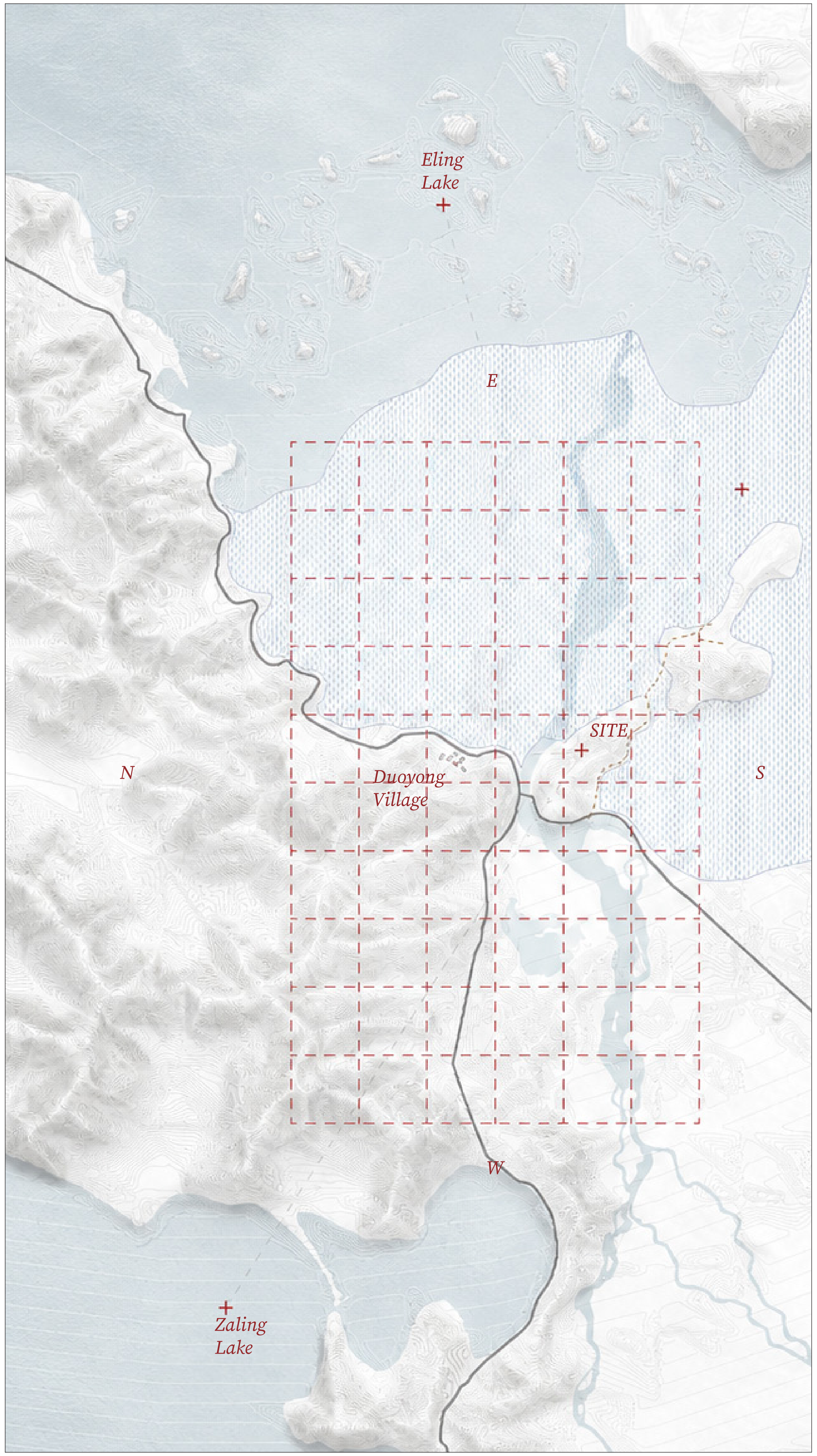
Third, logistics and operations create real-world limits in extreme areas. Because the construction season is very short, transport routes are limited, and getting supplies is difficult, choosing a site depends heavily on logistics. For example, the weight limits of helicopters or the need to coordinate many teams means that logistics must be part of the site-selection plan from the very beginning, not just something to think about during construction.

Because of these challenges, modular and prefabricated designs are the best solution. By building parts in a factory and shipping them in containers, we can finish work on-site much faster. This reduces the need for a long "construction window" and makes setup more efficient. Using modular hubs that aim for zero emissions and self-sufficiency also makes the station more independent. This reduces the need for constant outside supplies and makes the whole system much stronger.

Policy & Governance Framework

Beyond nature and engineering, policy and governance create the "hard boundaries" for a project. For example, environmental rules under the Antarctic Treaty or the shared rules between countries in the Arctic affect everything. Laws regarding how modular buildings are transported, put together, and permitted also change the project's timeline and how it is run.

Because these rules often decide how big a project can be or how long it can stay active, they must be studied during the site-selection phase. Ignoring these laws early on can lead to delays or even stop the project entirely.



Figue 16 . Site analysis diagram.

Design Proposal Site

Origin of the Yellow River

This study ultimately selected the Origin of the Yellow River region as the site for design validation. Located within the core environment of the Yellow River source area, this region has a strong geographical identity and high ecological sensitivity. It carries important natural and cultural value, while also presenting a practical need for scientific research and ecological monitoring in alpine environments. The site is surrounded by lakes and wetland systems, which provide a real and complex natural context for environmental observation, sample collection, ecological response studies, and site-adaptive design. At the same time, the selected location is close to a regional road and maintains a certain connection with the only nearby village, making transportation, logistical supply, and basic operation possible under remote conditions. Overall, the site achieves a good balance among ecological representativeness, research demand, landscape character, and basic accessibility, and was therefore chosen as the final validation site for the prototype design in this study.

Site Selection Rationale

During the early stage of site selection, this study focused on several key conditions required for research stations in alpine regions, including ecological sensitivity, scientific representativeness, environmental complexity, and basic accessibility. The Origin of the Yellow River region responds well to these criteria. First, the area is located within an important ecological environment of the Yellow River source region, with diverse landscape types such as plateau lakes, wetlands, and alpine meadows. These conditions provide a strong spatial basis for long-term environmental monitoring, sample collection, and ecological research. Second, compared with extremely inaccessible areas, this site retains strong environmental representativeness while still allowing a certain degree of transport connection and logistical support, making it more suitable as a validation setting for the prototype design.

In addition, the relationship between natural elements and traces of human activity around the site forms a boundary that is relatively clear yet sensitive. On the one hand, the lakes and wetlands create an ecological ground that must be respected and protected. On the other hand, the presence of roads and a nearby village indicates that the area is not completely isolated, but rather exists in a condition that is accessible, yet should be approached with caution. This characteristic is highly consistent with the foldable architectural strategy proposed in this study, which emphasizes light intervention, deployability, and low environmental disturbance. For this reason, the region is not only a geographical site choice, but also an important context for testing whether the design method can truly work.

Site Characteristics

The most distinctive feature of this site is its combination of natural sensitivity and practical supporting conditions. In terms of the natural environment, the surrounding lakes and wetland systems indicate a high ecological value, while also introducing more complex environmental constraints, such as changing ground-bearing conditions, hydrological influence, seasonal freeze–thaw cycles, and stricter requirements for limiting ecological disturbance. These factors mean that the architectural design cannot remain only at the level of form, but must respond directly to the relationships among topography, climate, and the ecological system.

From the perspective of implementation, the nearby road provides a basic possibility for module transportation, construction access, and later maintenance, while the presence of the only nearby village suggests a certain level of support in material supply, short-term staff stay, and local cooperation. Such limited but essential supporting conditions are especially important for research stations in alpine regions. They reduce the very high implementation cost of a completely isolated site, while still preserving the remoteness and research authenticity of the location. This makes the site a suitable place for testing how the prototype could be applied in reality.

Relationship Between Design and Site

Placing the design prototype in the Origin of the Yellow River region for validation is not only about choosing a site with symbolic meaning. More importantly, it allows the study to test the adaptability of the foldable architectural system in a real alpine environment. The wetlands and lakes on the site require the building layout to remain cautious and controlled, so as to avoid excessive disturbance to the fragile ecological ground. At the same time, the presence of roads and a nearby village indicates that the design must also consider transport logic, deployment routes, and forms of logistical organization. In this sense, the site is not simply a background for the design, but an active factor that helps shape the architectural system itself.

Therefore, the design validation on this site focuses on three main aspects. First, it examines how the building can adapt to the edge condition of an alpine wetland environment through a lightweight and deployable form. Second, it tests how the modular system can achieve relatively efficient deployment by making use of existing roads and supply conditions. Third, it explores how spatial organization can create a balance among scientific research, human habitation, and ecological protection. In this way, site selection is no longer only a case description, but becomes a central basis for evaluating the feasibility of the proposed design strategy.

Deployment Process: From Transportation to Full Assembly

The construction logic of this project does not rely on a conventional on-site building process. Instead, it is based on a light-intervention deployment system that combines off-site prefabrication, compact folded transportation, and rapid on-site assembly. Its primary aim is to reduce disturbance to fragile environments, improve transportation and construction efficiency in remote areas, and respond to the constraints of ecologically sensitive sites through a reversible building strategy. Accordingly, the overall assembly process can be understood as a continuous sequence consisting of factory prefabrication, transportation to the site, site positioning, foundation intervention, module unfolding, structural connection, envelope assembly, and system commissioning.

Prefabrication and Pre-Departure Preparation

The primary components and systems of the building are first prefabricated within a factory environment. Unlike conventional construction, which often relies on extensive on-site fabrication and assembly, this proposal emphasizes the off-site integration of folded structural units, envelope components, insulation layers, and selected functional modules. This strategy improves construction precision and reduces uncertainties during site operations. By shifting complex processes into a controlled factory environment, the on-site implementation of the project is transformed from a process of construction into one of deployment, thereby significantly enhancing efficiency.

At this stage, the modules are not only structurally fabricated but also pre-integrated with selected energy, water, drainage, and equipment interface systems in order to ensure continuity during later assembly. At the same time, each module must be assigned a clear coding system and installation sequence to support unfolding, positioning, and connection after arrival on site. Before departure, folding tests, joint verification, and interface testing should also be conducted to ensure the reliability of the system throughout transportation and deployment. This prefabrication logic not only minimizes on-site errors but also establishes the basis for future reuse and standardized expansion.

Transportation to the Site

After prefabrication, the building modules enter the transportation stage in their folded configuration. This compact folded form significantly reduces the volume of each unit, increases transportation efficiency, and decreases reliance on heavy transport equipment and high-standard road infrastructure. This feature is particularly important for remote areas or sites with limited infrastructural capacity, as it enables the building system to be transferred and deployed across regions under relatively modest logistical conditions.

