FOLDING PODS

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Study and small-scale design application of deployable structures

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MASTER-/DIPLOMARBEIT

Faltbare Raumzellen
Folding Pods

Untersuchung und klein-maßstäbliche Anwendung von Faltstrukturen

Study and small-scale design application of deployable structures

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ABSTRACT

ENGLISH

The quest for architectural space has most probably never been greater than in the present time. Architecture is created at the stake of space, which it encloses. While dwelling space has acquired a more permanent status over time due to evolutionary habits of people, this was not always the case. In the history of mankind deployable structures accompanied them in the quest for new habitable environments. Even in present times activities of people are mostly temporary and time bound, but the structures which shelter them are permanent with a lifespan exceeding by far the intended use and function and even the owners lifetime. Architectural structures which are temporary not used still enclose a precious amount of space. Today architecture aspires at being adaptable to different given circumstances and respond to users' needs.

The aim of this paper is to test out, the potential of deployable structures designed to encapsulate space when needed by the user and to release space, when not in use by employing folding mechanisms. The theoretical part of the thesis will take a look at Micro-architecture as a means of compressing and condensing functionality.
Folding structures will be investigated in order to gain an understanding of different deployment mechanisms.
Further, in the practical part the Kresling folding pattern will be tested in a design application aiming to translate the paper folding mechanism into material and load bearing structures with shape-shifting capacity.
A small-scale capsule was designed - attached to an existing building, investigating the potential interaction with the built environment and as a modular configurable unit serving as a temporary living / working space in different locations.

DEUTSCH

Die Nachfrage nach Raum im architektonischen Sinne ist heutzutage größer den je. Auch wenn Wohnraum einen permanenten Charakter entwickelt hat aufgrund der Sesshaftigkeit der Menschen, das war nicht immer der Fall. In der Entwicklungsgeschichte der Menschheit waren wandelbare Strukturen stetige Begleiterscheinungen auf den Entdeckungsreisen deren Nutzer. Auch in unserer Gegenwart sind die Tätigkeiten der Menschen meistens temporär und an gewisse Zeitordnungen gebunden, aber die Strukturen, die sie beherbergen sind permanent mit einer Lebensdauer, die geplante Nutzung, Funktion und die Lebenserwartung der Nutzer weit übertreffen. Architekturgebilde, die zeitweise nicht genutzt werden nehmen permanent den umbauten Raum in Anspruch. Architektur heutzutage strebt Anpassungsfähigkeit zu unterschiedlichen Zuständen und den Bedürfnissen deren Nutzer.

Ziel der Arbeit ist das Potenzial von wandelbaren Strukturen auszutesten, die fähig sind einen geschlossenen Raum zu schaffen für die Dauer der Nutzung und durch Formänderung den beanspruchten Raum zu verkleinern, wenn es zeitweise nicht genutzt wird.
Der theoretische Teil der Arbeit untersucht Mikroarchitektur als eine Strategie Funktion zu komprimieren. Unterschiedliche Faltstrukturen werden zur Formfindung untersucht.
Im praktischen Teil der Arbeit wird das Kresling-Faltmuster anhand von 2 Anwendungsmöglichkeiten erläutert. Das Faltprinzip des Papiermodells wird in einer Struktur mit Materialstärken und Tragfähigkeit übersetzt.
Eine kleinmaßstäbliche Raumzelle wurde entwickelt, als auskragendes Fassadenelement an einem bestehenden Gebäude mit der gebauten Umwelt agiert und als eine modular-konfigurierbare Einheit als temporärer Wohn-/Arbeitsraum die an variablen Standorten einsetzbar sind.

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1. INTRODUCTION

Present society lives at an incredible pace, where changes of various living circumstances are forcing people to also take into account changing their living environment. Conventional architecture lacks the capability of instant change possibility and adaptability. The optimal design solution is most of the time only optimal for the time the design was produced at, for the circumstances, which the designer took into consideration and for whom he/she was appointed to produce it. Changes in functionality, design or ownership are only possible through time consuming resource investments.
The demands for today's architecture is no longer limited to fast optimized production but expands to potential adaptability to yet unknown circumstances. However, it is highly unrealistic to postulate a new form of architecture to replace the traditional forms, as people are deeply tied to their habits, which architecture has no right to break. But there is a need for creating alternatives to the exiting built environment, which would offer more flexibility to the users in terms of usable space and changing circumstances.
Per se architecture is traditionally viewed as a static system that is fixed in its position and bound by the different constraints of the site it is located on. Movement of the system as a whole is rather undesired and if it occurs it is rather faulty and dangerous for the users of the structure (earthquake, load failure). This is tightly bound to the habits of humans, who settled down. However human existence was not always bound to a certain location and also their accommodation was not a fixed structure either, as it had to be carried around assembled and dismantled in order to fit the lifestyle of nomadic population.
"Creating space is the main action for an architect. It can be done with sturdy material in a fixed situation but also in another way. A more adventurous approach is to have the material move or have the whole building change its location. In moving the building it is possible to stay at the ultimate place chosen and leave without disturbing the environment. In moving the material one can respond to changes also in climate or adjust to a new situation."[1]
Architecture experiments provide an excellent ground for questioning certain establishments in our society, raise awareness and providing new innovative solutions to the field of architecture. Especially small-scale architecture projects can provide an alternative to conventional one, testing certain utopian concepts like flexibility, movement, kinematics, automation, high-tech materials.
Modernism already paved the way of architecture to mass production quality and speed. It overlooked however, certain important aspects, which caused its downfall and rejection by the public. It relied highly on standardisation with no regard to individual needs and rejecting the idea of customization and the importance of social dimension in architecture. Through technological advances nowadays customization has become more accessible to a wide range of users making it possible in theory to create customized products according to the users' special demands. Architecture is also one of the fields profiting from the latest advances. Nevertheless this situation does not only function in one direction, where users can change their built environment at a click of a button, but has also a reversed effect of influencing the habits of their users. Whereas previously working in an office was tied to a specific physical location at a given time, nowadays the idea of an office, for instance, has somehow blurred out. The physical space to complete this work is no longer necessity, it does not rely on the presence of a building, a desk, a wired phone and drawers to store paper documents. Nowadays only a computer and/or a phone with internet connection is needed in order to establish communication with co-workers and potential clients. Storage has been completely virtualized and made available through cloud computing to anyone authorized to use the information. One can literally sit in a coffee shop, in a hotel room, in an airport or on the beach terrace with nearby WIFI and complete his/her tasks. From this point of view an office building has become superfluous. The task of the architect is also to recognize these shifts in social paradigms and develop new adaptive, resource-efficient structures. Le Corbusier insisted in his iconic work *"Towards a New Architecture"* precisely on this aspect, that *"the first duties of an architect in times of renewal is to revisit the established values in contemporary society."* [2]
When thinking of the key moments that caused a revolution in the field of architecture it can be

Fig. 1.01: Visualization collage - Rooftop Pods, London

noticed that most advancements that brought architecture forward were from other fields, which inspired architects to introduce them in their projects or discourse, be it in the form of new materials like reinforced concrete, which was (re)invented by gardener Joseph Monier for flower pots and was first used in bridge and dams by engineers, mass production and standardization, which was used by factories like the automobile industry, paving the way of modernist architecture or computer-aided design CAD which was developed by a computer scientist, and opened totally new possibilities.
Architecture, like any other discipline today, has become a field fragmented by specialization, meaning that different disciplines were created linking aspects of architecture with other fields of study and professions like structural engineering, material science, construction, mathematics, computer science, history, graphical and performing arts, sociology, psychology and many others.
Buckminster Fuller saw this tendency rather as a threat stating *"society operates on the theory that specialization is the key to success, not realizing that specialization precludes comprehensive thinking."* [3]
However it is precisely the interlinking between different disciplines that create truly meaningful ideas according to Adrover Esther Rivas. In her book *"Deployable Structures"* she describes the term *"syntegration"* to refer to the comprehensive knowledge needed when operating with domains, which spread across a variety of different fields. The term unites the notions of *"synergetic"* and *"integration"* referring to the process of interlinking knowledge and research from different disciplines resulting in the emergence of new ideas. [4]
It goes without saying that architecture is not a passive domain only receiving influences from other fields but also actively creates correlations within other disciplines, like in microbiology, where cellular structures are often associated with architectural building blocks, which cluster to form living organisms.

2. RESEARCH AIM AND MOTIVATION

Starting with general observations of the tendency in today's society of moving towards a condensed lifestyle, whether favoured by technological advances, which made smaller and more efficient products available or by necessity due to less resources and financial means, this thesis is set to investigate the trend particularly in architecture. What tendencies have been developed in using space more effectively? What strategies can be employed in order to create temporary sheltering structures, which can provide interior space, when needed and when not to be able to reduce their size and take up less storage space or change location. By investigating experimental approaches to architecture and the statements they made in the architectural discourse of their time, the preoccupation with space optimization has never been more acute than in present times, having been raised to a new lifestyle. In this context investigating the potential of small-scale deployable structures of creating functional architectural space was used both as a conceptual design process and as a structural system. The result is a sequence of design applications of a deployment system inspired by Kresling folding pattern, which was translated into a load bearing mechanism, functioning as a cantilevering facade add-on or a self-supporting modular folding pod.

The theoretical part of the thesis is set to explore the paradigms, which have determined the tendencies towards space minimisation and how this also influences conventional architecture and how it can be used as a kind of shareable facility in the contemporary context. For the design part of the thesis the idea of creating space that could contract and expand its content was narrowed down to the field of deployable structures exemplifying and categorizing small-scale deployable structures, experimenting with folding patterns and implementing these into a folding pod unit as extensible dwelling or working unit. The paper offers a pathway from a theoretical discussion related to space saving strategies in the field of architecture to form-finding and design applications of the deployable mechanisms exemplifying one strategy of resourceful us of space inspired by the art of paper folding - origami.

While the research process evidenced the diversity of methods, which and be employed in the field of architecture the intention was to test out the abstract concept of folding literally and not as a theoretical concept, which would describe the act of folding and unfolding architecture. In the concept phase of the design process the complexity of folding structures can be easily underestimated. Therefore smaller design tasks was set, in the form of modular one-room capsules. While crafting origami folds it became clear that in order to be able to use the pattern into a deployable structure, form is determined by geometrical relations of the folding pattern, which cannot be easily changed. While the art of origami offers a vast repository of folding patterns creating a great variety of shapes, the design task becomes less a task of form-finding but rather a process of investigating the geometrical properties of folding patters suitable to fit the desired functionality.

While paper seems the perfect material for intricate patterns, at a larger scale additional material and elements are needed in order to recreate the folding and unfolding process, while also providing stability and load bearing capacity. Deployability adds new challenges to the performance of a structure, which may appear conflicting at times. Investigating the means by which structure can perform the task of stability and movement is an important part of the thesis and solutions coming from different mechanical devices were used in order to achieve stability and movement of the system.

3. MICRO-ARCHITECTURE AND MOBILITY

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Micro is the Greek term for “small” defining in this context small-scale architectural structures *“while retaining function and possibly form as well [...] Because of its unusual and spectacular appearance, micro-architecture is sometimes understood as a gimmick or fashion when in fact it has its own inherent rules of behaviour, much like the bonsai tree.”* [5]

Downsizing cannot define the main creation process of micro-architecture, there has to be also a process of abstraction and optimization involved in order to fit a function into a smaller hull.

Due to its reduced size, compact form and function micro-architecture is very often associated with mobility, making it easy to manoeuvre from one location to another or even dismantle and reassemble for a totally new use. Mobility however is not the prerequisite for a structure to qualify as micro-architecture. Needless to mention that the term is very loose, what qualifies as a small-scale structure for one user, may be regarded as regular sized space for another, depending on his or her background and lifestyle habits.

In the course of this paper further terms relating to micro-architecture will be used, which will be clarified as to what they will refer to, namely mobile architecture and experimental architecture.

The researched literature did not offer a clear distinction between micro-architecture and mobile architecture, as sometimes micro-architecture projects were listed as mobile architecture, even if they were anchored to their location by foundation elements and did not necessary have moving parts besides doors and windows. These projects would rather classify as movable structures with the aid of additional vehicle e.g. trailers or cranes.

In this thesis the term micro-architecture will be used as a collective term for the analysed projects and mobile architecture in this case is understood as a subclass of micro-architecture as the discussed projects are small-scale and some share the additional feature of movement and/or mobility. A very strict classification was not deemed as relevant to the purpose of analysing small-scale/movable structures. Rather the research of such structures was important to understand the functionality of reduced space and the mechanisms used to generate movement. Furthermore the issue of movement will be dealt with in Chapter 4. Deployable Structures. The projects presented in this thesis qualify as micro-architecture, since they were selected from publications both printed and virtual dedicated to small-scale and mobile structures. Moreover the idea of mobility is also of importance to the thesis. Generically mobility in the field of architecture is either understood as a structure, which is capable of shifting its physical location or one that is composed of parts that move. Gerhard Kalhöfer described this duality as either way, *“architecture is set in motion and is sent on a journey at the end of which, a different situation or circumstance may be encountered (…). Mobile architecture also shifts its interest through movement from space to the space-between. It is interested in the user taking action, rather than in the representation of the exterior appearance.”* [6]

This thesis will focus on mobile architecture in the second meaning, namely on shape shifting mechanisms, which can be applied to architecture in order to reduce its size and reduce the space they encapsulate either as a means of storage or for ease of transportation.

Micro-architecture seemed the right way to start the research with, when the intention is to create a design, which is able to change its shape and the spatial configuration it provides. The reduction in size and function helped focusing on the structure as a folding mechanism. Lydia Haack describes in the article *“Micro-Architecture - Experiments in Space Optimization”:* these small-scale structures as *“spatially compressed innovations that address different issues and that seek design harmony not through individual elements, but in the interaction and attractive force of all the components involved. Space optimization follows Mies van der Rohe’s principle of ‘less is more’, not through reduction to less but a reduction to the essentials”* [7]. The main goal of the thesis is to produce a structure, which is capable of enclosing space, when needed but releasing it when no longer in use. This aim made it necessary to take a closer look at experimental architecture, in how certain aspects of the design are abstracted in order to better focus on the concept be it in functionality or material innovation. Also the term experimental architecture shares the same ambiguity problem and constituting a discipline of its own, whose task was described by Lebbeus Woods *"to take us to places and spaces we haven't been before."* [8] However in the context of the paper its meaning will be delineating the techniques employed in the design process either regarding unusual form or functionality or the innovative materials used to optimize structure.

Before however taking a look at miniature architecture, it is also important to notice, that this trend has revolutionized technology. In technology, miniaturisation is a common way of seeking improved efficiency through ergonomic improvements, reductions in weight and energy consumption. This tendency to miniaturisation has created a new lifestyle, *"smallness, mobility and multifunctionality have attained a new status symbol"* [9] in the form of communication devices. Internet has created a virtual infrastructure, which made the creation of a global network possible. Being part of this network has such an enormous influence on our idea of mobility. Everything is moving but it is not always in a physical way. One can also move his mind by staying at home connected to the whole world by means of modern communication. A vast amount of people is already living a second life on the internet, that often seems more interesting, than life in the real world. They are connected at any given time, whether at home or on the go.

Returning to the idea of scaling down things, if minimisation is seen as an opportunity for multifunctional design, it eliminates the physical distance and changes the spatial context and space requirements. Whereas architects used to require a drawing table of 2 x 1 m ($2m^2$), a 30-inch monitor on a 1.6 x 0.80 ($1,3m^2$) table, if not a laptop itself is sufficient today. [10]

The space requirements have been reduced by at least 1/3 without mentioning the other major technological advances in performance, which also take less space.

Although flexible living modes draw on an age-old tradition and a wide variety of cultures, recent changes in living conditions and technical advances have greatly increased the relevance of flexibility. As working and private life increasingly overlap, a mobile independent lifestyle becomes more important. Today more than ever, people are seeking a way of living, which is not tied to fixed patterns and predetermined locations.

The concept of space and time and the separation between office and house is blurring. We can work anywhere we want to, supported by increasingly compact working equipment. We become less dependant on the built environment. This leads to other demands in architecture. Therefore architecture should adapt to accommodate the changing requirements on the built environment.

Internet revolutionized our idea of mobility but this is not the main reason to be mobile. Mobility is of all times and there are many other reasons to stay mobile and to build mobile structure. Often mobility is not initiated by architects or designers but created for a specific purpose or for urgent situations, namely to provide instant relief for people, who lost their home due to natural or man made hazards.

"*Architecture whose functions fade away dies. How should one design a building to avoid demolition problems? Today human needs in reference to architecture change rapidly, and it is permanence that causes problems."* [11]

Permanence is problematic in the sense that even though the building as a structure could still function for many years the change in functionality or upgrading to the state of the art involves sometimes higher costs than simply demolishing and constructing a new building instead. This way of disposing of things in general has created the environmental problems of today's world. While small-scale structure may not offer the solution society is looking for, but it may offer an alternative to conventional dwelling and the enclosures produced for this purpose, and may introduce an alternative form of space usage.

In the following, a selection of small-scale projects created by renowned architects, who produced some of the most iconic architecture of the 20th century, will be discussed, experimenting with the small-scale approach, evidencing their preoccupation with the optimization and compression of space and the reduction to the bare essentials for dwelling, giving them the opportunity to test new design concepts and fabrication methods. The following chapter will look at projects of architects of modernism and at daring projects from the 60's which proved programmatic and imagined to a certain extent the realities and advances of today's global society.

3.1. Micro-architecture projects

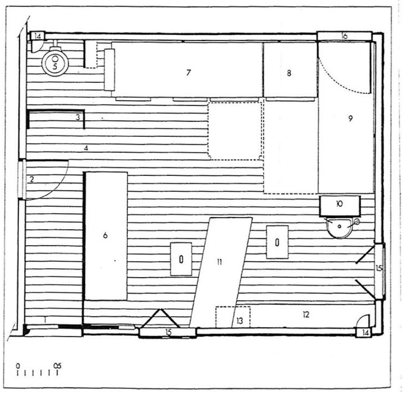


Fig. 3.1.01: "Le Cabanon" 1952 - in Roquebrune, Cap-Martin

Fig. 3.1.02: "Le Cabanon" 1952 interior furnishing

Architecture is a form of reaction on environmental conditions people live in. It is usually a fixed structure, even though its dwellers have to cope with various changes in their living environment and their behavioural patterns as a result of their constantly changing needs.
The idea of transformation and translocation is not something new to architecture and is derived from the inhabitants necessities (e.g. nomad population). However it acquired new potential in modernism at the beginning of the 20th century, when automation and mass production revolutionized peoples' lifestyle. Also the emergence of the automobile as an affordable commodity made fast mobility more accessible then ever. These ideas where also applied to the way buildings were planned and erected.
Le Corbusier postulated in his manifesto *"Towards a New Architecture"* in 1927: *"A house is a machine for living in. An armchair is a machine for sitting in"*.[12] That is a house is an effective tool, which can improve the living experience considerably. He was fascinated with the economy of space in automobiles, trains, ships and airplanes, which by means of standardisation and mass-production created the optimal space to fit the human body. He tried to attain this economy in his housing projects. In his view a house was a (dwelling) capsule with human scale. In this context it is interesting to mention one of his latest small-scale project *"Le Cabanon"*, in Roquebrune, Cap-Martin (South-East of France). A minimal living unit of 2,66 x 2,66 m in size, which he used as a vacation cabin, which blends perfectly with the natural surroundings and has a minimal impact on it. The interior combines the natural material with standardized design aesthetics for the furnishing.
The modernist aesthetic was put into practice by the architects of that era using standardized prefabricated construction materials and an efficient design of floor plans, in which any unnecessary elements were done away with. The "plan libre" - free floor plan - promised to the users endless flexibility and freedom in configuring their living environment. However by mid 60's the modernist movement in architecture failed its users.
One of the faults in modern architecture was its lack of adaptive capabilities to different circumstances of social or environmental nature. However some of its ideas of offering flexibility and standardisation opened new perspective into the field of architecture by taking advantage of the precision and efficiency of industrial production, which was further explored in the coming decades. If standardization and mass production failed at the large urban scale it pushed forward the small-scale products.
Other architects understood this issue and experimented with these production techniques and applied them to small-scale, modular projects.

Buckminster Fuller proved to be visionary in foreseeing many issues of today's globalized world, which he also tackled in projects like the "Dome House" - series and the "Dymaxion House" featuring lightweight construction materials, factory manufactured kits, on site

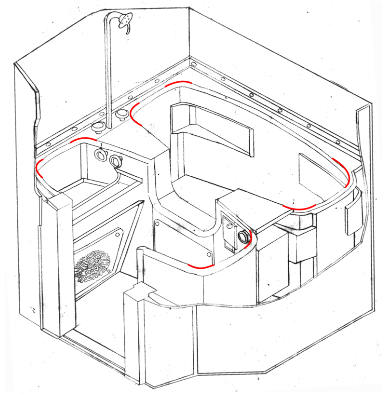


Fig. 3.1.03: “Dymaxion bathroom” 1930 Buckminster Fuller

Fig. 3.1.04: “Dymaxion house” 1930 Buckminster Fuller

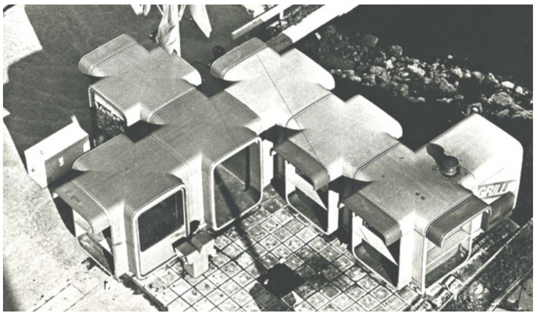


Fig. 3.1.05: K67 - glass fibre kiosk by Saša Mächtig

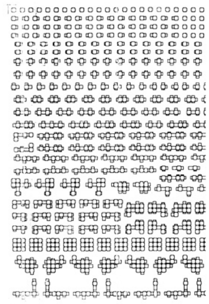


Fig. 3.1.06: K67 - fruit and vegetable stand in Ljubljana - Saša Mächtig

Fig. 3.1.07: K67 - modular units configuration

assembly. The latter invention was initially commissioned by the U.S. Army for mass-production as an accommodation for soldiers in the Persian Gulf. It included an one-sheet aluminium bathroom. The cladding panels for the house were manufactured out of aircraft aluminium, taking the advantage of a surplus of such materials and factories during that time. [13]

The 60’s gave rise to a wave of utopian theoretical projects, which insisted on the idea of mobile moving architecture ranging from urban scale like in Archigrams science fiction project series *“Walking Cities”* and Yona Friedman *“Spatial City”* to micro-scale inflatable bubble space, which were rather a second transparent skin for the human being and inviting him to various forms of interaction with his artificially gained protective layer.

Among the fantasy projects experimenting with the concept of modularity of architecture in the 1960’s one made it actually to mass production. It was the design *“K67”* of Slovenian architect Saša Mächtig, who responded with an initiative design to the demand of the city planning officials for new kiosks in Ljubljana. He attempted to extend the function of the kiosks intended to accommodate tobacco shops and newspaper stands by making the design modular and offering in theory the possibility of endless configurations. Mächtig employed for the execution of the prototype the newly developed material fibre glass and the aesthetic of modernism. In the second generation the kiosks were designed from parts, which could be disassembled for ease of transportation. Even though the architect did not intend the individual units to function in isolation, this flexibility however extended their functionality, being also adaptable for individual demands, reconverted into café shop or beehive. From the 60’s to 90’ when production was seized there had been produced 7,500 units which where shipped worldwide.

Fig. 3.1.08: “The Mobile Office”, or “studio in a suitcase” by Hans Hollein sequence from the screening of „The Austrian Portrail“, broadcasted on 7.12.1969 ORF

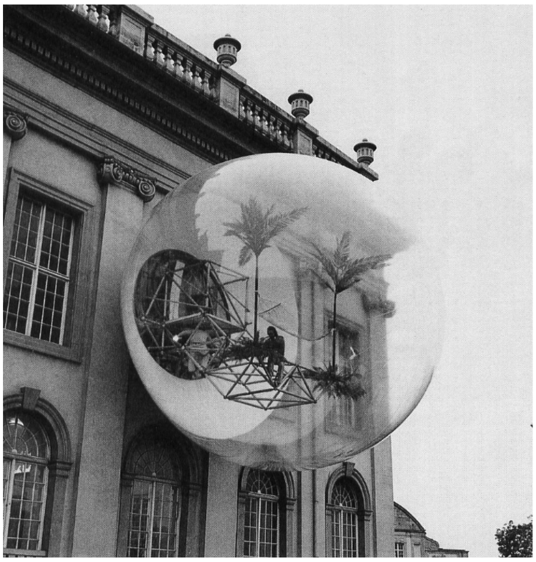


Fig. 3.1.09: Oasis no. 7 - Haus-Rucker Co. at Documenta 5, Kassel, Germany 1972

Maja Vardjan, curator of the Museum of Architecture and Design in Ljubljana describes in her catalogue essay, what distinguishes the K67 is *“its position between architecture and industrial design, embeddedness in the framework of a modern city and society, the rituals of daily life, and, last but not least, its persistent capacity to reinvent itself.”* [14]

When discussing the future potential of emerging technologies it would be the right time to mention the utopian architectural experiments of the 60’s and 70’s, which swept the architectural discourse of the time. Due to their playful and sometimes satirical approach they are often dismissed as an utopian ‘paper architecture’. Even if the resulting projects did not convince people to dispose of their belongings and move into inflatable bubbles or embark on space-ship-like structures and indulge in new experiences, and probably will never make it outside a museum exhibition, the radical statements the architects made through the design language resonate far into the future.

Hans-Hollein sensed the potential before the technology was even available. Hollein proposed 1969 the inflatable mobile office, which could be packed into a suitcase and provided take-along-workspace to inflate. As a demonstration he installed his mobile design office near Schwechat Vienna Airport on the field.

As a matter of fact, he boldly postulated in an essay “*Everything is Architecture”* 1967. The human being generates artificial circumstances, one of which is also architecture. Through this action of building he is determining his environment.

To Hollein architecture was a medium of communication. He also urged architects to stop thinking of architecture only in terms of a physical structure and understood the power, which media will play in the future of human experience, giving as an example the fact that the physical existence of monuments like Acropolis or the Pyramids of Egypt are irrelevant since most people only experience it by media, at that time only through printed press or TV.[15] Today a multitude of other digital means is ready to take one on a virtual trip. He was also fascinated with the potential of the phone to connect people from far away needless to mention, what impact the means of communication have on our present society and our urge to stay connected.

The Group *“Haus Rucker Co.”* (literally translating - ‘house mover’) proved even more radical in their design on the one hand satirizing and scandalizing the elder generation of architects, but also exploring new paths opened by new technology and materials. *“Taking their cue from the Situationist’s ideas of play as a means of engaging citizens, Haus-Rucker-Co created performances, where viewers became participants and could influence their own environments, becoming more than just passive onlookers.”* [16] The installation for the art exhibition, Documenta 5, in Kassel, Germany entitled *“Oasis No. 7”* showcased a scaffolding

Fig. 3.1.10: Mind Expander - Haus-Rucker Co. Vienna, 1967-69

Fig. 3.1.11: VR headset FOVE - product advertising

platform flanked by two palm trees. In order to shield this relaxation spot from the outside world it was encapsulated in a thin pneumatic bubble. The whole structure dangling attached to a facade.
The project series *"Mind Expander"* proposed head sets with the property of altering the perception of the user in different ways. *"The Fly Head"* for instance due to the curved shell distorted the vision and the audio gear inside played different noises, distracting also the hearing of the user from the outer noise. From today's perspective it does not seem something extraordinary, but it is straightforward, that their playful installations foreshadowed the emergence of virtual reality on the go, in the form of the VR Gear sets for smart phones, which instantaneously deliver the experience of a 3D cinema or brings you to places you could hardly access without the help of a drone equipped with camera. They envisioned a world made of disposable architecture. Nowadays the paradigm shifted from disposable to recyclable since the excesses of past decades have produced so much waste and explored resources with no consideration for the future generation, that we are forced to use what passed generations have discarded. This makes it necessary not just to consider space saving structure but also optimize the use of material in order to save and reuse the available resources.