In selecting transportation routes, preference should be given to existing roads, previous construction traces, or paths associated with minimal disturbance, so as to avoid creating new compacted surfaces or zones of mechanical intervention in sensitive landscapes. In ecologically fragile environments, transportation itself already constitutes the first layer of site impact. Therefore, the transportation strategy is concerned not only with how the modules arrive, but also with how they arrive through the lowest possible level of intervention. In cases where heavy machinery cannot access the site directly, the modules may also be transferred over short distances through light lifting equipment, towing devices, or manual assistance, thereby enhancing the adaptability of the system to complex terrain and environmental conditions.

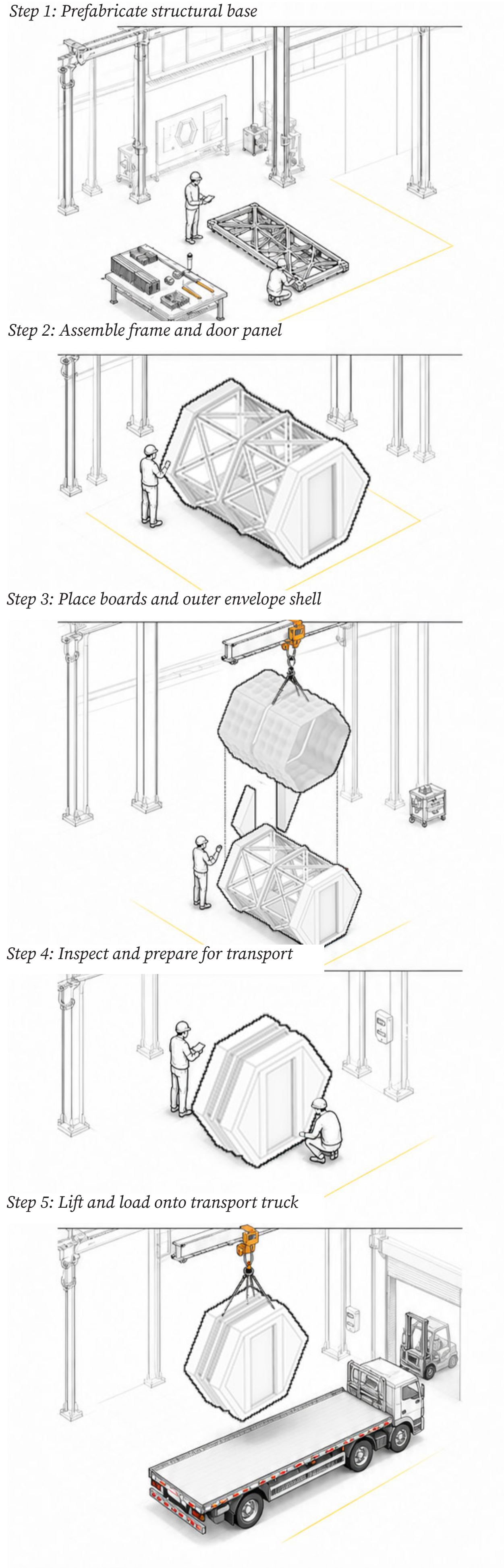


Figure 17 . Setup steps 1.

Site Arrival and Positioning

After the modules arrive on site, the building process does not immediately proceed to the unfolding stage. Instead, it begins with site confirmation and positioning. This process includes the reassessment of topographic slope, drainage direction, wind exposure, landscape orientation, and ecologically sensitive areas, ensuring that the arrangement of the building system genuinely responds to site conditions. Since this design concerns not only the deployment of individual modules but also the spatial relationships among multiple modules across the site, the positioning stage plays a critical role in aligning the architectural organization with the characteristics of the natural environment.

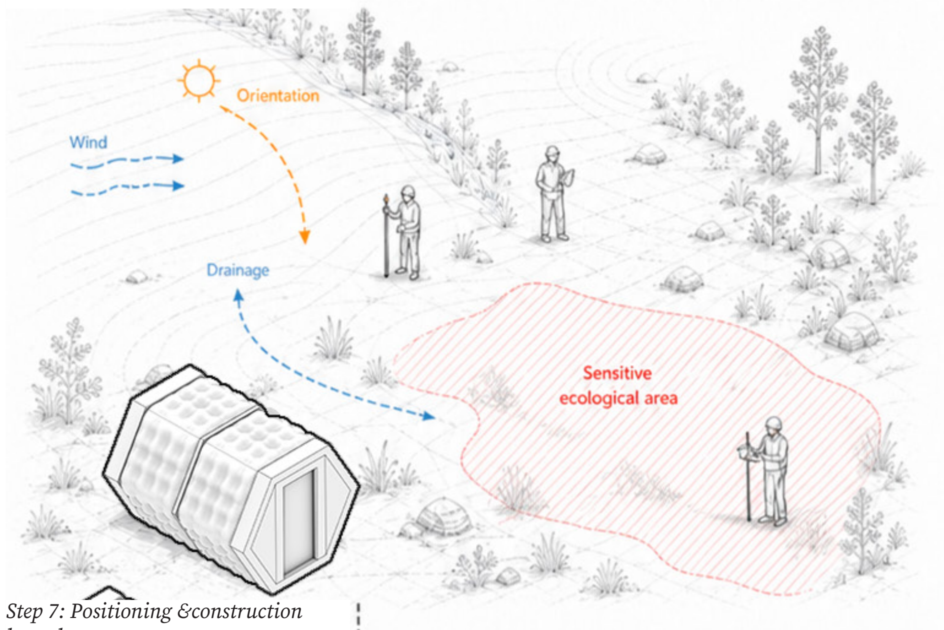
At the same time, site positioning must define the precise locations of point supports, module connection nodes, and temporary construction boundaries in order to control the spatial extent of intervention. By limiting construction activities to the minimum necessary area, the uncontrolled spread of people, equipment, and materials across the site can be effectively avoided, thereby reducing continuous disturbance to the existing ground surface, vegetation, and micro-topographic systems. In fragile ecological settings, this sequence of positioning before intervention reflects a more refined and low-expansion deployment logic.

Foundation and Point-Support Installation

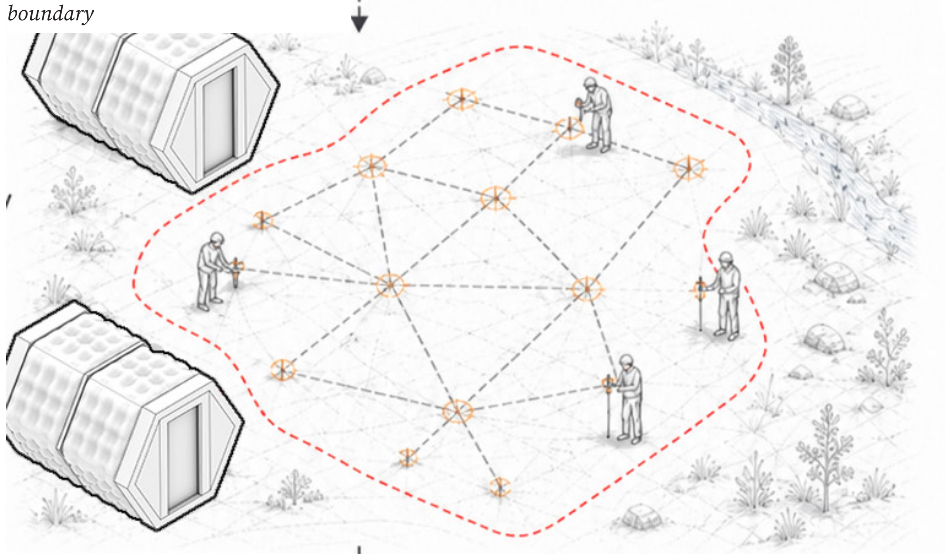
Once the overall position has been determined, the building establishes a relationship with the ground through minimal contact rather than through the large continuous footprint typical of conventional construction. Accordingly, the foundation stage does not aim for extensive excavation or complete ground hardening. Instead, it adopts reversible point-support systems, such as screw piles, micro-piles, or isolated support pedestals, in order to provide the necessary bearing capacity and leveling conditions for the upper modules while minimizing disturbance to the ground surface.

The significance of the point-support system lies not only in reducing the scale of foundation work, but also in elevating the relationship between building and ground, thereby alleviating the building's long-term impact on existing landforms, hydrological processes, and fragile surface systems such as permafrost or wetlands. On sites with uneven terrain or significant local differences in bearing capacity, local adaptation can be achieved by adjusting support heights and connection bases, without requiring large-scale grading. This approach further reinforces the "light-touch" character of the project and preserves the technical possibility of future disassembly and removal.

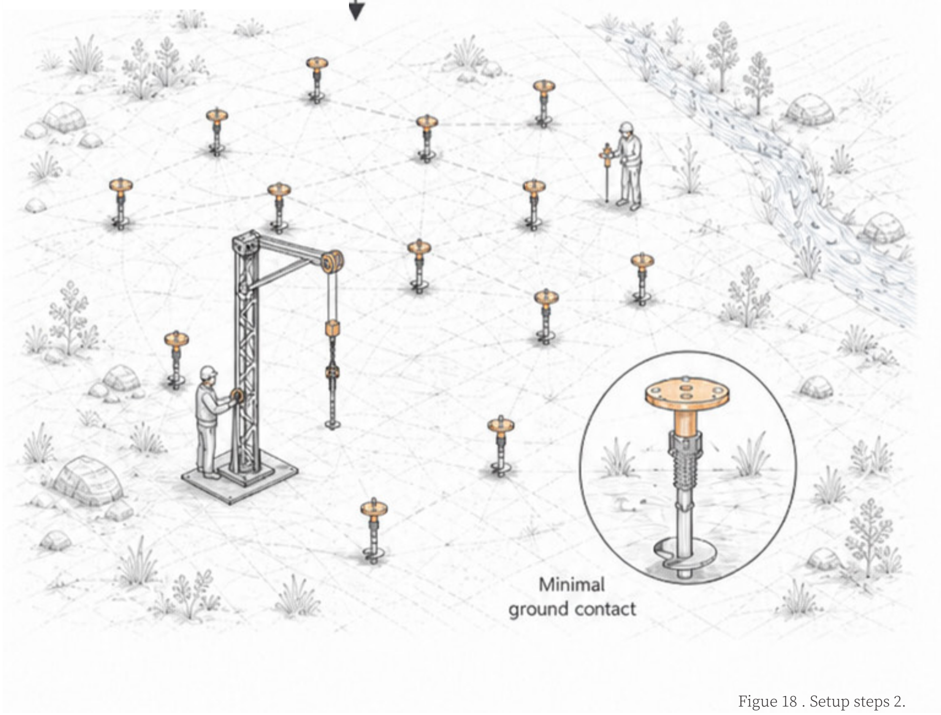
Step 6: Site confirmation



Step 7: Positioning &construction boundary



Step 8: Install reversiblepoint supports



Figue 18 . Setup steps 2.