3.2. Minimal space requirements

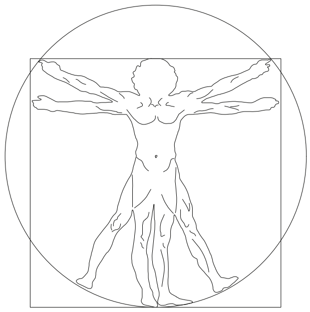


Fig. 3.2.01: The Vitruvian Man- represented by Leonardo da Vinci

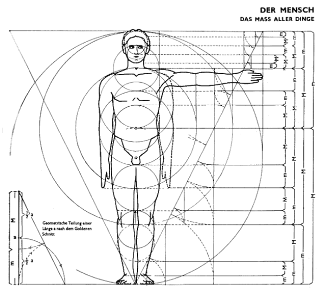


Fig. 3.2.02: Ernst Neufert - Measurement Basis

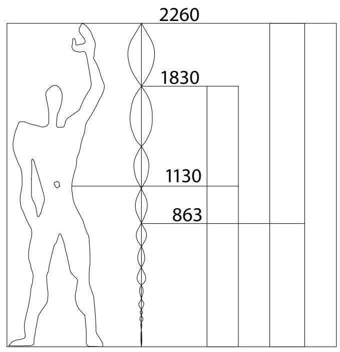


Fig. 3.2.03: Modulor - Le Corbusier

When considering minimal dwelling space the minimal necessary space required by anatomy to ensure the physiology of a human being has to be discussed together with the notion of anthropomorphism. Protagoras postulated in Greek antiquity *"Man is the measure of all things"* defining also the concept of anthropomorphism – *"the attribution of human characteristics or behaviour to a god, animal, or object"* [17] - Oxford Dictionary. Anthropomorphism in architecture specifically was introduced to the Western World by the Roman architect Vitruvius, who had a particular interest for the human body proportion. As architecture is produced in order to house the human body and its necessities and habits consequently it has to follow the measurements and proportions of the body. It was however not until the 1930's that a manual of architectural standards was published by architect Ernst Neufert entitled *"Architects' Data"* focusing on rationalizing the buildings and graphically illustrating the measurements of architecture in relation to the human body to ensure the proper functioning of a building and the health and well-being of the inhabitants. The function of a house is to provide protection against weather and an environment, which maintains the well-being of its inhabitants. More precisely the atmosphere, which the interior should provide is describe as well oxygenated air, pleasant warmth, air humidity and sufficient light. These conditions are of course determined by external factors like location, main orientation of the house on the plot, space configuration inside and the used materials. The fresh air influx in a dwelling is very important for the proper functioning of the human body. It is recommended that the carbon dioxide content in a dwelling should not exceed 1‰ with a single exchange rate of air during an hour. In the conventional free standing buildings an exchange rate of 1½ to 2 (even with closed windows) occurs, so the required air space volume is of 16-24 m^3 meaning that at a room height of 2,5 m a single adult needs a floor area of 6,4 - 9,6 m^2 to ensure proper oxygen intake, when the inhabitant performs moderate physical activity. [18]

As previously mentioned Le Corbusier was also fascinated with the relation between the proportion of the human body in relation to the architecture he produced. The aspect of human scale was of main importance in his design. For this purpose the *"Modulor"* was defined as a measuring unit, by which he described mathematical proportions in the modern human body and applying them also to his projects. He described the proportions of the Modulor as *"range of harmonious measurements to suit the human scale, universally applicable to architecture and to mechanical things".* [19]

Another example of interior space optimization of the required space in a kitchen was undertaken by the Austrian architect Margarete Schütte-Lihotzky, who developed the *"Frankfurt Kitchen"* out of the necessity to reduce the space allocated for cooking in an apartment. The First World War left Germany in an acute housing crisis, which was set to be solved by social housing projects in the 1920's addressing the needs of the working class. The Frankfurt Kitchen was intended for a 2 room apartment of the time, therefore a traditional kitchen

Fig. 3.2.04: Frankfurt Kitchen - Margarete Schütte-Lihotzky, reconstruction MAK, Vienna

Fig. 3.2.05: Aircraft - on board kitchen

would not have fit in the scarce space of the time. The commissioned architect set to study and rationalize the processes of the house wife and the result was an optimized space where distances are reduced to the minimum requirements in order to eliminate any unnecessary movements and pathways in the process. The resulting design resembled a "*command centre (…) in which the role of the housewife was revalued and the quality of work and leisure time enhanced".* [20] The Frankfurt Kitchen has reminiscences in the modern fitted kitchen, which however due to changes in gender roles has left the enclosure of a kitchen as a separated room and merged with the living room, making the act of cooking more of a social event then a duty. The aesthetic of the Frankfurt Kitchen is still visible in aircraft on board kitchen, which have a very limited space available and have to store and deliver food for the passengers according to a predetermined and rationalized path movement.

3.3. The minimal floor plan

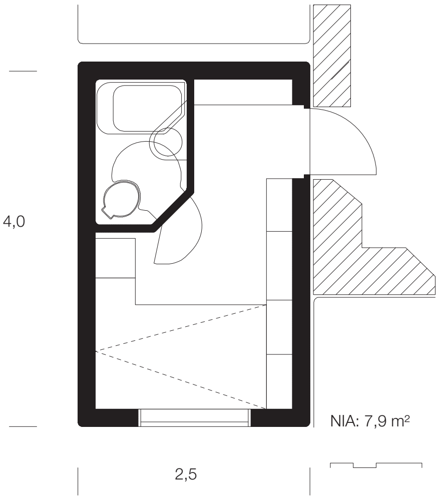


Fig. 3.3.01: Nakagin Capsule Tower - floor plan capsule

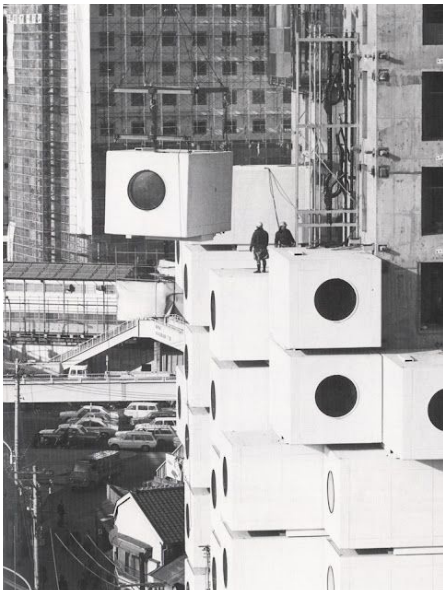


Fig. 3.3.02: Construction site - installing capsules 1972

What is the minimal requirement for living? When thinking of the design of a minimal space it is the first question to be asked in order to start the reduction process to the bare essential, without stripping the design of quality. Projects with interesting floor plan solutions will be discussed in terms of minimal space they provide, this step being also important for the later design process.
Needless to say, there cannot be a one-size-fits-all floor plan solution to answer the needs for every user. It depends of course on a great variety of factors like national regulations, cultural background, climatic region, social status, personal habits just to name some aspects. However, these needs are constantly changing, so a spatial configuration may be fit for the user only at a given time and become insufficient or too lavish at other time. Unfortunately, the built environment is not yet designed with the capability to adapt to the user's life changes. It would be also difficult or even impossible to tackle adaptability of all factors that may occur like financial, climatic, spatial configuration, location.
One of the most iconic examples of the visionary movement of metabolism, which was actually built is the Nakagin Capsule Tower in Tokyo, Japan designed by architect Kisho Kurokawa. It consists of two fixed towering structures, which house the circulation, to which 140 individual pod units could be attached by bolt and nut fixtures. An individual capsule includes a bed, storage area in the cleverly designed furnishing and a bathroom. Following the idea of metabolism that everything surrounding us consists of renewable cellular structure, the capsules were planned to be replaced with upgraded versions after 25 years. However, there was no feasible model to meet the intention of the architect, so after 45 years the original capsules are still in the same position with irreversible traces of time and the entire structure facing demolition due to investment speculations. This intention sparked sharp criticism of the architectural scene in many published articles:
"(…)Demolishing the building instead of renovating it is a testament to the power of a profit-driven society. Since Kurokawa's death, there has been no real initiative to preserve this monument dedicated to forward thinking. Instead, it has become a demonstration of the lack of appreciation for not just architectural history, but also the possibility that was once encapsulated in the structure."[21]
The New York Times featured an article *"Future Vision Banished into the Past"* on the demolition initiative characterizing the structure as *"… the crystallization of a far-reaching cultural ideal. Its existence also stands as a powerful reminder of paths not taken, of the possibility of*

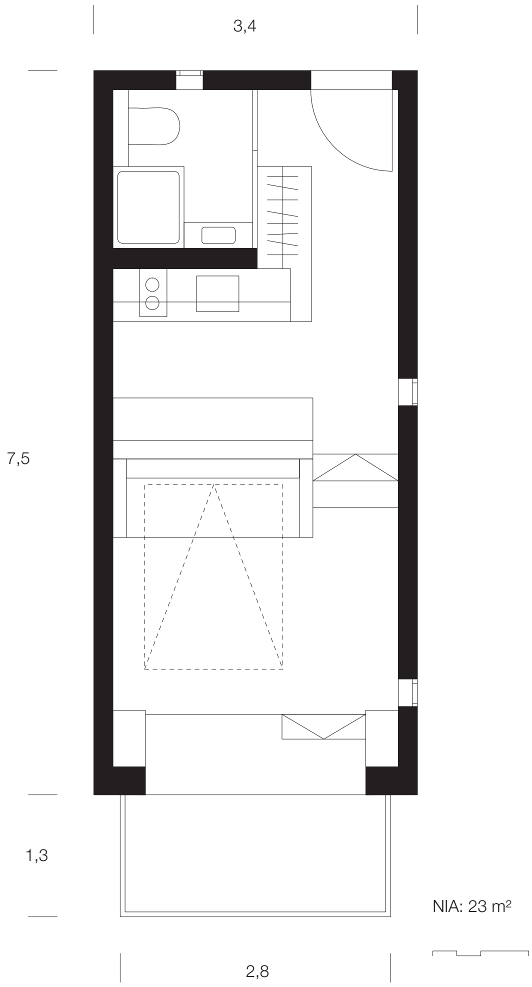


Fig. 3.3.03: Kasita floor plan

Fig. 3.3.04: Kasita living unit

Fig. 3.3.05: Kasita - plug-in rack for units

worlds shaped by different sets of values."[22]

However, this time society might be the one in need of finding new housing concepts and embracing temporary accommodations and new ethical considerations.
Based on recent observation, there is an increasing demand on temporary small-scale translocatable accommodation structures. Some of the structures will be presented as they influenced the course of the design and helped in creating an understanding for the conveniences and problems that space reduction brings along.
There is a general tendency towards minimalistic living concepts in terms of space availability, resource usage and ownership. It comes as an answer to the instability of the economic market in the Western World since 2008, which left many people with distrust in their economic capability of owning property and who sought to liberate themselves from the rigid models of either renting or buying a house. This called into being the "*Tiny House Movement",* which rose in the USA but also found supporters across Europe, along with a wide range of projects, which deal with a reduced lifestyle and the promise of independence from the grips of consumerist society.
What started out of a financial crisis, mutated later to a new lifestyle, trying not to reduce just the space required for living, but also of possession in general, expanding it to an environmental-friendly existence, where one is intended to minimize his carbon footprint through lifestyle choices. Although the denomination is somehow loose regarding the square area of an accommodation in order to classify as a tiny house and whether the structure has to be movable or on solid foundation. These unclarities have also sparked a great deal of legal debates forcing officials to reconsider building regulations. However, legal details will not be discussed in detail as they differ very much from country to country and as it would drift