Module Unloading and Initial Unfolding

Once the foundation system has been completed, the folded modules are unloaded sequentially near their designated positions and transition from transport condition to deployment condition. This stage is a critical turning point in the overall assembly process, because the architectural space is not produced through piece-by-piece construction, but rather released progressively through the unfolding of folded units on site. The modules generally need to be unfolded in a predetermined order so that structural forces, construction operations, and on-site spatial relationships remain under control.

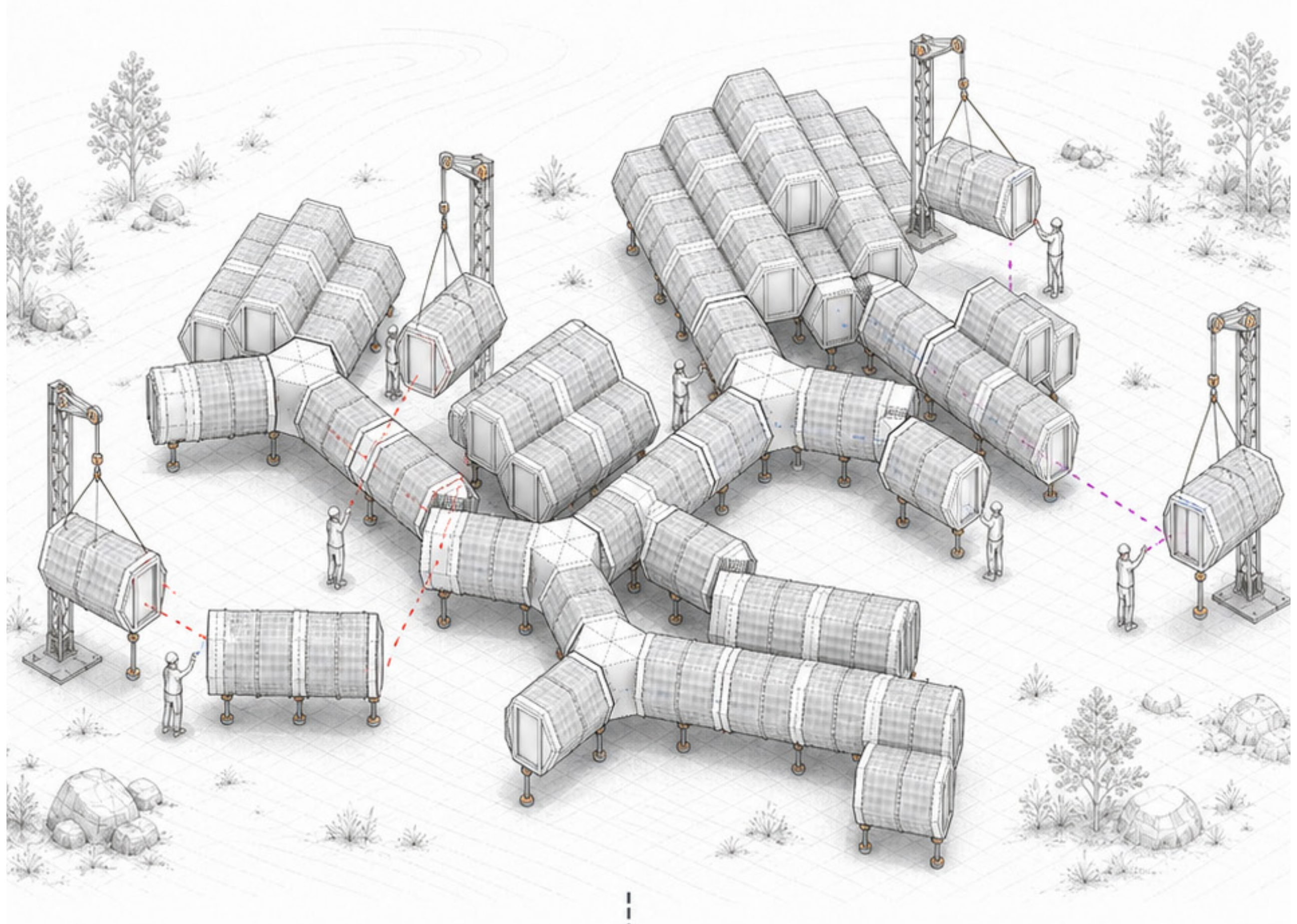
During unfolding, hinged joints, guiding elements, and auxiliary support systems work together to mediate the transformation of form, allowing each module to shift gradually from a compact folded state into a usable spatial condition. Once the module reaches its intended angle and position, the structure is temporarily locked in place to allow for subsequent calibration and connection. Compared with conventional wet construction processes, this unfolding logic resembles an act of “spatial release” rather than building in the traditional sense. Its advantages lie in the clarity of operations, the speed of implementation, and the reduction of on-site waste and temporary facilities.

Structural Fixing and Inter-Module Connection

Once an individual module has been unfolded, its lower structure is formally fixed to the point-support system, while its upper part begins to establish structural and spatial relationships with adjacent modules. In a modular settlement, the connection between modules is not a simple matter of joining units together; rather, it is a critical process that determines the overall spatial organization, functional zoning, and environmental adaptability of the project. Different connection types can respond to different site conditions and programmatic needs. Linear connections are suitable for clear circulation patterns, angled connections can accommodate changes in direction across complex terrain, and hub-based connections help generate shared central spaces.

Therefore, structural fixing and inter-module connection together constitute the process through which the architecture transforms from an individual unit into a collective settlement. During this stage, the modules gradually establish a continuous structural system, circulation network, and functional organization, allowing living, working, storage, and service spaces to shift from a dispersed arrangement to an integrated spatial framework. This process not only demonstrates the expandable potential of the modular system, but also reveals the adaptability and variability of folded architecture in response to different scales of demand.

Step 9: Place modules on supports



Step 10: Ready for deployment

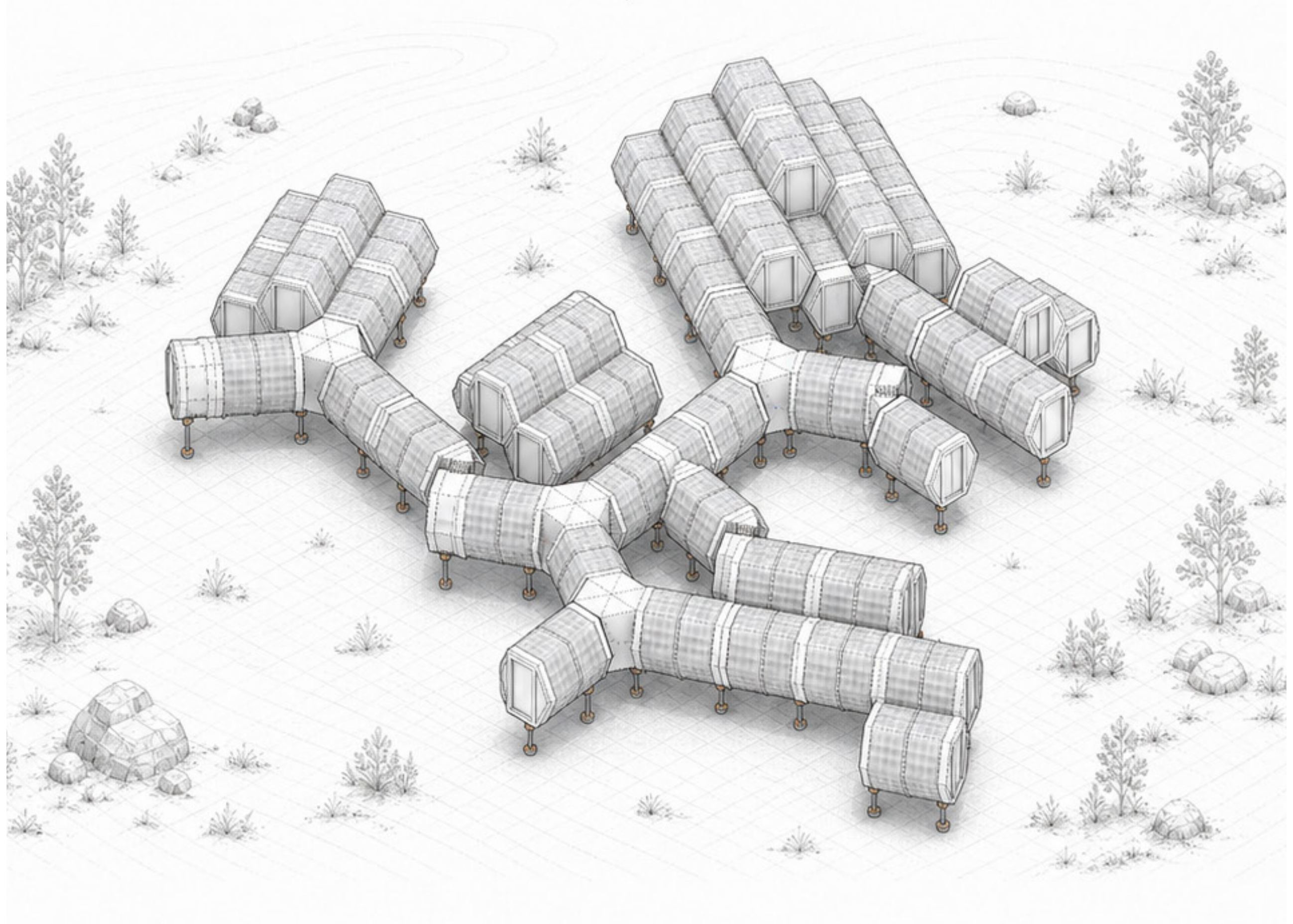


Figure 19 . Setup steps 3.

Assembly of the Envelope and Buffer Space

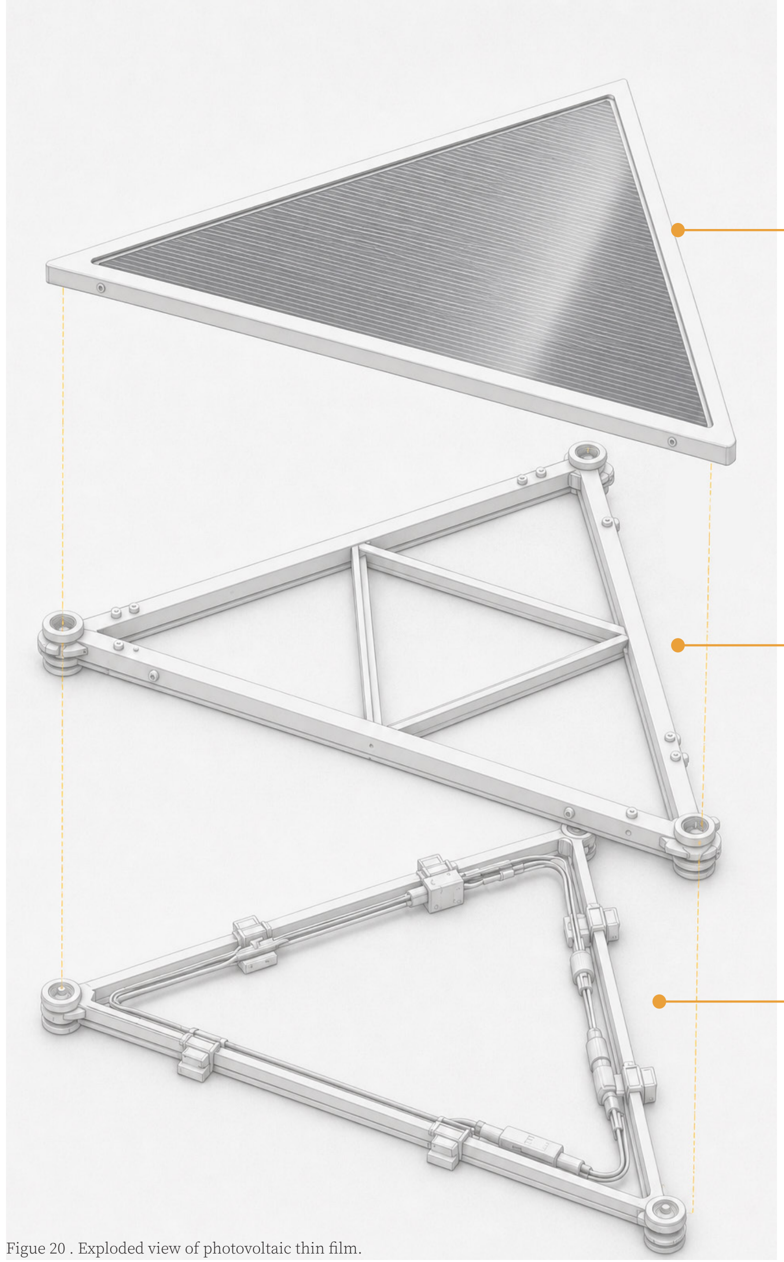
After the main modules have been assembled, the building has not yet fully developed its capacity to adapt to environmental conditions. It still requires the installation of an outer envelope system and semi-outdoor buffer spaces. In this project, the buffer space is not merely an auxiliary spatial component, but an important environmental transition layer between interior and exterior. It can serve multiple purposes, including wind protection, snow shielding, shading, temporary occupation, changing space, equipment transition, and microclimatic regulation, thereby reducing the direct impact of the external environment on the primary indoor space.

Particularly in cold, windy, or highly exposed environments, this type of in-between space can significantly improve the thermal performance and overall comfort of the main building. If flexible photovoltaic membranes or other lightweight energy-related components are integrated into the envelope system, the buffer layer may further take on roles such as energy generation, shading, and nighttime visibility. In this way, it is transformed from a mere spatial boundary into a composite skin that combines environmental mediation with energy support. As a result, the envelope system is no longer simply the outer covering of the architecture, but becomes a key interface linking climatic adaptation, energy production, and spatial experience.

Triangular BIPV Basic Unit

The basic unit of the semi-outdoor buffer space adopts a triangular geometry. The triangle responds to the folded-plate form of the main modules and also provides structural stability and combinational flexibility. Through the assembly of multiple triangular units, the system can form external surfaces of different scales according to site conditions, solar orientation, wind and snow pressure, and spatial requirements. In this sense, the triangular unit is not only a continuation of the formal language, but also the basic construction logic through which the outdoor buffer space is generated.

Each triangular unit consists of three layers. From top to bottom, they are the photovoltaic panel layer, the structural layer, and the integrated service layer. The upper layer is the photovoltaic panel layer, which collects solar energy and forms the primary external skin of the buffer space. Depending on specific technical conditions, this layer can be made of lightweight photovoltaic panels or flexible photovoltaic membranes, reducing the weight of the component while maintaining its energy-generation capacity. The photovoltaic surface is not treated as an independent technical attachment, but as an element that directly participates in shaping the external form of the building. In this way, the energy system becomes part of the architectural language.

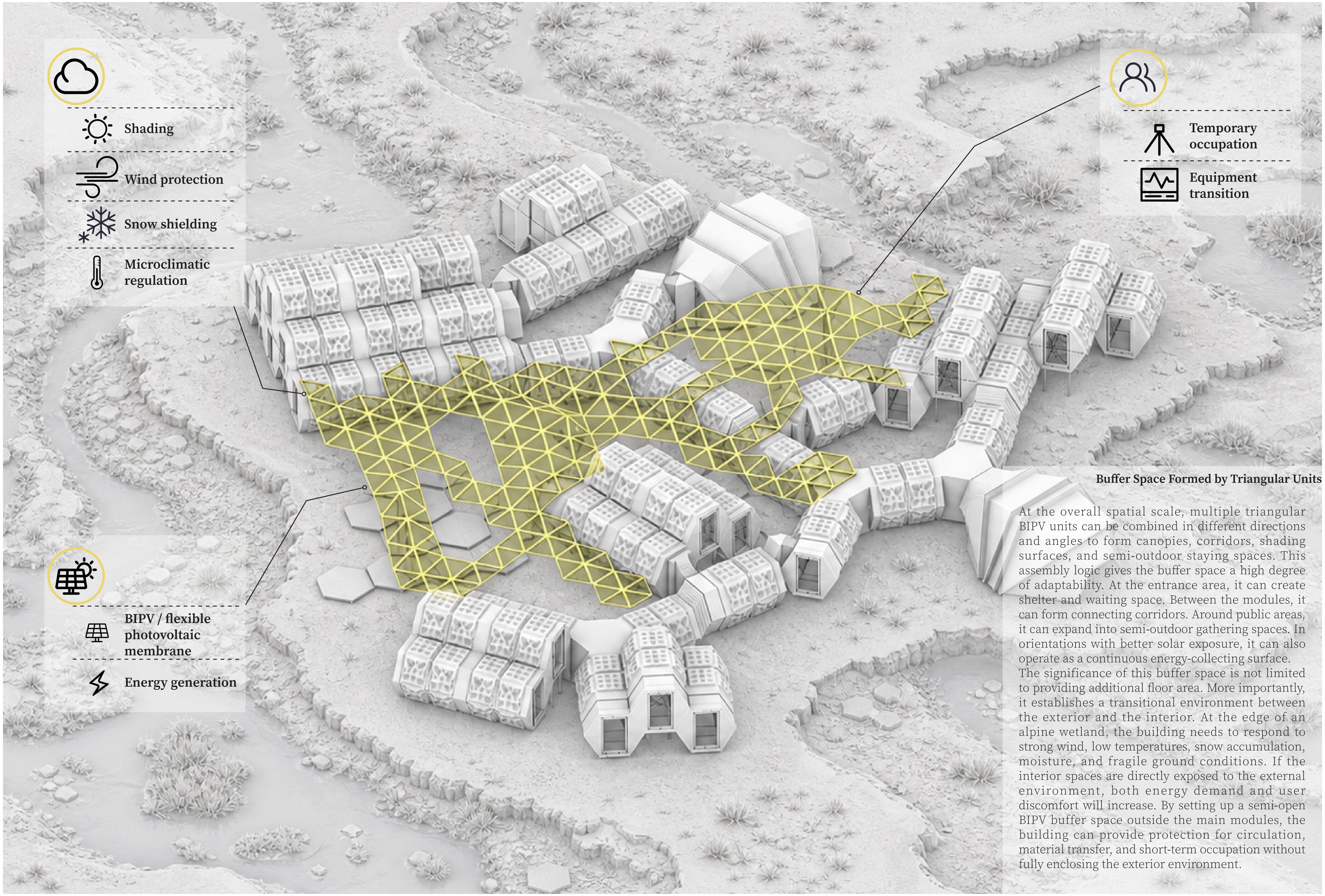


Figue 20 . Exploded view of photovoltaic thin film.

The middle layer is the structural layer, which provides support, connection, and geometric stability for the triangular unit. Since the semi-outdoor buffer space must respond to wind, snow, and temperature changes in alpine environments, this layer needs to be lightweight, prefabricated, and replaceable. It can be connected to the main modules through frames, joints, and secondary structural elements, allowing the triangular units to form a continuous but not overly enclosed external interface. The role of the structural layer is not only to support the photovoltaic surface, but also to provide a basis for expansion and maintenance of the entire buffer system.

The lower layer is the integrated service layer, which accommodates cables, interfaces, fixing elements, and local maintenance access. This layer connects the energy collection system with the operational systems of the building. As a result, each triangular unit is not only an independent shading component, but also a functional module that can be integrated into the overall energy and service network. By integrating cables and interfaces within or behind the component, the system reduces the visual impact of exposed equipment and improves the convenience of future maintenance and replacement.