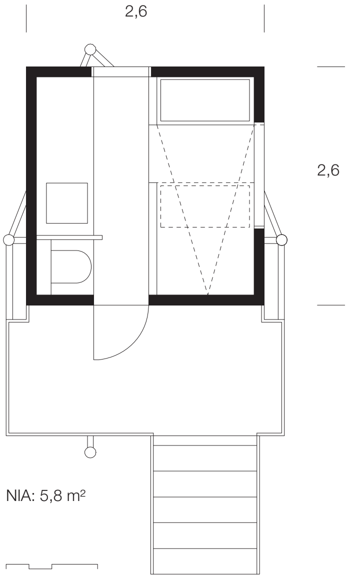


Fig. 3.3.06: Micro compact House - floor plan

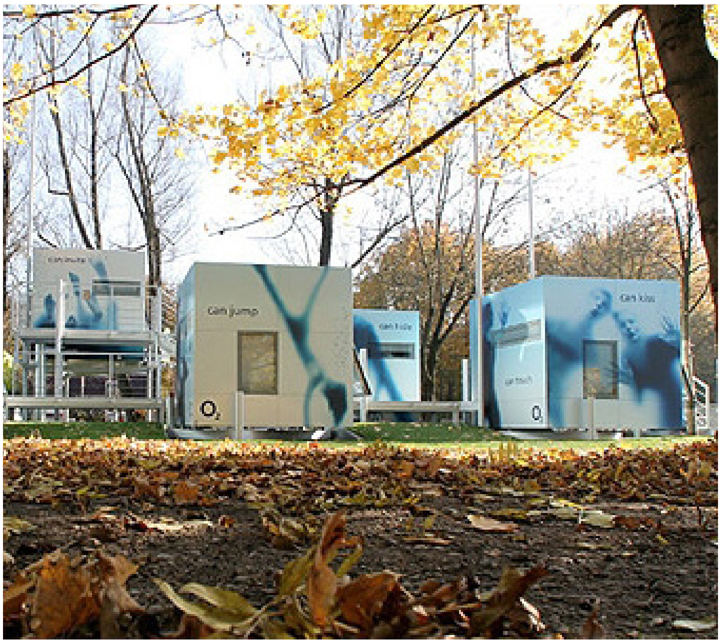


Fig. 3.3.07: Micro compact House - O2 Student Village

away from the goals of this paper. As a general rule a site is required to install the housing unit along with approval from local institutions in order to connect to communal facilities.
One conceptual project which raised out of the Tiny House Movement is the *"Kasita"* modular living unit (fig. 3.3.03 - 05) developed by Jeff Wilson, former Professor at Huston-Tillotson University, Austin. The website of *"Kasita"* advertises the micro home as *"a product, aiming to house the future."* [23] The end result has not only the perfection of a product design but also the experimental background of the designer having lived for a year in a 3 m^2 dumpster in order to better understand the challenges of living in a constricted space. The unit is intended to fit a multitude of possible uses: dwelling, office, commercial. The prototype contains the essentials of a home: bathroom, kitchen a convertible living/bedroom and a generous bay area with floor-to-ceiling glazing for optimal lighting. The different areas are designed with different heights giving different special experiences and using these level differences in the floor as storage. The units can be also stacked and provide a take-away living unit in urban environments. The first location for the docking rack to place the individual units is planned in Austin, Texas but is intended to also extend to other cities offering its future users the possibility to have their apartment transported to a different location.
The DIY movement Tiny House became an attractive design task, in which especially young architects would get involved coming up with creative design solution. The competitions focusing on a minimal mobile living space are testimony to this – *"Tiny House Design Competition"* by the Magazine Volume Zero [24], *"Rise Tiny Home Design Challenge"* by Rise web-site [25], *"Co-machines"* by Onoff online network [26], *"Hong Kong Pixel Homes International Competition"* [27], just to name some of the competitions initiated in 2017, which had as main focus the design of minimal space dwellings.
One of the architectural practice which devoted to creating an exemplary prototype for one-room living space is Horden Cherry Lee, London in collaboration with the Technical University of Munich and Tokyo Institute of Technology started developing the Micro Compact House *"mc-h"* as an answer to the increasing demand for short-term accommodation targeting students and users who travel for business or leisure. The compact living box was developed by using the fabrication technology used in the aircraft and automobile industry

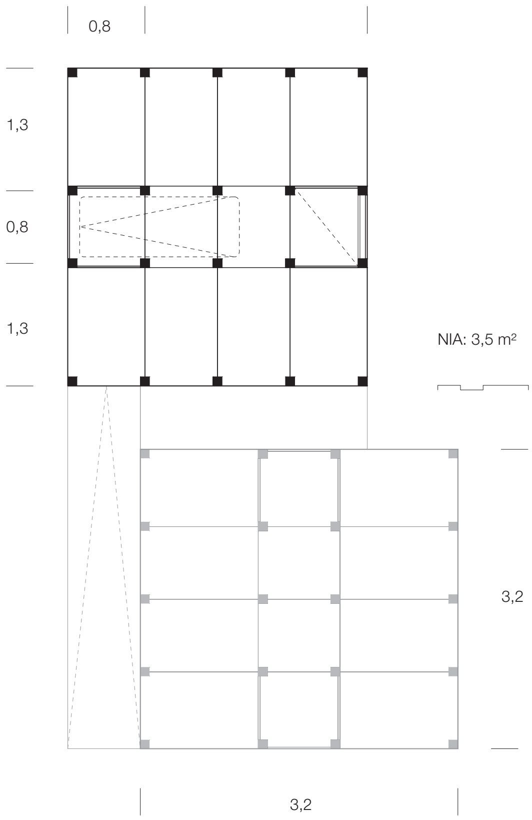


Fig. 3.3.08: “Living in the Wall” - floor plan reconstruction

Fig. 3.3.09: “Living in the Wall” temporary installation 21er Haus, Vernisage - June 21, 2016 Vienna

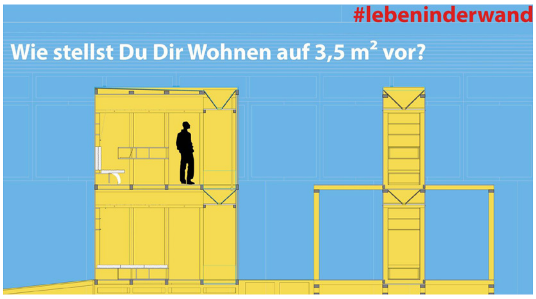


Fig. 3.3.10: “Living in the Wall - How do you imagine living in 3,5m²?” -Exhibition advertising poster

and was inspired in terms of scale and space order by the Japanese tea house according to the description of the Micro Compact Home website. [28]
The units are assembled in a partially automated factory in Uttendorf, Austria taking 3 months to manufacture a unit. The structure is made either of wood or aluminium frame and the standard dimension is a cube with 2,6 m side length. A student village consisting out of the units was commissioned by Studentenwerk, state owned dormitory provider for students in Munich, Germany as a pilot project to test the units.
An interesting experimental project realized by Vienna University of Technology is the installation *“Living in the Wall”*, which was exhibited in the courtyard of 21er Haus – Museum of Contemporary Art as part of the thematic exhibition *“Translocation - Transformation”* of Chinese artist Ai Weiwei. *Living in the Wall”* thematized the baroque usage of the wall to provide a hidden infrastructure, the structural element wall was infused with life. The resulting structure was used as a meeting point for students, professionals and performing artists and provided during the summer months of 2016 not just an example of paradigm shift regarding the housing necessity, but also a platform for discussion and interaction of various groups. The structure consisted of 3,5m² enclosed space, which had the purpose to visualize to the public how much space a person has at disposal in a refugee camp. The functional quality of the wall was reinterpreted from that of a structural element occupying space to a living space provider, questioning whether a tiny space can be a feasible short term solution for people in need of shelter and short of financial means. The design concept was intended to provide an alternative solution to buildings in need of revitalization or as a form of short-term emergency shelter or social housing alternative. [29]

A step towards minimizing the living space in order to offer more affordable dwelling opportunities in the growing city of Vienna, has also been defined as a priority by city officials. The city of Vienna has a vast program of housing opportunities addressed for different groups of users with little income. The global trend “smart living”, which features more compact dimensioned floor plans, than the regular available apartments as a new dwelling concept of minimized living space was also launched in the city.
National standards regarding minimum dwelling space vary a lot around the globe, it would

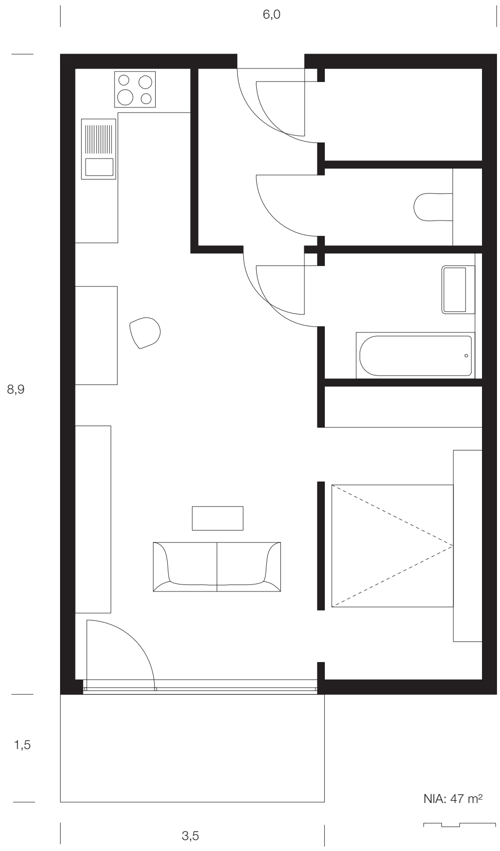


Fig. 3.3.11: Type A apartment, Vienna - floor plan

Fig. 3.3.12: Type A apartment "smart living"- isometric view

be futile listing the differences here and all the factor that affect it. But as a means of comparison and for getting a broad idea of differences and similarities for the purpose of dimensioning dwelling units, general terms of the regulations from Austria, Vienna and Chinese National Standards will be shortly discussed regarding minimal space, representing two environments, which have been personally experienced. Even though there is not a great discrepancy between the dwelling space requirements of the two regulations today it is significant to mention that national housing standards are a product of various factors like political, economical and cultural circumstances as well as demographic fluctuations. Unquestionable the more space one individual owns the better, but as the dwelling space is a purchasable good, the individual can only afford one in the range of his financial means. With the exploding housing prices in big cities it is not a question of how large an accommodation can be, but rather how affordable. Affordability limits of course quantifiable space and its quality. At this point regulations come in play defining national/local standards to insure minimum standard and to regulate the market avoiding the creation of overpriced housing with poor living quality and the negative consequences such spaces have on the inhabitants. The Building Regulation of Vienna (Wiener Bauordnung) recommends for a day room not less than 10 m^2 with a height of 2,5 m and natural light of 1/10 of the floor area. The size of a single (type A) apartment consisting of living/cooking space, anteroom, bathroom and toilet is described by the rental law as an accommodation with no less than 30 m^2 [30], but in order to be accessed through the public housing program of the city it should not exceed 50m^2. The beginning of the 20th century found the capital of the former Austro-Hungarian Monarchy with a population of around 2,0 mio. people as opposed to the 1,77 mio. in 2017 but with fewer built square meters for dwelling space. The housing situation was very tense since the housing market was determined by private investors and high speculative intentions. The unaffordable rents forced citizens with low income to generate the *"bed rental"* – phenomenon (*"Bettgeher"*) [31], where families would rent in their apartment a place to sleep the night for people unable to afford not even a room. Needless to say, today's regulations are a result of a historical development. Vienna's population has actually decreased af-

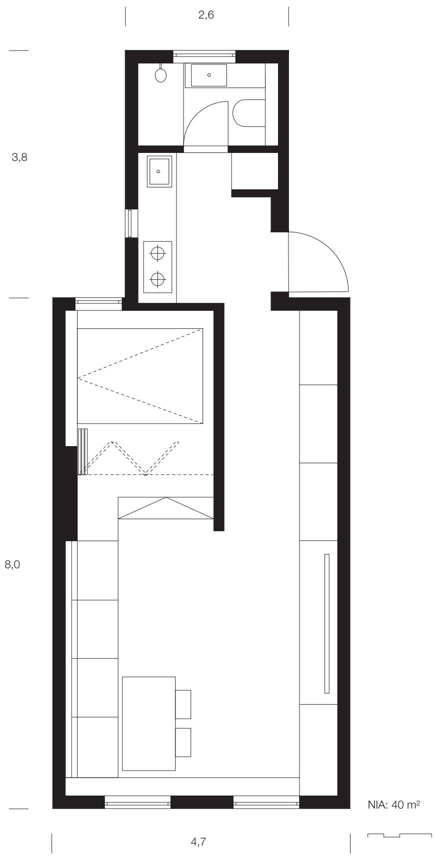


Fig. 3.3.13: More Design Office - Folding apartment - floor plan

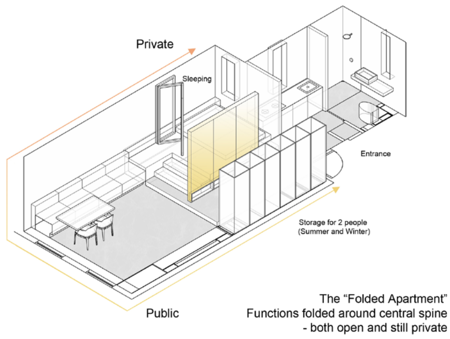


Fig. 3.3.14: Folding apartment - isometric view

Fig. 3.3.15: Folding apartment - interior

ter the 2nd World War and only started to rise after the fall of the Iron Curtain, which had an impact on the housing regulation and defining the minimal standard shrunk form 35m² in the 1970's to 30m² in the current regulation. In the past century, a lot has been done to improve the housing situation by establishing a state owned public housing system as an alternative to private investment. This housing model proved highly beneficial for Vienna and its inhabitants. According to the website of Wiener Wohnen every fourth Viennese benefits from the public housing service.[32] The new influx of population calls for new forms of housing models with reduced net internal area at an affordable price. This tendency is not intended to strip housing of quality, but to make it more efficient and affordable for modern living. The first smart apartments "Smartwohnen" were ready to use 2014 and made available through the social housing program of Vienna aiming to align to international trends of "smart living" in big cities, but compensating for the loss in private space with a wider offer in communal space in the newly developed projects. Another statistical fact, which explains the high demand for small apartments in Vienna is also the fact that 45% of the registered households in Vienna are officially registered as single households, more precisely out of the 840.000 registered households 370.000 are occupied from an administrative point of view by one person. [33]

On the other half of the globe a look will be taken at one of the fastest growing city in the world, Shanghai with an urban population of over 20 mio. (2010) and adding 1 mio. every year in total population (urban and rural) since the beginning of the 90's. [34] The influx of population is due to migrant workers from other provinces. It is hard to draw any parallels between the two cities since they are rather at opposite poles, Vienna being a rather small European city and Shanghai being one of the fastest growing cities in the world especially in terms of population. The typology of residential buildings also differs very much. In Vienna the closed block type is the most used form, whereas in Shanghai a great proportion of the old building substance are low-rise lilong houses, different variations of dormitory type in former worker villages and the newly imported high-rise tower typology, which have different variation of minimal space. As the high-rise apartment is rather a Western typology an apartment floor plan in a multi story lane

Fig. 3.3.16: Better Shelter - assembly kit

Fig. 3.3.17: Better Shelter - Refugee camp

house as a traditional Shanghainese housing typology will be analysed in terms of the floor plan distribution even if it is no longer a feasible building typology for the booming city, but it will offer a solid insight into cultural differences regarding space usage and functions configuration for dwelling.
The chosen project is a small apartment in a multi-story lane house in the French Concession, Shanghai revitalized by More Design Office 2015. The project is entitled *"Folding Apartment"* and it refers to the concept of folding the functions around a "*central spine"*[35], as opposed to a linear progression from public to private. It is also mentioned that the living room area is oriented to the North-South, which led the architects to design a translucent folding wall to the bedroom area in order to increase the light gain coming from the bedroom South oriented window. By elevating the bedroom area, storage space is created and the steps can be also used for sitting. Also a consistent cross-ventilation is insure since every room in the apartment has a window.