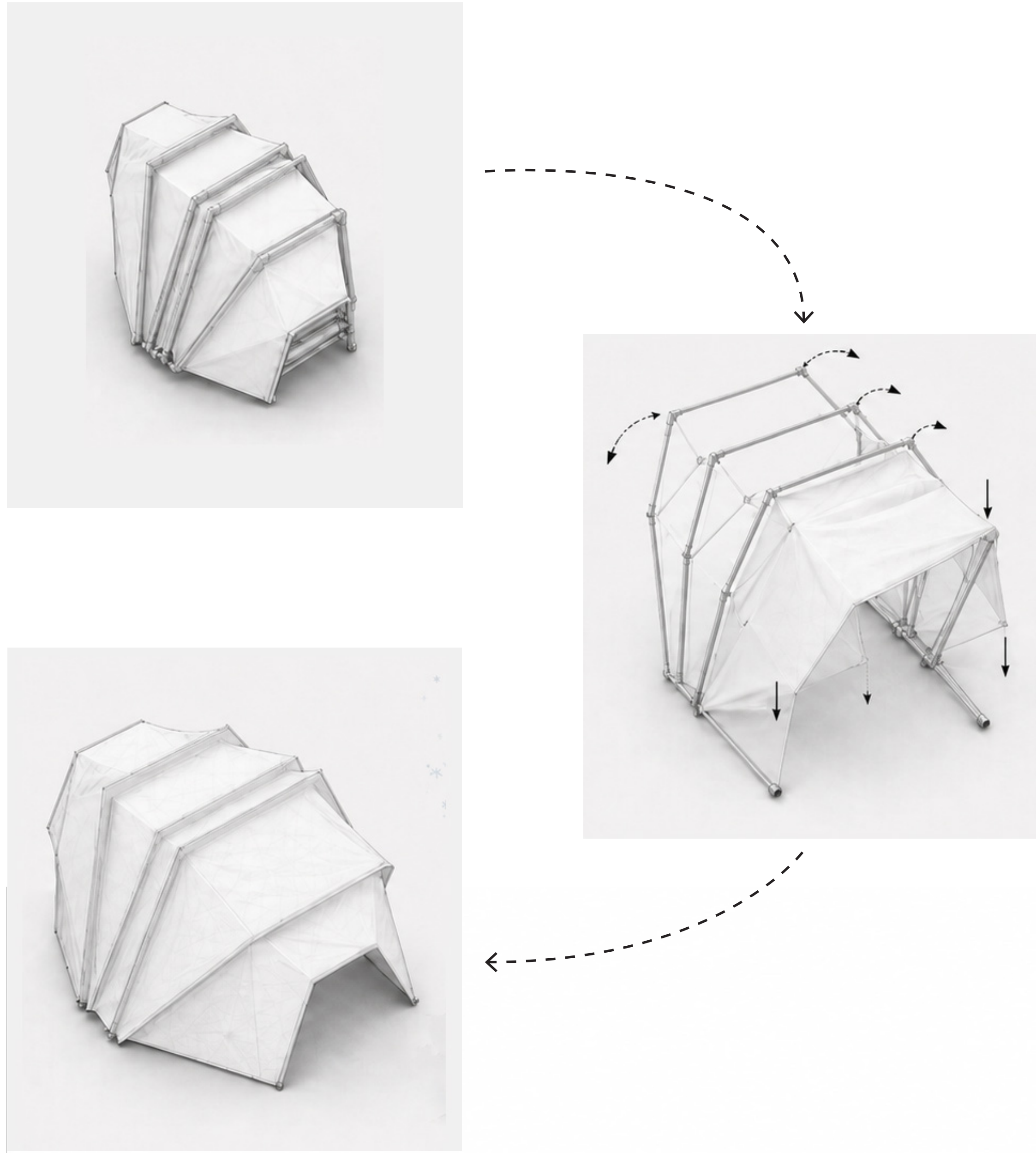
Therefore, the triangular BIPV unit can be understood as a composite architectural component. It simultaneously performs as a skin, a structure, and a service carrier. The upper layer responds to energy and climate, the middle layer responds to construction and stability, and the lower layer responds to equipment and operation. The integration of these three layers transforms the semi-outdoor buffer space from a passive shelter into an active interface that participates in both environmental mediation and energy production.



Figue 21 . Overall axonometric drawing.

Buffer Space Formed by Triangular Units

At the overall spatial scale, multiple triangular BIPV units can be combined in different directions and angles to form canopies, corridors, shading surfaces, and semi-outdoor staying spaces. This assembly logic gives the buffer space a high degree of adaptability. At the entrance area, it can create shelter and waiting space. Between the modules, it can form connecting corridors. Around public areas, it can expand into semi-outdoor gathering spaces. In orientations with better solar exposure, it can also operate as a continuous energy-collecting surface.
The significance of this buffer space is not limited to providing additional floor area. More importantly, it establishes a transitional environment between the exterior and the interior. At the edge of an alpine wetland, the building needs to respond to strong wind, low temperatures, snow accumulation, moisture, and fragile ground conditions. If the interior spaces are directly exposed to the external environment, both energy demand and user discomfort will increase. By setting up a semi-open BIPV buffer space outside the main modules, the building can provide protection for circulation, material transfer, and short-term occupation without fully enclosing the exterior environment.



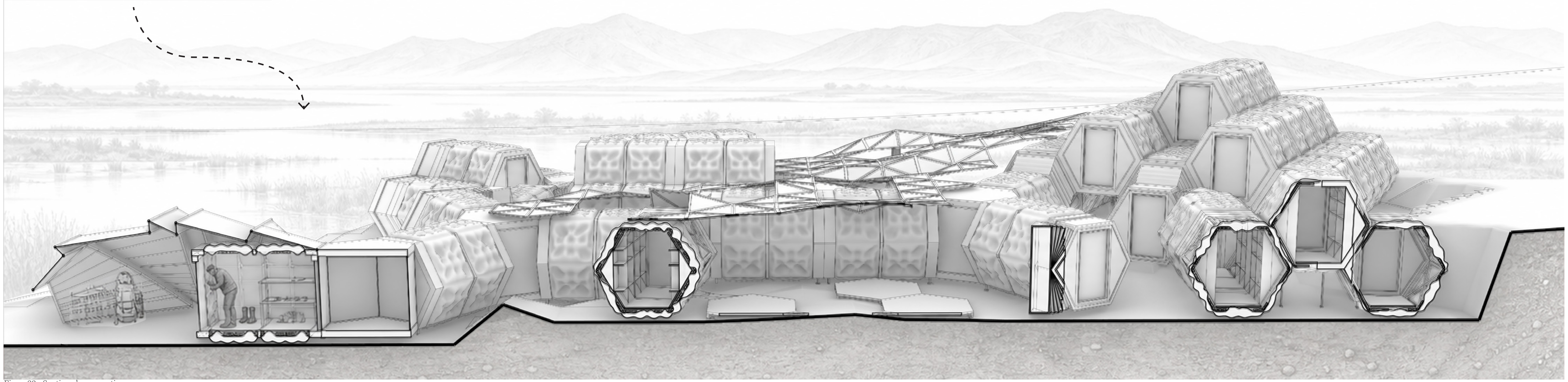
Tent-like Entrance Buffer Space

In addition to the external buffer space formed by triangular BIPV units, a tent-like buffer space is also introduced at the entrance area. This space is located between the fully exposed outdoor environment and the airlock, creating a second climatic transition layer before entering the interior. Its logic is similar to the outer layer of alpine tents or polar camp shelters: before entering the controlled indoor environment, users first pass through a relatively sheltered intermediate zone where they can pause, adjust, and prepare.

In an alpine wetland environment, people entering the building from outside often carry snow, moisture, mud, and cold air. If they enter the airlock directly, the environmental pressure from outside will be concentrated on the airtightness and insulation system of the building. The tent-like entrance buffer can reduce this pressure before users reach the airlock. People can briefly stop here, remove snow from shoes and clothing, organize research equipment, wait for others, or conduct simple material handovers. This reduces the possibility of cold wind, snow, and moisture directly entering the airlock.

This space is not a fully enclosed interior room, but a semi-outdoor climatic buffer zone. It maintains a certain degree of openness while providing basic shelter through lightweight frames, membranes, or folded components. Compared with a fully enclosed building volume, the tent-like buffer is lighter, easier to assemble, and more consistent with the temporary and adaptive characteristics of deployable architecture. It can be opened, reinforced, or partially replaced according to seasonal changes and intensity of use, responding to the complex and changing climatic conditions of alpine regions.

In terms of use, the entrance tent does not only function as an environmental buffer. It also extends the daily activity scenarios of the research station. It can serve as a small space for temporary communication, waiting, unloading supplies, and organizing equipment. When researchers return from outdoor observation or sampling, this space becomes a pause point before entering the interior. When materials arrive from outside, it can also function as a simple transfer and transition area. In this way, the entrance is no longer merely a point of passage, but a key node connecting the external environment, the semi-outdoor buffer system, the airlock, and the interior living spaces.

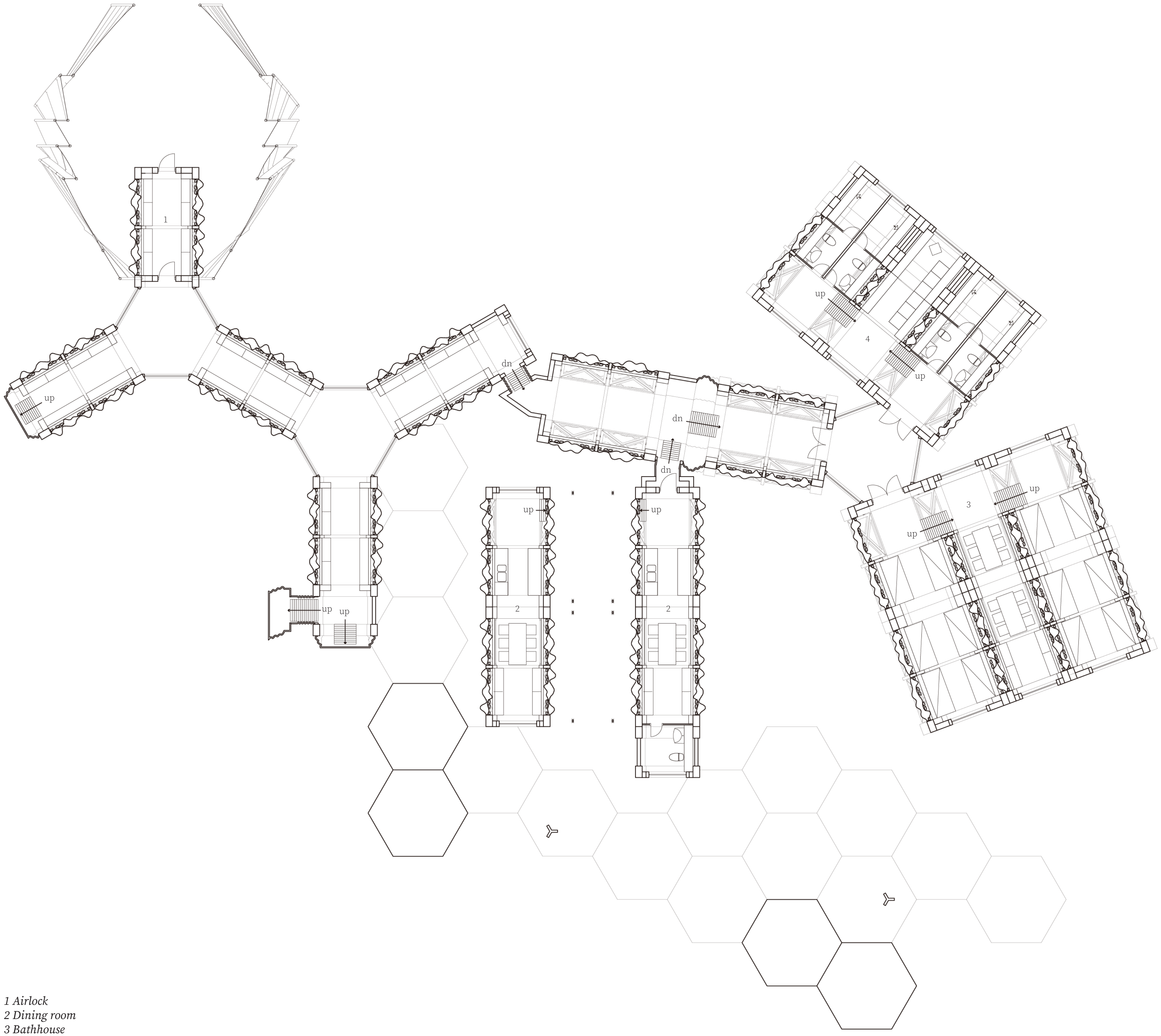


Figue 22 . Sectional perspective.

Infrastructure Integration and System Commissioning

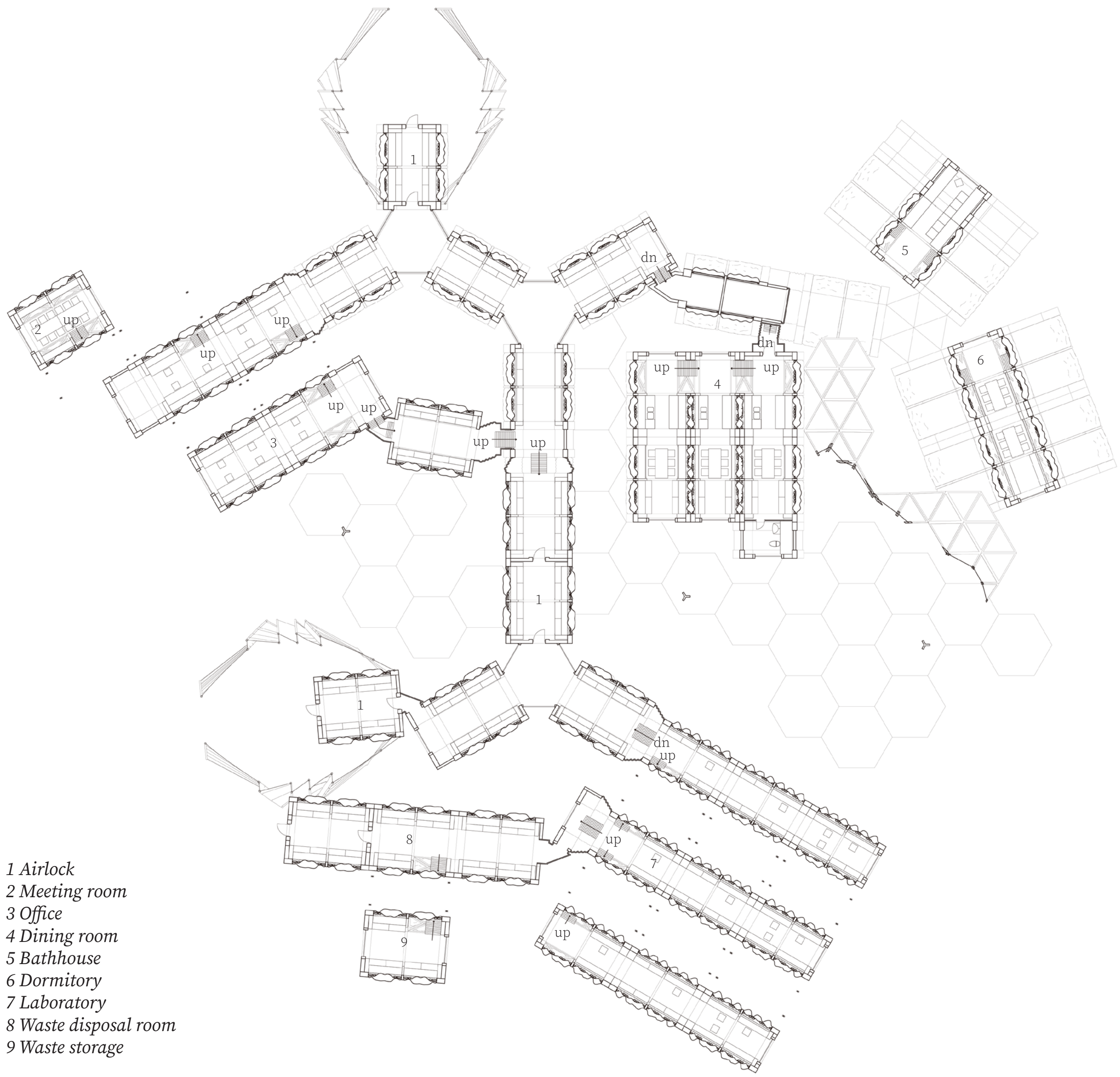
Once the spatial structure and envelope system have been basically assembled, the building enters the stage of infrastructure integration and system commissioning. The focus of this stage is to transform the building from a state of physical completion into a state of functional operability. Energy systems, including photovoltaic and storage devices, as well as lighting, water supply and drainage, rainwater collection, and greywater recycling systems, all need to be connected, tested, and performance-verified during this phase in order to ensure stable and continuous operation in later use.

At the same time, the airtightness of the envelope, the stability of locked joints, the integrity of the insulation system, and the effectiveness of the ventilation strategy must also be comprehensively examined. In folded architecture, joint areas are often both the core of structural transformation and the locations most vulnerable to performance degradation. Therefore, careful verification of joints and interface systems before occupation is especially necessary. Only after this stage is completed can the building truly shift from an assembled structure into an environmental system capable of supporting sustained use.



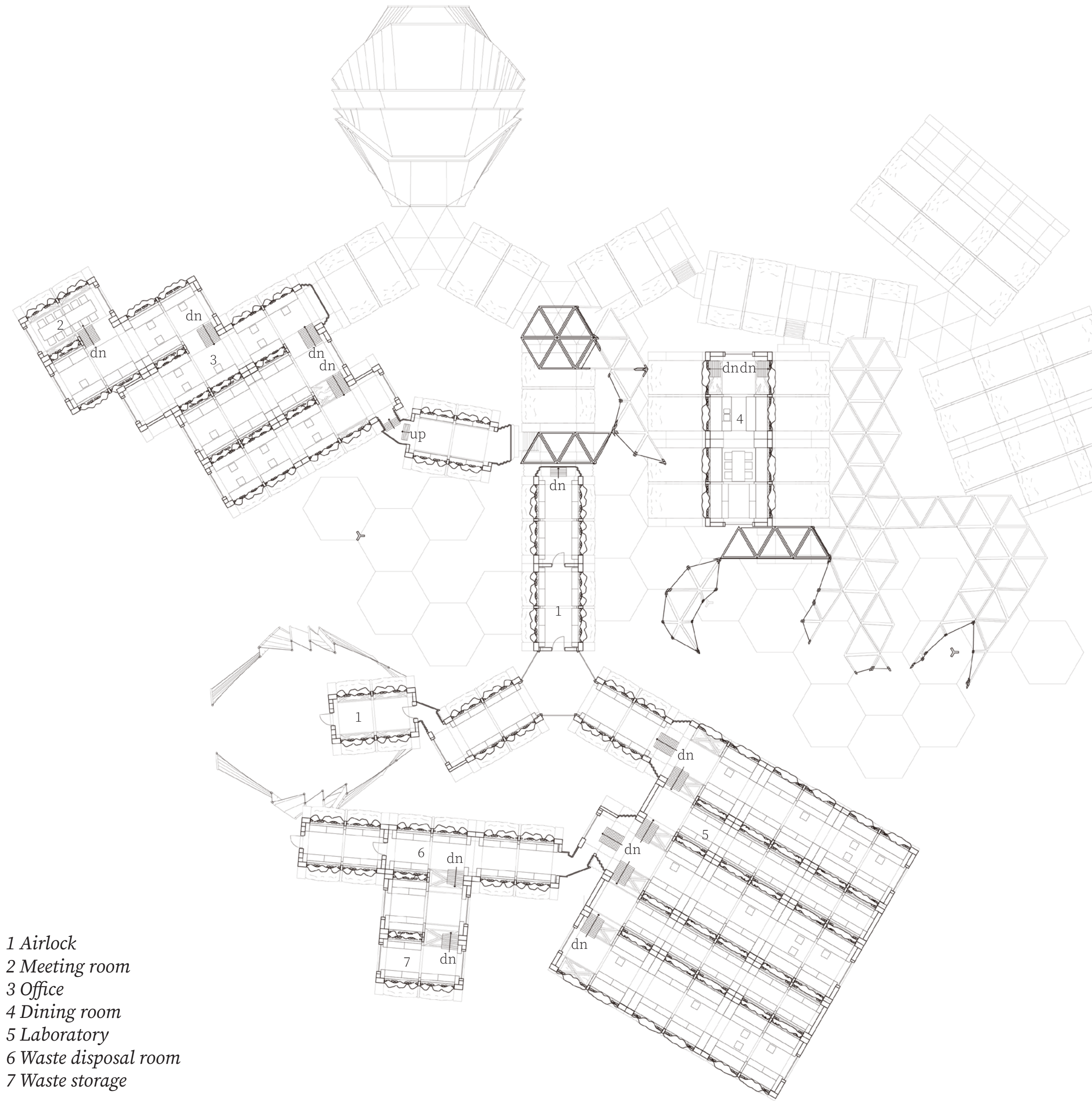
1 Airlock
2 Dining room
3 Bathhouse
4 Dormitory

Figue 23 . Floor plan - 1.