Regardless of the building typology, the minimum size for a single apartment in urban areas, consisting of living/bedroom, kitchen and bathroom is defined as no less than 22 m^2 and the height of bedroom and living room must be no less then 2,4 m according to the Design Code for Residential Buildings in PRC, 2011. [36] Regulations in China have been established only in the 1980's. Even if they are less precise in the specification they make, there can be observed a similar tendency in reducing dwelling space. No comparison for the single room apartment can be made since there was no specification prior to 2011 but for instance the requirements for a living room was downsized from 12 m^2 (2003) to 10 m^2 (2011).

This juxtaposition serves the purpose of showing the differences of living space requirements, which consequently cannot be similar due to demographic challenges, climatic conditions and cultural differences, which should generate particular residential housing typologies.

However there are also extreme cases of people having to live temporarily on limited spaces during humanitarian crises in refugee camps. According to the United Nations Refugee Agency, Emergency Handbook Guidelines, the minimum shelter space per person should be no less 3,5 m^2 with 2 m ceiling height and an accessible camp area of 35 m^2 per person being considered acceptable.[37]
Ikea Foundation in collaboration with the United Nations High Commissioner for Refugees (UNHCR) developed *"Better Shelter" - "the weatherproof, quick-to-assemble and sustainable make-shift home for refugees, IKEA's temporary housing solution for aiding displaced families and individuals who are fleeing conflict, disaster and climate change"*.[38] The shelter is delivered in 2 flat packed cardboard packages 80 kg each. The modular structure consists of steel pipes, which are hinged together and cladded with polyolefin (recyclable plastic polymer) panels button-zipped to each other. A unit offers 17.5 m^2 space inside, twice the area of a conventional emergency tent, with a limitation in length of 5.7 m due to emergence escape safety. These shelters have an extended lifespan of 3 years and are *"a clear demonstration of scalable design that has the ability to make a worldwide impact"*.[39]

Criteria	Nakagin Capsule	Kasita	m-ch	L.i.t.W.	Type A Vienna	Folding Apartment Shanghai	Better Shelter Ikea
NIA m² Net internal area	7,9	23	5,8	≈ 3,5	47	40	17,5
Price € * property not included ** local price range	17.600-26.700 [40]	116.000* [42]	38.000* [44]	-	183.000-370.000 **	160.000-400.000 **	960* [51]
Price per m²	2.200-3.400	5.000	6.550	-	3900-8000 (outside city centre) [46]	4000 - 10000 (outside city centre) [49]	55
Rent €/month	360-540 [41]	500 [43]	150 [45]	-	630-900[47] 360(7,5 €/m² in social housing apartments) [48]	500-1000 [50]	-
Modular	++	++	+	+++	+	-	+++
Construction method	prefabricated	prefabricated	prefabricated	on site	on site	on site	prefabricated on site
Movable	auxiliary	auxiliary	auxiliary	auxiliary, requires dismantling	No	No	auxiliary
Compactness	+++	++	+++	-	+	-	+++
Facilities	sanitary	sanitary, cooking	sanitary, cooking	-	sanitary cooking	sanitary cooking	-
Incorporated design elements	bed, furniture, sanitary appliances	sanitary, kitchenette, convertible bed/ sofa,storage	sanitary, kitchenette, convertible bed to dining table	(possible) bed, kitchen, living room	-	storage + wall bed+storage sitting steps	-
interior flexibility	-	+	-	+++	+++		+++

Tab. 3.3.01 Comparison of the discussed floor plans

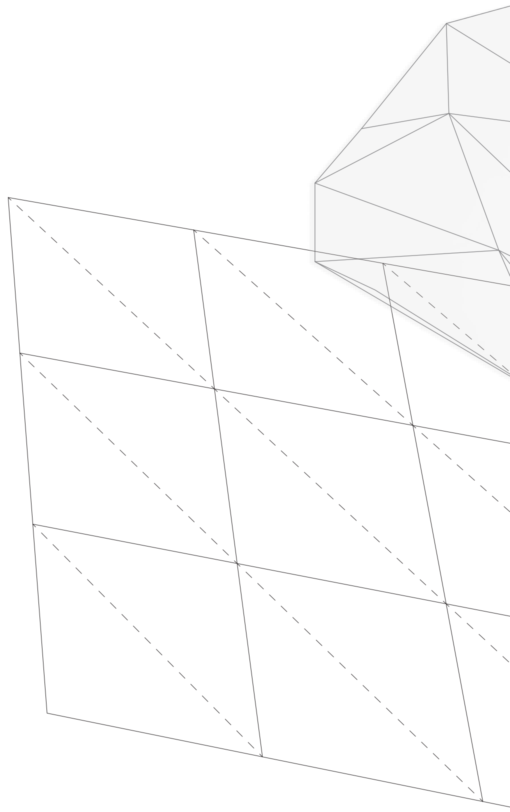
In table 3.3.01: Comparison of the discussed floor plans a juxtaposition of the different projects is presented for a better overview quantifying and qualifying the floor plans. The comparison includes net internal area (NIA m^2), acquisition price of a unit or apartment, acquisition price per m^2, rental price per month if available, the modular quality of the units, construction method, movable (whether it can be transported to a different location), how compact the floor plan is, what facilities it offers and whether they are incorporated in the interior design and flexibility referring to the user being able to reconfigure the interior or extend it. The comparison offers an overview of micro housing units and single apartment units in Vienna and Shanghai.

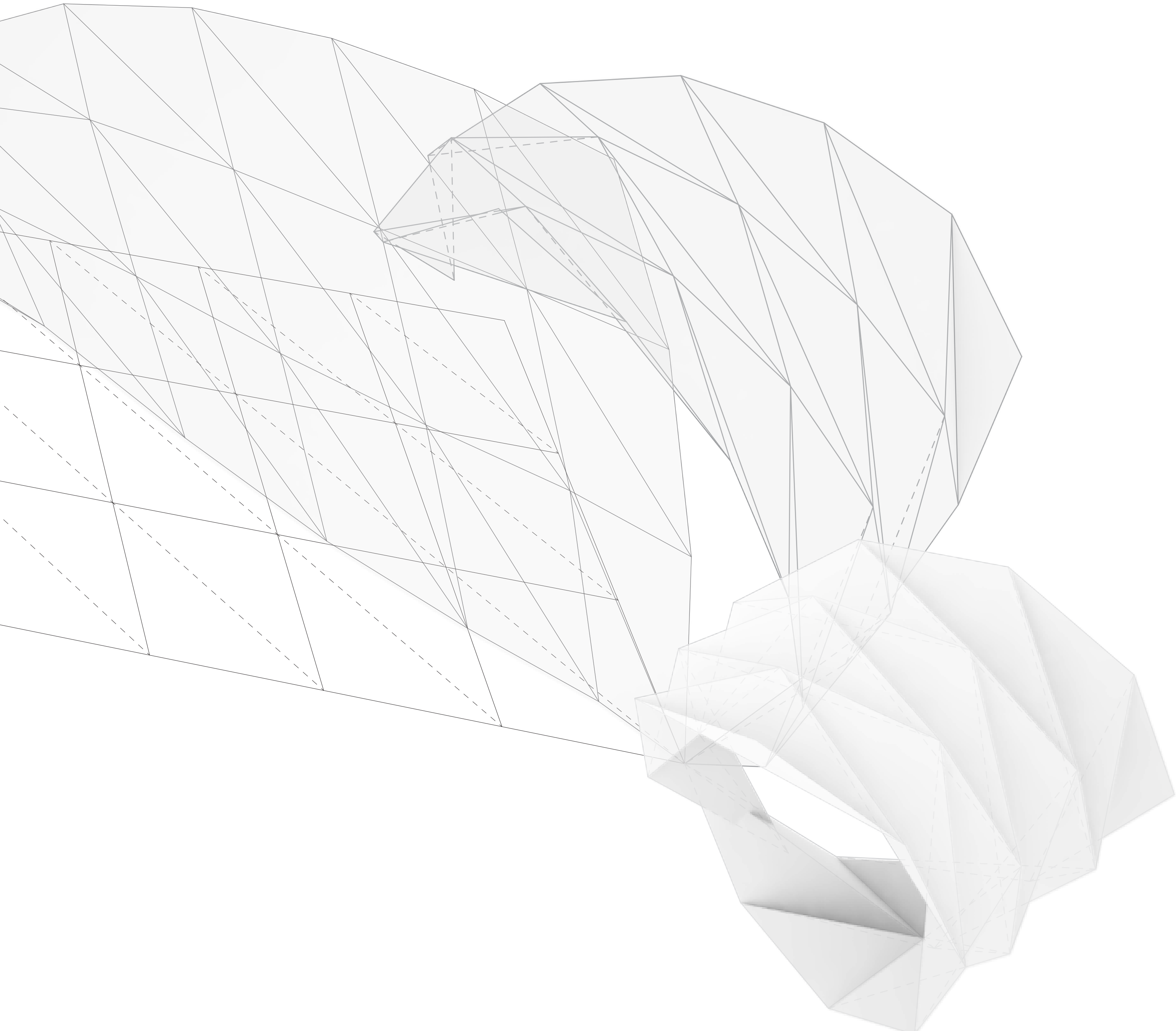
The prices for the micro housing units do not include the acquisition price for land property, transportation, installation and maintenance costs. Also the prices for the presented single apartments in Vienna and Shanghai are not the exact purchase prices for the respective apartments, but rather represent a price range in which a similar apartment can be purchased or rented.

"Living in the Wall" does not offer terms of comparison in terms of investment, but it provides a new concept to approaching minimal space and use of space-in-between.

The discussed projects also offer a range of different functions, which also precondition the circumstance they would be used. The first 3 projects were designed as experiments for a reduced lifestyle featuring an optimized living space, an art installation which reinterprets the structural element wall, single apartments from Shanghai and Vienna and a shelter meant for refugees. Every project addresses different users, evidencing the main and essential purpose of a dwelling to provide protection from the outer environment with the simplest means available, best evidenced by *"Better Shelter"*.

It becomes obvious that structures not tied to a location cannot become a feasible alternative for the large public, if no auxiliary services are provided to transport and maintain the units. The simple acquisition and installation of a unit on a private owned property is no ideal model of usage for the units. In order to take advantage of the full potential a service infrastructure, private or communal, is needed in order to manage, maintain and reconfigure the units location, if needed, similar to serviced apartments, hotels or dormitories.





4. DEPLOYABLE STRUCTURES

Fig. 4.01: Solar array NASA testing folding prototype

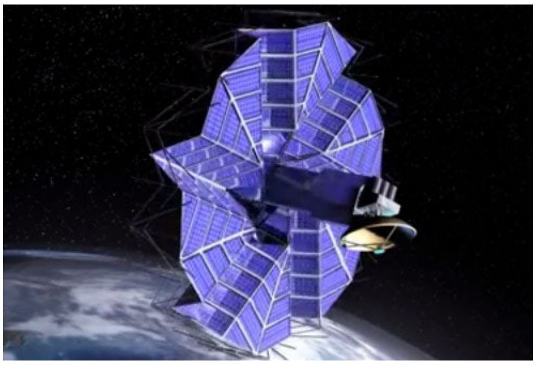


Fig. 4.02: visualization of solar array in space

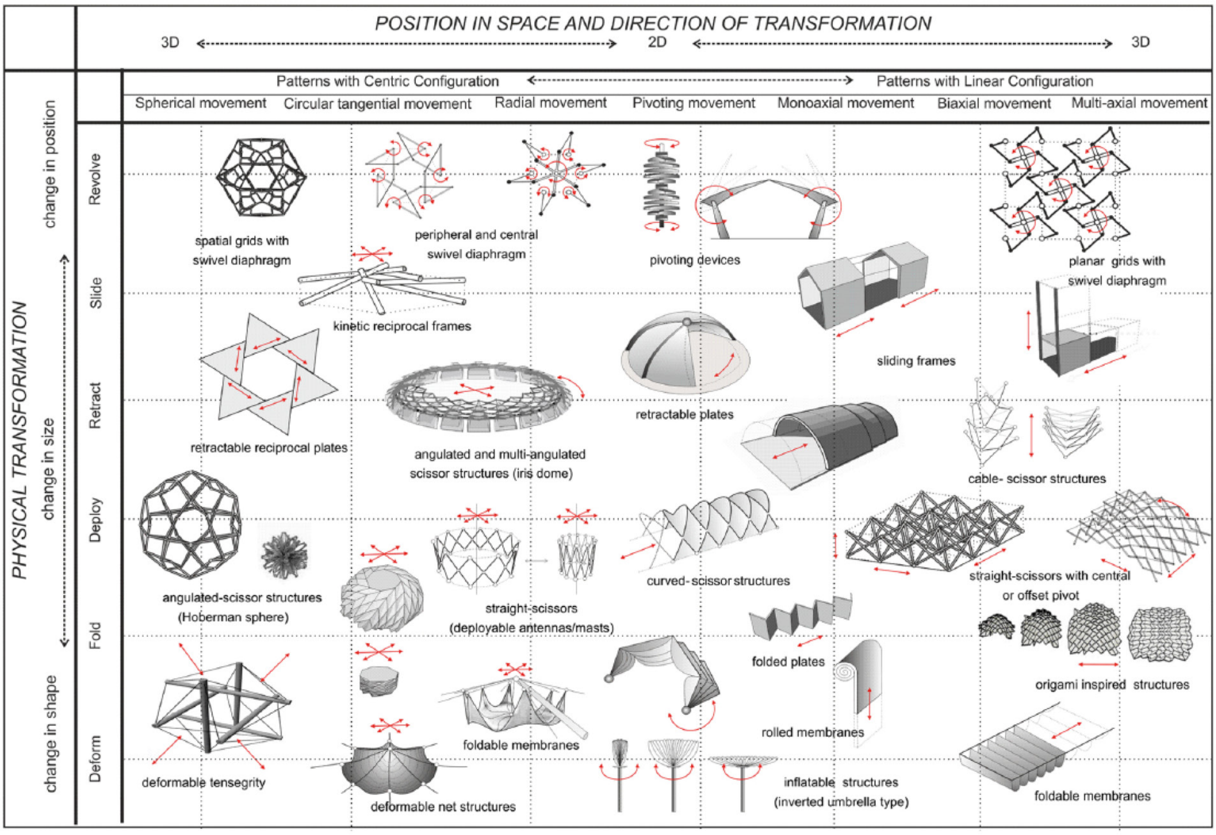
While deployable structures are not a new invention for modern society, since they served as a dwelling form for many past civilizations and are still in use today, it was not until the beginning of the 20th century and the development of the automobile industry and other mechanical fields, that kinematics found also its way into projects of architects and designers. The emergence of the aerospace industry in the 1950's and its space exploration missions made it necessary to look into the potential of deployable structures for use in space missions. Today the demand for temporary lightweight deployable structures, which are easy to transport and fast to install pushed the interest of many specialists from various fields of study to further develop and optimize deployable structures.
Due to being a relative novel field of study, there are many scholars, who took interest in deployable structures and formulated definitions to describe them, varying from broad to very precise specifications. Some will be listed below, so as to exemplify the large spectrum deployable structure operate upon.
In generic terms deployable structures denominate a broad category of structures that transform from a close and compact configuration to a predetermined expanded form, in which they are stable and can insure load transfer.[52]

They *"can expand and contract due to their geometrical, material and mechanical properties."*[53]

"Such structures may pass from a folded to an erect state; and in many cases the component parts are connected throughout topologically, but alter their geometry through the process of deployment. In the process of deployment the initial mobility is transformed into a final rigidity. But that is by no means the only possible scheme for structural deployment."[54]

Furthermore, when attempting to classify deployable structures one realizes the true extent of the topic. As new systems are emerging, most classifications will not keep up with the pace of innovation and may be already outdated. The classifications are also closely related to the field by which they were initiated. Classifications for mechanics or robotics will vary from those initiated by material science or architecture.
Needless to say the versatility of these structure makes a large span of applications possible with scales ranging form millimetres to hundreds of meters. In the medical industry it was used for designing stents, small devices which would unclog blocked arteries, by the automobile industry for developing safety air bags, in the space industry for developing space exploration equipment such as solar arrays, telescopic lenses and inflatable booms.[55]

One classification of deployable structures, which provided a comprehensive overview and seemed to suit the purpose of this thesis is by Carolina M. Stevenson in *"Morphological principles: current kinetic architectural structures"* in table 4.01. Notice must be taken, that it is by no means a complete categorization and also it is simplified since combinations of systems are not listed.
However in more recent studies deployables have became a subclass encompassed in the broader field of adaptive structures, characterized by their ability to change shape, the mechanical and physical properties, according to



Tab. 4.01: Classification of deployable structures according to Stevenson C.M. in: “Morphological principles: current kinetic architectural structures”

external influences. Adaptability and responsiveness to exterior stimuli will be only mentioned in the projects exemplified, but will not be part of the design application of this thesis as it would involve much more complexity for the design task in order to be achieved.
Last but not least mention must be made, that Nature offers probably the greatest and most complex inventory of deployable structures like plants, insects and even the human body, which science has just begun to comprehend and tries to emulate through biomimetics.
The discussion on deployables is inexhaustible and will create many more comprehensive research papers and projects in order to achieve new insights and advances in the field.
For the purpose of this theses the subject will be narrowed down to the study of plate structures and actuated joints to achieve deployment in the design application.
Moreover moving away from the theoretical discussion of deployables, small-scale architectural projects, which make use of deployable mechanisms will be investigated for getting an overview of the state-of-the-art and a better understanding of the techniques and mechanisms architectural professionals have employed in their projects.
The complexity of the design tasks forces architects to explore new methods and mediums of different disciplines to provide new solutions. The advances of computational design offers architects a great extent of freedom in exploring new forms, these forms with their flexible features and temporal and/ or spacial transformability potentials are mostly incompatible with conventional structures. Hence, architects and engineers are seeking for new structural configurations to achieve architectonics with the required stability and flexibility both structurally and functionally.
Deployable structures allow elements to be

Fig. 4.03: Heart stent prototype, designed by Zhong You and Kaori Kuribayashi-Shigetomi

Fig. 4.04: Hornbeam leaves - mature leaf deployed, sprout folded

folded in a compressed state for the ease of transportation or storage before being expanded once they reached the destination. Deployable shelters can provide a viable solution as temporary relief in case of emergencies, natural disaster or any other situation, where a temporary accommodation is required. The presented projects illustrate how folding is used as a design concept in order to generate deployable structures. However only small-scale structures and mechanisms will be discussed to keep in accordance with the set goals of the thesis, even though architects have ventured in creating large scale structures like membrane roofs, retractable stadium roofs, inflatable arenas just to name some.

4.1. Deployable small-scale structures in architecture

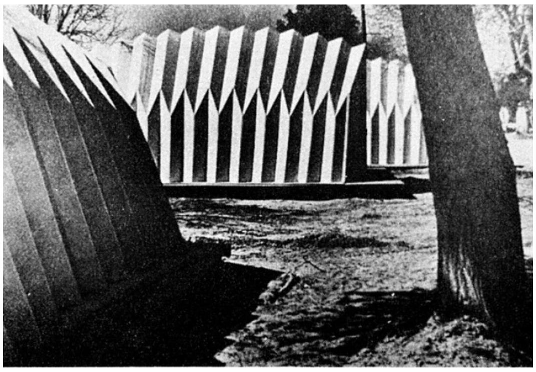


Fig. 4.1.01: California shelter for farmworkers Hirschen van der Ryn

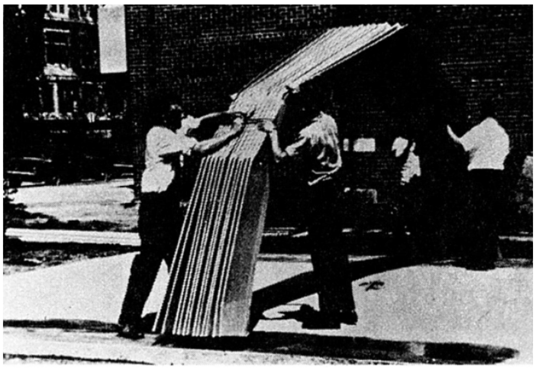


Fig. 4.1.02: California shelter for farmworkers folded structure

Fig. 4.1.03: Tricycle House - People's Architecture Office (PAO) - interior configuration for resting

Fig. 4.1.04: Tricycle House And Garden - People's Architecture Office (PAO) and People's Industrial Design Office (PIDO),Beijing

A record of temporary shelters for Californian farmworkers created by Hirschen van der Hyn and Yates is presented by Prof. Sedlak in his study on *"Paper-board Structures"* [56] presented at a conference at Surrey University, UK in 1975. The paper investigates the use of cardboard material as a structural element. It also accounts for the early uses of folding structures for temporary accommodation. The quality of anti-prismatic shapes to improve the load-bearing attributes of the material was recognized early on. This attribute is also used in rigid structures, where wide spans have to be bridged and folded plate structures are used due to their increased stiffness and optimized performance of material achieved through the creased geometry. These static properties were put to use by architects like Felix Candela, Pierre Luigi Nervi, Renzo Piano in rigid wide spanning concrete structures. The temporary shelters show an incipient state of the preoccupation of architects and engineers with folding structures and their potentials.

Moving to our days the concept of folding is often used in experimental design projects. *"The Tricycle House"* project designed for the 2012 *"Get it Louder"* Exhibition in Beijing, was intended to remove the house from its foundation. The temporary shelter mounted on a tricycle proposed an alternative solution to the inconvenience of property ownership and translocation practices. It also experiments with folding plastic material, polypropylene, which does not break when creased. Appliances in the house include a sink and stove, a bathtub, a water tank, and furniture that can transform from a bed to a dining table to a bench and counter top. The sink, stove, and bathtub can collapse into the front wall of the house. The folding tricycle house is accompanied by the tricycle garden. *"The Tricycle House suggests*

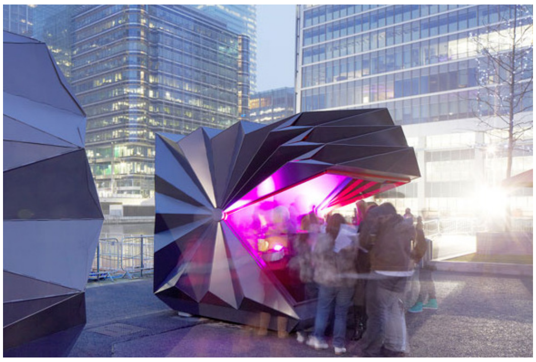


Fig. 4.1.05: Prefabricated origami kiosk in London - Make Architects

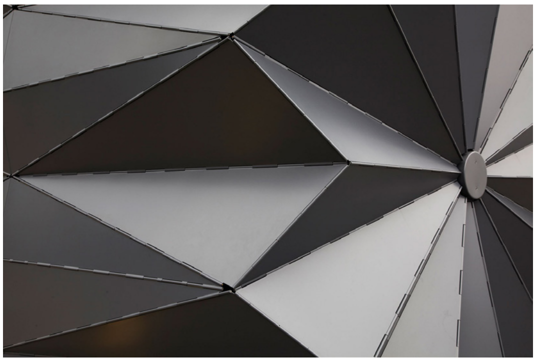


Fig. 4.1.06: Detail folding origami kiosk in London - Make Architects

Fig. 4.1.07: Rolling Bridge at Paddington Basin, London, UK - Heatherwick Studio, 2005 - folding process

Fig. 4.1.08: Rolling Bridge at Paddington Basin, London, UK - Heatherwick Studio, 2005 - folded state

a future, where the temporary relationship and the public nature between people and the land they occupy is embraced." [57] As radical as it may seem the project managed to combine deployability and means of transportation in one project by using simple materials and a tricycle.

Make Architects designed two prefabricated aluminium kiosks for the Canar Wharf Ice sculpting Festival in London. The structure uses folding elements based on the Yoshimura folding patterns allowing the unit to open up and enclose the interior space. The elements were prefabricated from lightweight aluminium sheets interconnected with hinges to allow folding and transported to the site by lorry. The interior can be customized according to the users' needs, in this particular case they were designed to function as information point. While the project does not deploy and contract as a whole structure and the folding panels just change the state of the kiosk from open-functional to closed offering an excellent example of integrating design for functional purposes.

The *"Rolling Bridge"* at Paddington Basin, London designed by Heatherwick Studio is a deployable structure, consisting of 8 modular units, which are hinged together and with the help of hydraulic rams linked to the railing struts the bridge is able to curl into itself forming an enclosed octagonal prism. The structure in the process of folding mimics a caterpillar. In the deployed state it spans 12.1 m allowing pedestrians to pass from one bank to the other. The bridge needed to be deployable so the passage of boats and pedestrians was ensured over an arm of the Grand Union Canal. While a folding bridge is not a new invention in this case what is impressive is how functionality, aesthetics and engineering merged together to solve a practical problem of ensuring circulation. The bridge was described by De-

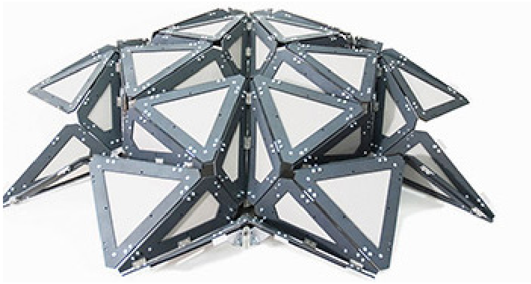


Fig. 4.1.09: Translated Geometries - responsive material system

Fig. 4.1.10: Self-adaptive membrane with kinetic nitrinol joints

Fig. 4.1.11: Bloomframe - Hoffman Dujardin Architects deployed balcony

Fig. 4.1.12: Bloomframe in Amsterdam residential project first implementation

zeen editor-in-chief Marcus Fairs as *"a typical example of Heatherwick's ability to look at a problem from a new angle."* [58]
The following projects showcase the use of newly developed materials with form-changing memory in order to achieve the folding process.
"Translated Geometries" is a master research project, that has been developed by students of the Institute of Advanced Architecture of Catalonia (IAAC). The projects proposes an *"architecture of transformation, a transition between forces, material phases, people, spaces and functions. Form does not always reflect the predictable function, but rather the phases that the new built environment can go to through their relationship with humans, nature and existing buildings."* [59] Shape memory polymers (SMP) were used in order to achieve responsiveness of the built prototype. SMP - material is able to change its state from stiff to soft and flexible upon exposure to heat. The actuation material was placed at the hexagonal nodes of a triangulated origami pattern, functioning as the trigger, which caused the structure to fold or unfold.
A further research project of the same institute combined the origami pattern with nitrinol-zinc springs - a space memory alloy- used to trigger a passive kinetic motor, which responded to solar radiation.[60] The result was a self-adaptive membrane-system consisting of the origami tessellation and the nitrinol joints, which are responsive to environmental stimuli and causes the skin to change its shape. Moreover it must be noticed that the shape memory materials are just the trigger, which initiate the movement in the structures. They are a link between the plates and the hinging elements. The shape memory material is the element which responds to the environment (heat or electrical stimulant) and transfers it to

Fig. 4.1.13: Ten Fold - Built prototype - closed state

Fig. 4.1.14: Ten Fold - Built prototype - unfolding process

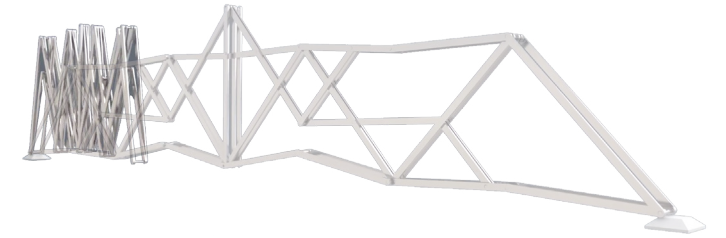


Fig. 4.1.15: Ten Fold Technology - scissors mechanism

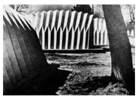
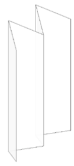
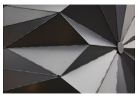
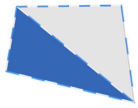
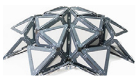
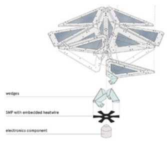
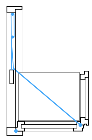
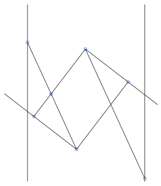
Fig. 4.1.16: Ten Fold Technology scissors mechanism - testing prototype

the connecting elements.