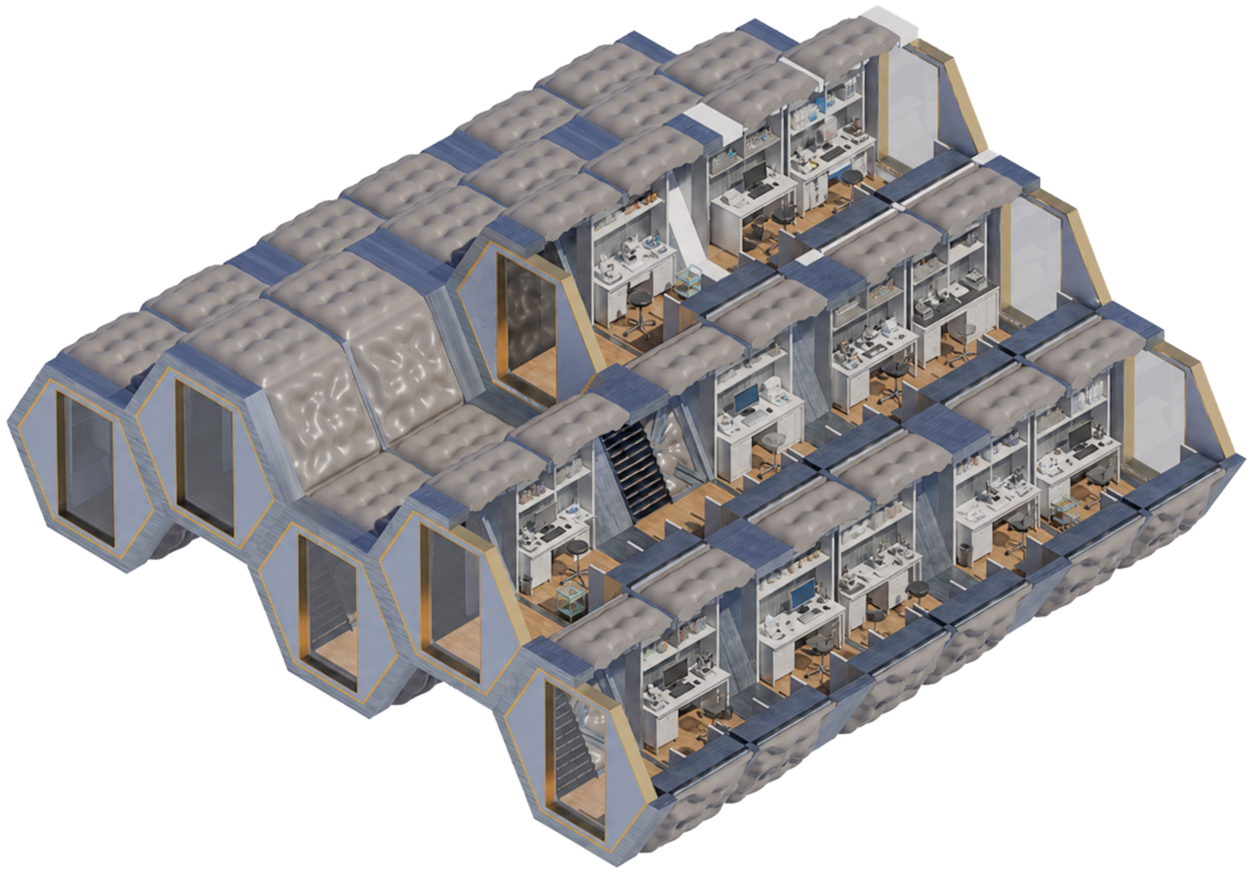
1 Airlock
2 Meeting room
3 Office
4 Dining room
5 Bathhouse
6 Dormitory
7 Laboratory
8 Waste disposal room
9 Waste storage

Figue 24 . Floor plan - 2.

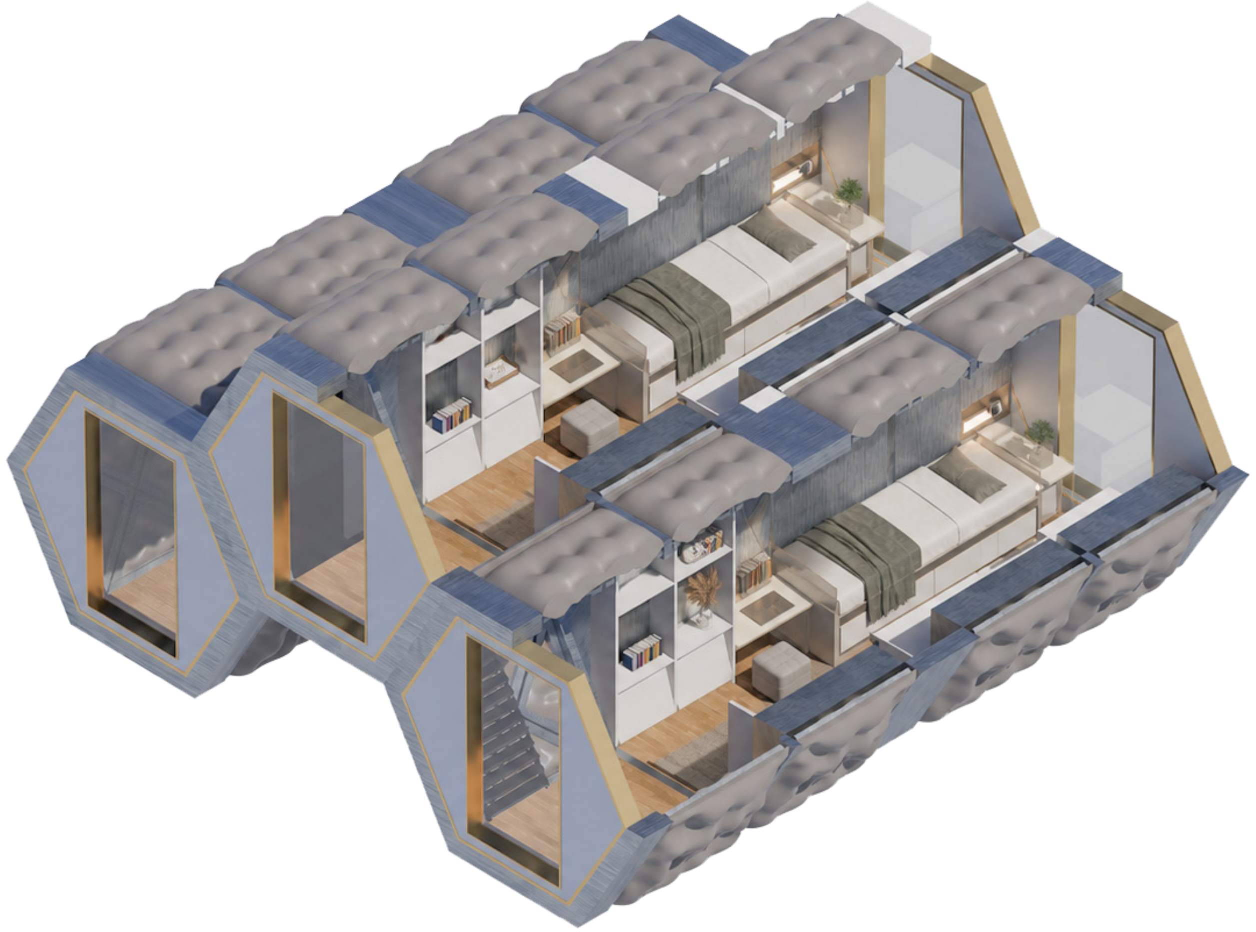


1 Airlock
2 Meeting room
3 Office
4 Dining room
5 Laboratory
6 Waste disposal room
7 Waste storage

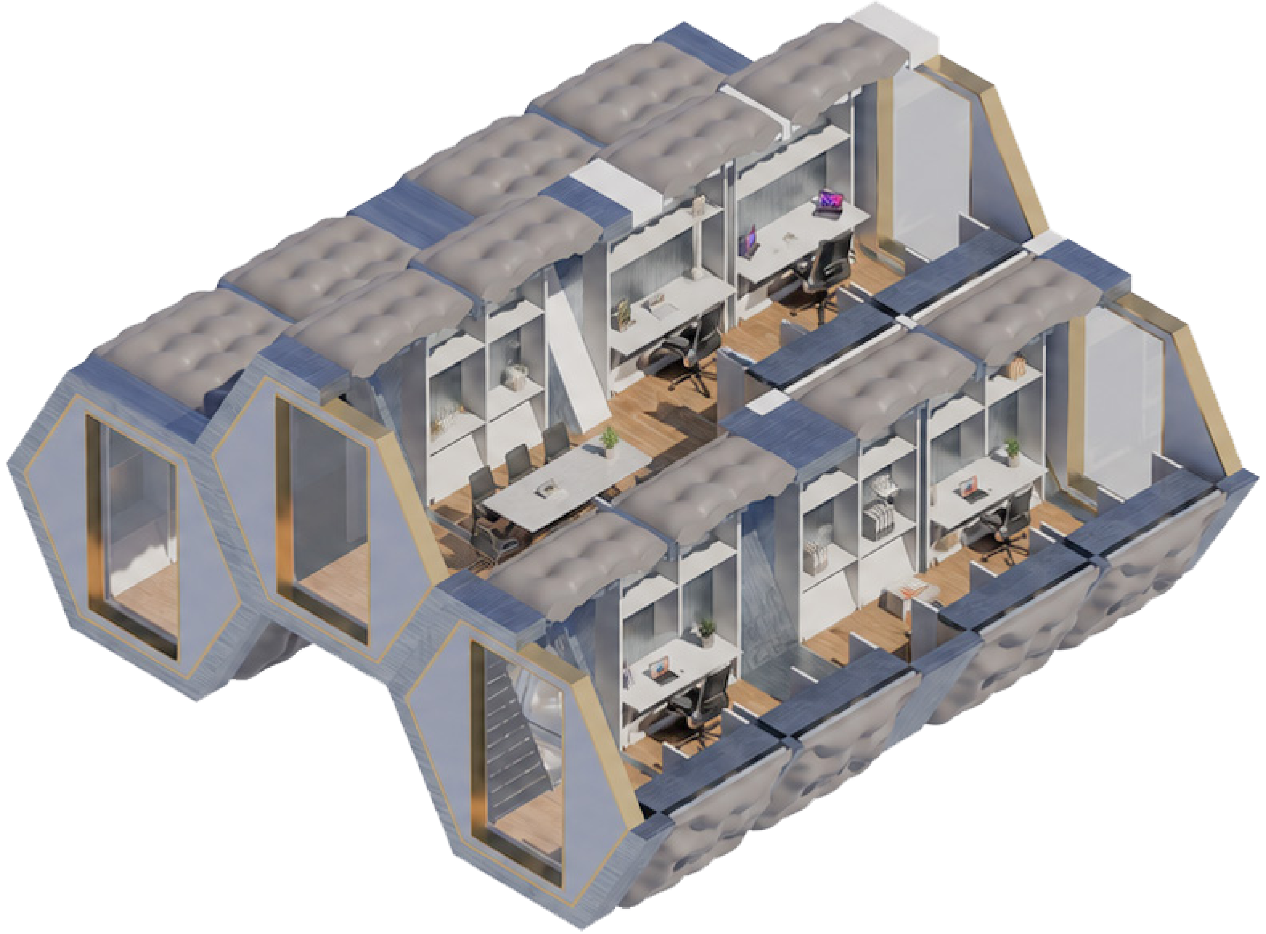
Figue 25 . Floor plan - 3.