The kinetic Bloomframe window (fig. 4.1.11-12) is a façade element which is capable of transforming into a balcony at the push of a button. It was designed by Hoffman Dujardin Architects from Amsterdam and the prototype was manufacture by Hurks Geveltechniek Veldhoven and Kawneer, specialized in the manufacturing and maintaining facade systems. The mechanism allows a planar facade element to be slanted into a 3-dimensional additional space, resulting into a balcony. In the closed position the window consists of two sections an upper and a lower part, hinged to each other and to the façade, which in the deployed state become balcony floor and balustrade. To the sides a set of kinetic railing pipes are deployed to ensure safety when in use. The deployment process is operated by two hydraulic struts integrated into the frame, which are connected to a scissor arm and chain wheel which help deploy and fold the window. The balcony supports loads up to 350 kg/m^2. The first façade element has been installed in a residential building in Amsterdam.[61]

The UK based company Tenfold Technology under the motto *"engineering new freedom"* [62] developed using a scissors-hinged system deployable enclosing spaces for various uses. A series of levers go up and another go down causing thus the structure to fold and unfold making usage of counterbalancing folding linkages. The built prototype claims to offer 64 m^2 space and fold to less than $^1/_3$ of that space, it opens and closes in 10 minutes using a hand-held battery-powered drill. In the folded state it is compact and can be transported on a trailer to another location. The website offers a variety of uses for their system from office, residential, retractable stages, roofs and bridges waiting for an investor to be put to use.

The above projects illustrate the potential of folding mechanisms for architecture design not just as an aesthetic element translating the potential to construct temporary spaces, which can collapse to reduced shape, when no longer needed. They also illustrate how to apply the folding principle, which in theoretical model such as origami, poses no difficulty due to low thickness of paper at model scale. Material thickness at an architectural scale is however a problem as the creases have to be solved by flexible elastically transformable material, differing from the one used for the folding plates, which need to provide stiffness. This makes

Project	Folding system	Diagram	Structure	Material	Function
	accordion pleat material property		self-supporting	cardboard	shelter
			self-supporting + stiff frame	polypropylene	shelter
	hinges		steel frames	aluminium plates, steel frame and rods	kiosk
	hydraulic struts (VGT) + hinged modules		steel frame modules	steel	pedestrian bridge
	heat-sensitive actuator+hinges		hinged plates (requires supporting structure)	shape changing polymer	potential use as canopy
	scissors, hinges, hydraulic strut		insulated structural aluminium frame, steel elements, glass	aluminium, steel, glass	facade element
	counterbalancing scissors		rigid frame + pivoting elements	steel, various cladding materials	shelter office

Tab. 4.1.01: Evaluation of the presented projects

the introduction of secondary elements necessary, which perform the movements and link the plates like hinges or depending on the geometry also variable-geometry-trusses (VGT) like hydraulic struts or scissor mechanism can be used to achieve deployment. For a better understanding of the used methods through which deployment is achieved a comparison of the discussed projects will be attempted in form of a table to sum up and create an overview of the employed mechanisms in order to achieve space compression and movement of parts in the system. As mentioned before, opposed to categorized theoretical models, in most realized projects a combination of mechanisms to create movement is used and therefore the above examples cannot be clearly assigned to distinct deployment typology. The range was kept narrow and mostly deals with hinged plates, scissors mechanisms and hydraulic struts. Movement in these systems is induced by external sources, human or mechanical and only in the case of shape memory materials, which are the trigger of movement and part of the system.

4.2. Design intention

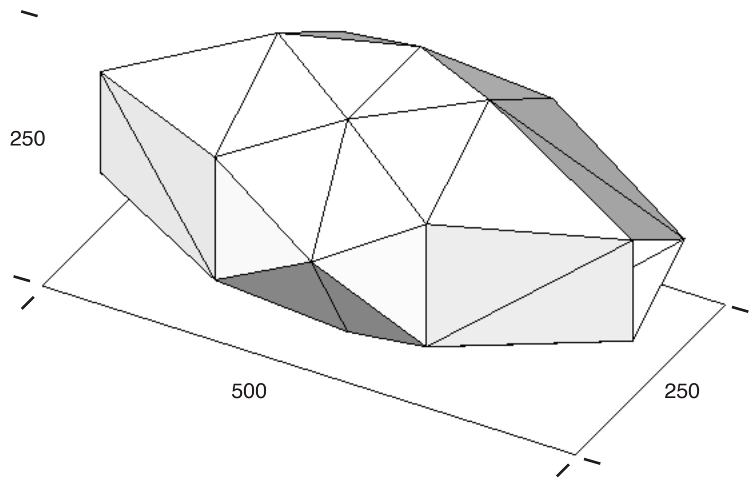


Fig. Fig 4.2.01: Folding pod - first design concept

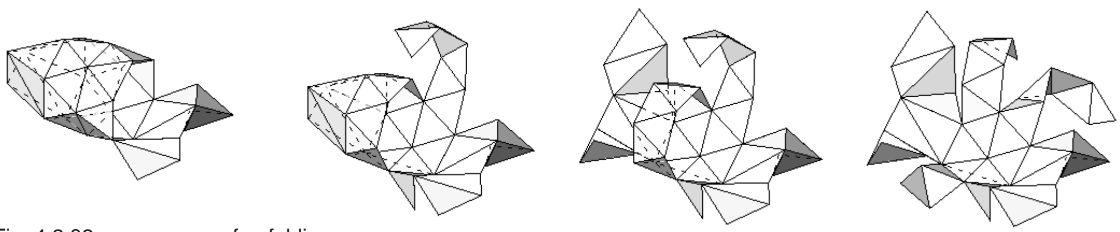


Fig. 4.2.02: sequences of unfolding process

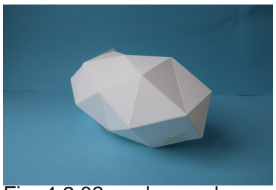


Fig. 4.2.03: polypropylene model

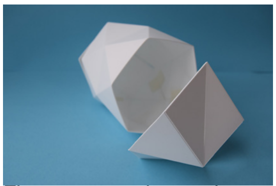


Fig. 4.2.04: polypropylene model open

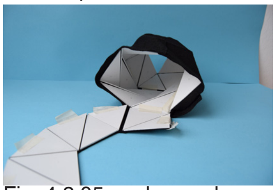


Fig. 4.2.05: polypropylene model

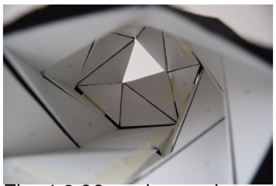


Fig. 4.2.06: polypropylene model

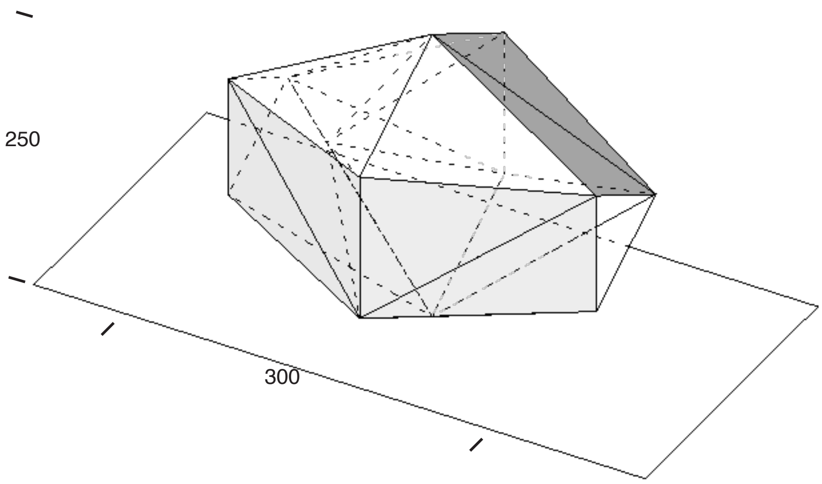


Fig. 4.2.07: folded unit

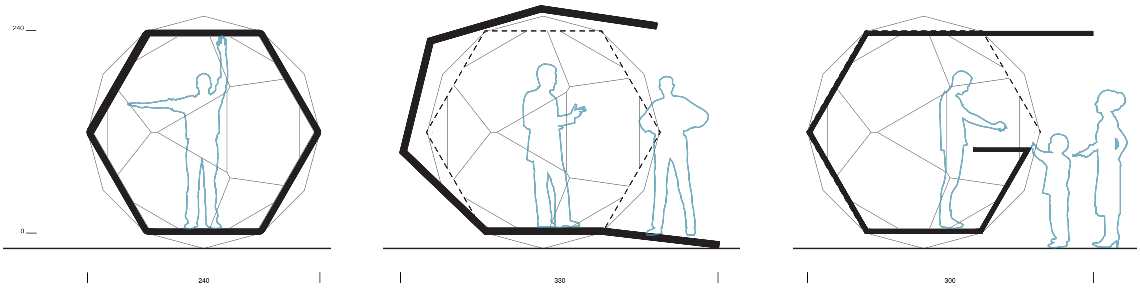


Fig. 4.2.08: cross-section schemes close to open

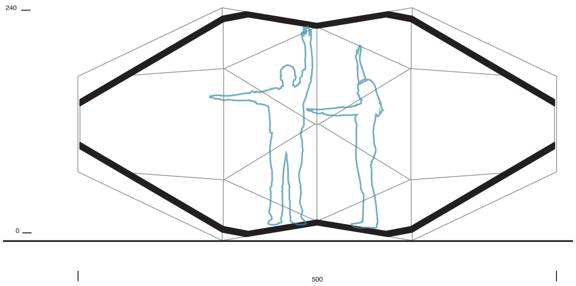


Fig. 4.2.09: long section scheme-evidencing height

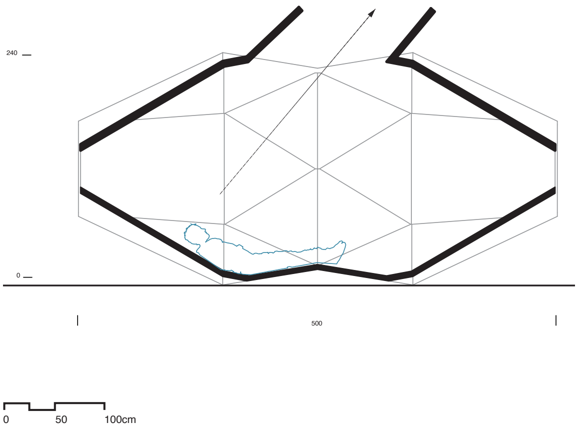


Fig. 4.2.10: long section scheme resting mode

The first mock-up model was a first attempt to materialize the design intention of an urban pod, which accommodates basic appliances with multifunctional purpose. The initial parameters were derived from the average dimensions of a parking lot of 2,5x5,0 meters. A hexagonal cross section was chosen as a profile in the middle with a height of 2,4 meters for achieving fairly usable space without fragmenting the surface in too many polygons.

The hexagonal section blended towards the outer edges into triangles, creating different spacial qualities for functions like resting or storage. The middle part was designed to fold inside-out and reduce the overall size of the pod for easier transportation and reduce storage space required for the pod, in case it was not used for some time. Potential functions for the unit were temporary shelter, kiosk or mobile office. The elements cladding the structure should also be developable and unfold in order to offer variation possibility in the degree of privacy of its users, from completely close to unfolded - open surface, which could be used as urban furniture element.

Further, several models were built out of paper, polypropylene sheet 1,5 mm and polystyrene triangles 2 mm glued to fabric.

The built models showed the potential and the limitation of the concept. It became obvious, that designing folding patterns required a deeper understanding of folding techniques like origami folding patterns. The structure has to be divided into a primary and secondary load-bearing elements - stiff frame elements and flexible joining elements for the folding parts in order to provide a stable structure, which would support live and dead loads and ensure deployment.

4.3. Origami folding patterns

In the quest for structural solutions, architects have been searching for new form-structure relations, different models of structural solutions in terms of responsiveness and thus they explore alternative disciplines, which can provide technical and aesthetic solutions in the field of architecture. The art of origami is a field of expertise, which provides form, structure and spacial qualities at the same time, therefore designers and structural engineers explore this field. Also the way origami patterns are represented as *"diagrams from the 2D space into 3 D space with resulting forms, which are free of plastic deformations"* [63] provide an affinity to the architectural vocabulary.
Origami has evolved from an art form into a tool that can be used for broad engineering and design applications due to increasing stiffness of material, create flexibility in the material or create deployable, flat-folding structures.
As stated in the research aim the present paper will mainly investigate the potential of folding patterns as a space saving design strategy.