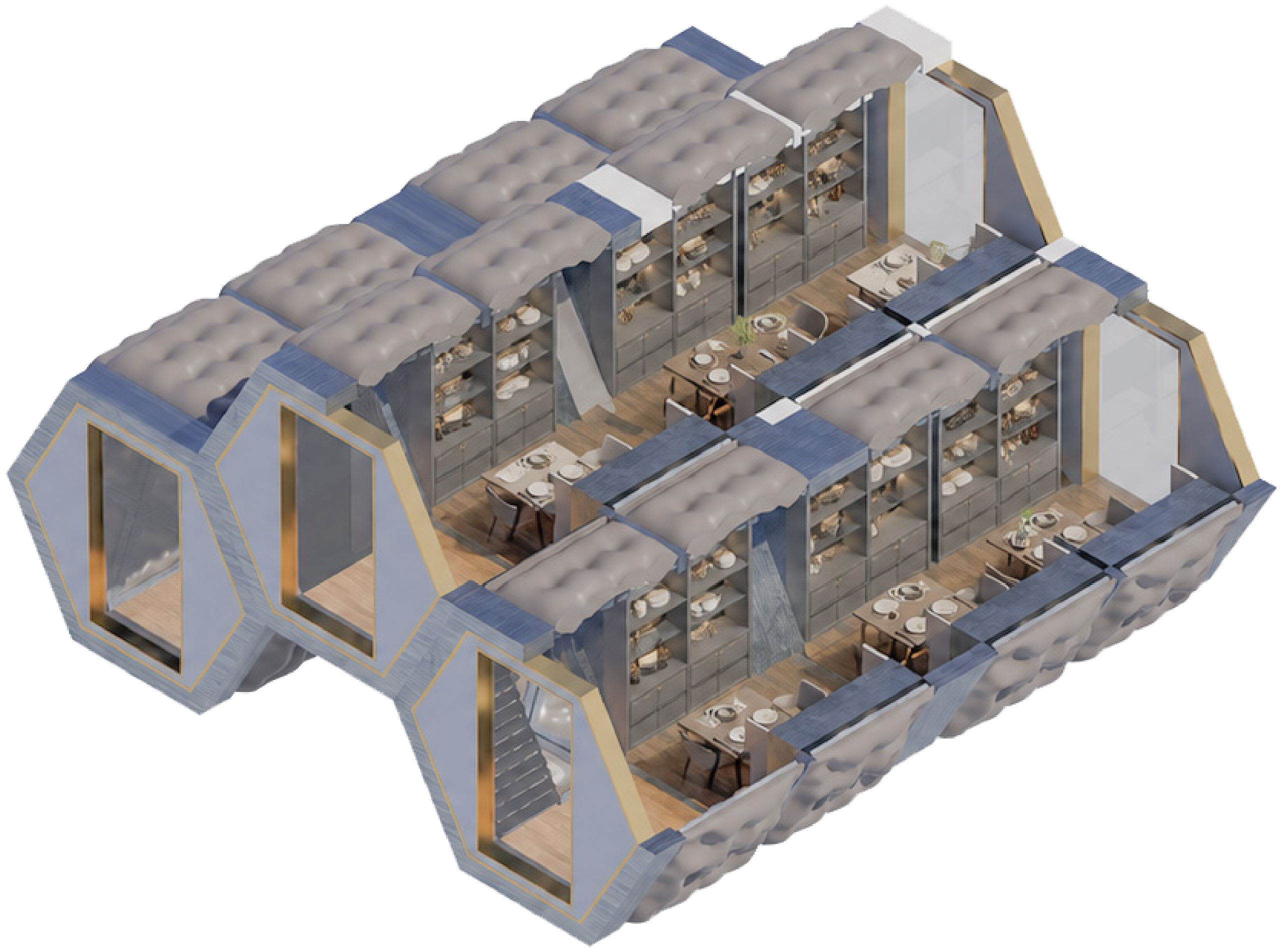
Figue 26 . Laboratory module interior configuration.



Figue 27 . Dormitory module interior configuration.

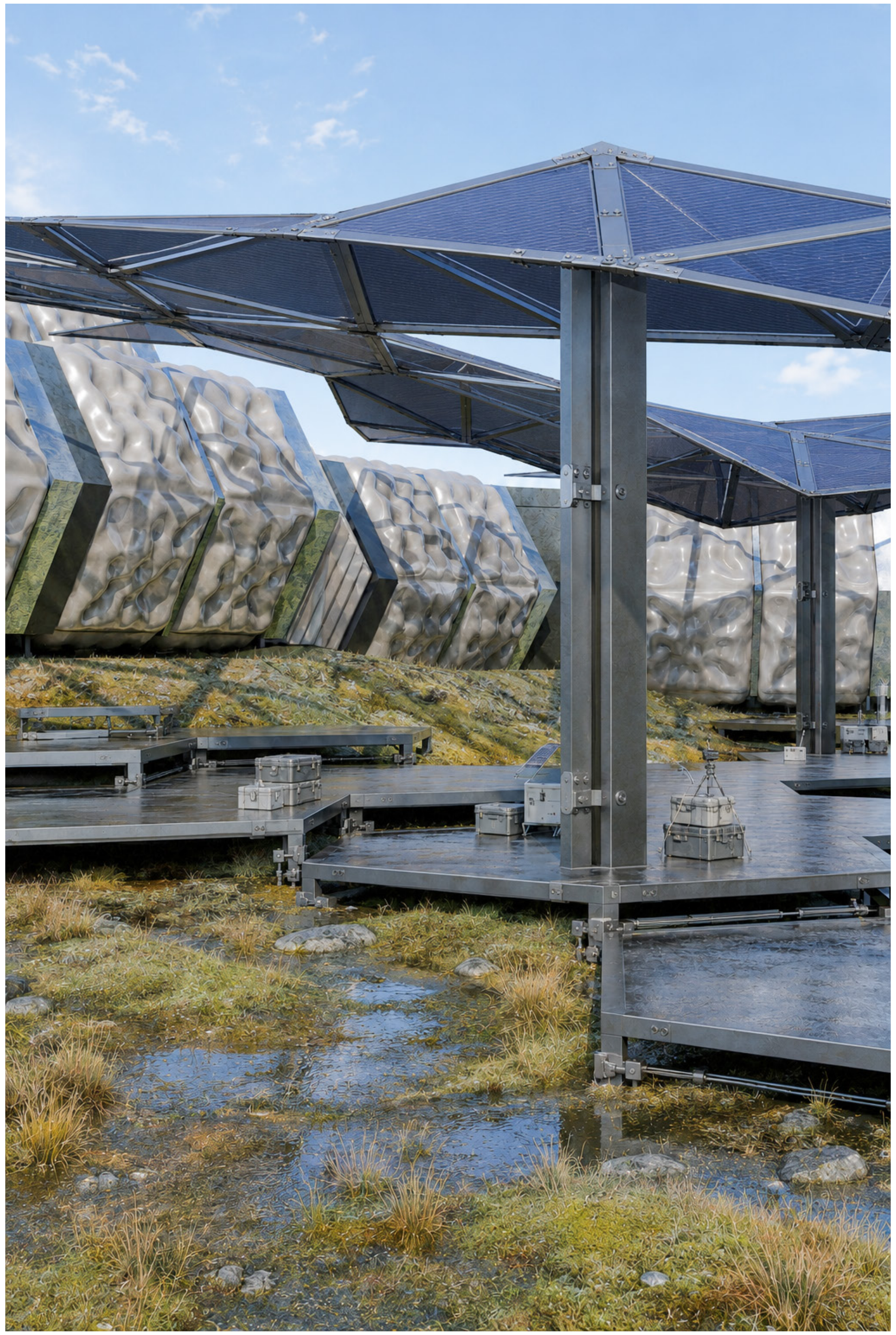


Figue 28 . Meeting & office module interior configuration.



Figue 29 . Dining module interior configuration.


Figue 30 . Exterior perspective.


Figue 31 . Eye-level perspective.

Figue 32 . Interior perspective - dormitory.

Figue 33 . Interior perspective - laboratory.

Discussion

This project investigates how a deployable architectural system can support scientific fieldwork in ecologically fragile environments while minimising long-term ground disturbance. Rather than proposing a fixed structure, the project develops a lightweight modular system that can be transported, deployed, assembled, and adapted to varying site conditions. In this sense, the architectural proposal functions not only as a spatial design, but also as a construction strategy, an environmental response mechanism, and a framework for temporary or semi-permanent habitation.

One of the central discussions in this project concerns the role of foldability. The folding capacity allows structural units to remain compact during transport and to expand upon deployment, establishing a direct relationship between geometric transformation and spatial performance. At the same time, foldability introduces technical challenges. When the building envelope is no longer static, the integration of thermal insulation, waterproofing, airtightness, and structural stability becomes considerably more complex. The folding system should therefore not be treated as a self-contained solution, but rather as a design strategy that requires further development through structural testing, material research, and full-scale prototyping.

The modular system also raises questions about the relationship between standardisation and site specificity. On one hand, standardised modules improve efficiency in fabrication, transportation, and assembly. On the other hand, fragile landscapes — such as alpine wetlands, permafrost zones, or plateau environments — demand careful calibration to local topography, wind exposure, snow load, hydrology, and ecological conditions. The project therefore does not aim to produce a generic structure that can be placed anywhere, but rather proposes a flexible system that can be adjusted to the particular environmental and logistical circumstances of each site.

The exterior grey spaces form another significant area of discussion. The triangular BIPV units are treated not only as energy-generating components, but also as spatial and climatic elements. Through canopies, covered walkways, shaded areas, and semi-outdoor buffer zones, the scheme creates a transitional layer between protected interior spaces and the exposed landscape. Entry tents further reinforce this transition by providing a secondary climatic buffer before the airlock is reached. These spaces support temporary occupation, equipment preparation, snow removal, and informal exchange, while also reducing the direct impact of wind, snow, and moisture on the interior environment.

At the same time, the project exposes a number of tensions that remain unresolved. A research station situated in a fragile environment must accommodate human activity, scientific operations, and technical infrastructure — needs that inevitably produce some degree of environmental impact. The design attempts to reduce this impact through point-load foundations, lightweight modules, and reversible construction, but a rigorous evaluation of its actual ecological performance remains necessary. Equally, the integration of BIPV, foldable structure, and buffer spaces improves environmental adaptability, but also increases the complexity of construction, maintenance, and long-term durability.

Future development of this project could focus on more detailed structural analysis, thermal simulation, BIPV performance evaluation, and physical prototyping of critical connection points. The folding mechanisms, envelope assemblies, and inter-module joints all require further testing at both the component and system level. The system could also be tested against a range of site scenarios to understand how it performs under different climatic, ecological, and logistical conditions. Through this further research, the project could develop from a design proposal into a technically more resolved and deployable habitat system for remote and environmentally sensitive contexts.

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Images

AI appendix

Artificial intelligence tools were used as supportive tools in this project, mainly for translating selected Chinese text into English and for checking grammar, spelling, and readability. AI was also used to make minor refinements to some self-produced drawings, such as improving clarity, texture, background details, and presentation quality. All design concepts, drawings, spatial decisions, and final content were developed, reviewed, and edited by the author.

Model photos - unfolding process