"All designers fold. That is, all designers crease, pleat, bend, hem, gather, knot, hinge, corrugate, drape, twist, furl, crumple, collapse, wrinkle, facet, curve or wrap two-dimensional sheets of material and by these processes of folding, create three-dimensional objects. These objects will perhaps not be origami-like in appearance, or the folding may only be a detail, but most will nevertheless have been folded - wholly or in part - in some way. Since almost all objects are made from sheet materials (Such as fabric, plastic, sheet metal or cardboard), (...) folding can be considered one of the most common of all design techniques" [64] according to origamist Paul Jackson.
In particular this is also the case especially in architecture where firstly raw materials are processed to different building materials fulfilling specific characteristics required to reinforce the building safety. Mostly these are delivered in sheet format. The building action can be also summarized as a process of assembling different materials together according to plans provided by architects, civil, electrical engineers.
The art of origami has come a long way. Its origins are somehow unsure but it is tied to the discovery of paper in China, which was later brought to Japan. The word *'origami'* denominates the process of paper folding, the verb *"ori"* meaning 'to fold' and *"kami"*, a noun, means 'paper' [65]. Different folding techniques were developed independently on the different continents. Friedrich Fröbel, a German pedagogue, who established modern education for children in the form of kindergarten in the mid 19th century used origami as a means to explain different geometrical operations to children using paper folding techniques.

Akira Yoshizawa is considered the grandmaster of modern origami and elevated the hand crafting of anonymous creators to a creative art, being the first to claim copyright for the folding patterns he designed. [66]
Furthermore the geometrical complexities of origami folding patterns were analysed by mathematicians in numerous publications one of the first being *"Geometric Exercises in Paper Folding"* by Sundara Row published as a revised English version 1901 in the USA.
The art of paper folding gradually found its way in various fields from packaging, automobile, medical and aerospace industry.
However the art of folding is not just a human invention as mentioned previously but is a common principle in nature. A great variety of plants use folding as a means of storage and protection (sprouts of plants) or as a technique of stiffening the material (palm leaves). Also a wide range of insects are equipped with folding wings.

A wide range of paper art is gathered under the umbrella term 'origami', an attempt to categorize in this paper would prove a futile attempt. The folded models served as form finding process for the design part of this thesis. The 'hands-on' approach was also helpful in gaining an understanding for the folding process in origami models and of the geometrical transformations which are involved in the process of making a sheet of paper a collapsing mechanism.
The folding patterns, which were investigated consisted mainly of rigid plate patterns with straight lines acting as hinges. Some curved patterns were also tested in paper, but were dismissed for the design purpose due to their geometrical complexity and required material attributes, which would have been difficult to fulfil at an architectural scale.

Fig. 4.3.01: Origami models

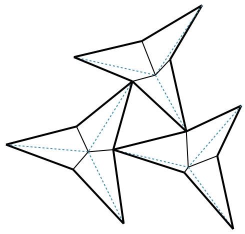


Fig.4.3.02: folding scheme triangular pattern
© Ron Resch

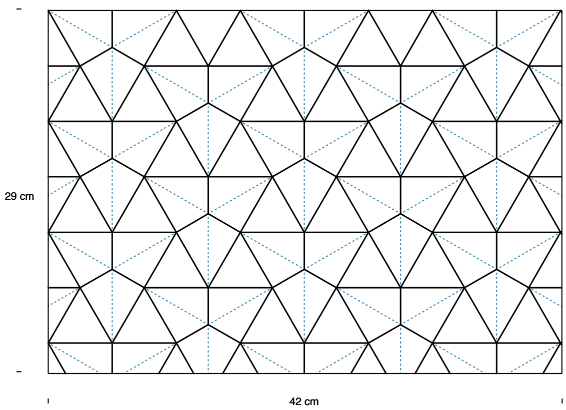
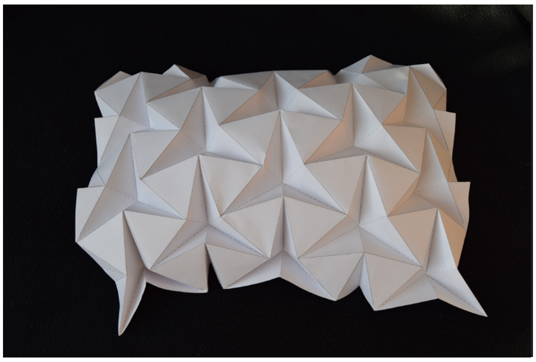
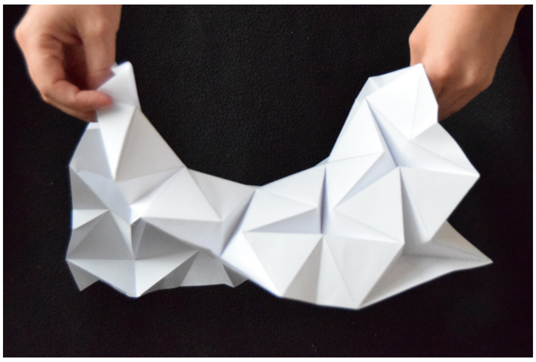


Fig.4.3.03: flat sheet -folding pattern

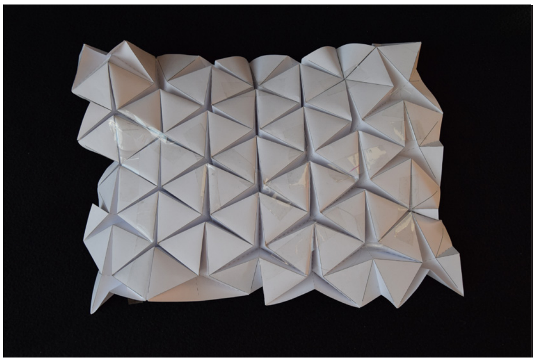
The regular triangular tessellation by Ron Resch is created from an equilateral triangle and its median lines to every vertex of the triangle, which will be tucked on the reverse side of the model and the smaller equilateral triangles, the mountain folds, are determined by a vertex of the initial triangle and the end of the median line, being the visible polygons in the collapsed state. The pattern offers great flexibility due to its positive Gaussian curvature, which also increases its complexity, but is not suited for structural purposes as it provides little stiffness. It is hard to control due to 6 edges converging at the centre of the collapsible triangles.



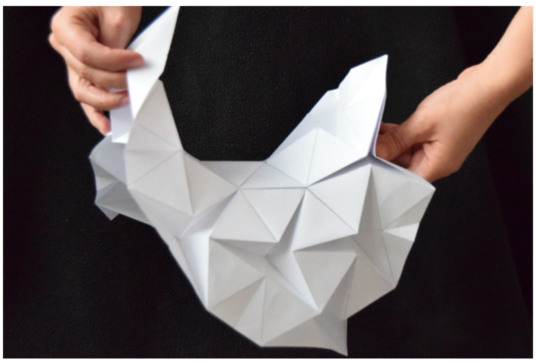
4.3.04: half-collapsed model



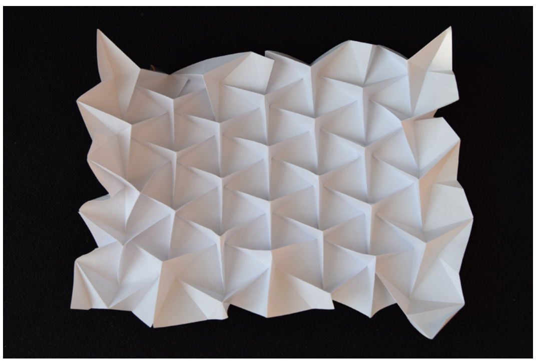
4.3.05: Deformation into curved surface



4.3.06: fully-collapsed model



4.3.07: Deformation into curved surface



4.3.08: reverse side

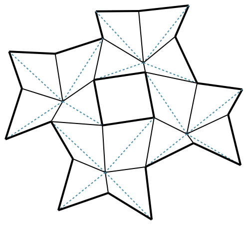


Fig.4.3.09: folding scheme quadratic pattern
© Ron Resch

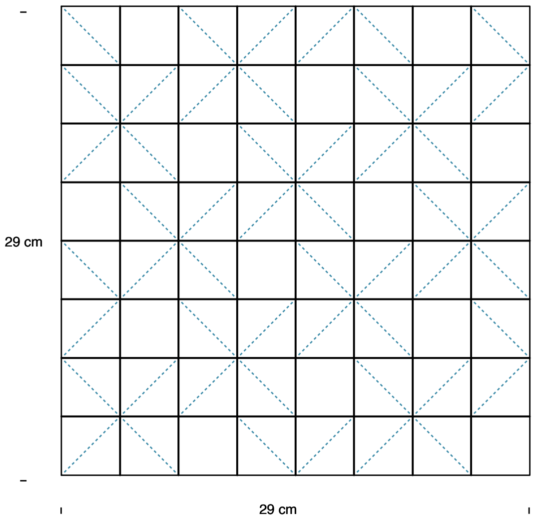


Fig.4.3.10: flat sheet -folding pattern

The quadratic pattern is similar to the previous pattern. The collapsed state is reached by diagonal valley creases, which are tucked in a 4-point star and reveal the cubic pattern. This pattern is also named the among hobby origamists 'water bomb'. It is very flexible and therefore not appropriate for structural purposes.

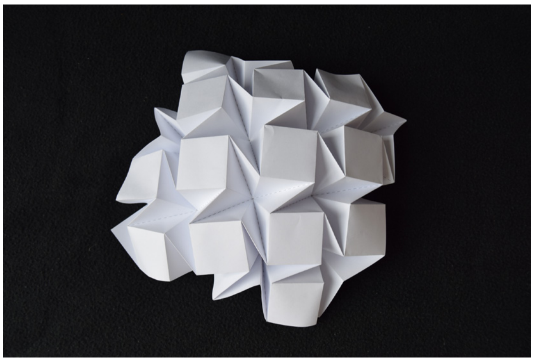


Fig.4.3.11: half-collapsed model

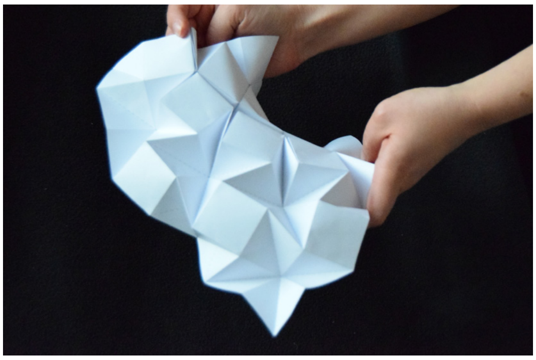


Fig.4.3.12: Deformation into curved surface

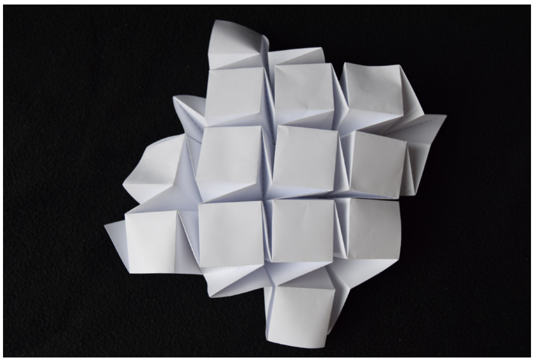


Fig.4.3.13: fully collapsed model

Fig.4.3.14: half-collapsed model side view

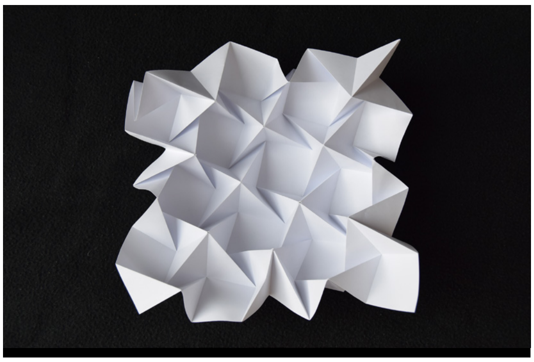


Fig.4.3.15: reverse side

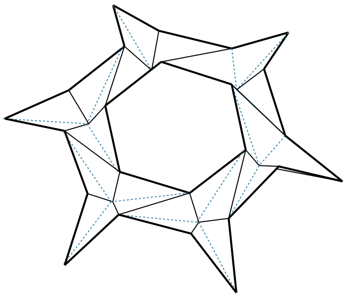


Fig.4.3.16: folding scheme hexagonal patter
© Ron Resch

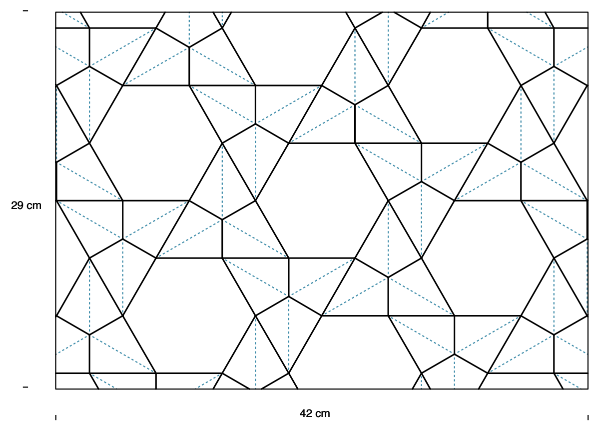


Fig.4.3.17: flat sheet -folding pattern

Another variation on the previous 2 patterns is this hexagonal pattern with equilateral collapsing triangles. This pattern seems to provide more stiffness than the previous 2 patterns al least when manipulating the paper model. There are many other variations based on regular polygons created by Ron Resch and also Tomohiro Tachi developed based on Resch's studies irregular folds, which he published in a research paper *"Freeform Origami Tessellations by Generalizing Resch's Patterns"*.[67]

The folding pattern on the next page (fig. 4.3.22 - 29) introduce 'openings' in the folded pattern making it from a typological point of view a kirigami pattern. The pattern can be folded also without the cuts. It is part of Tomohiri Tachi's folding tube patterns. In the cross-section of the tube is a quadrilateral shape but in the folded state it collapses into a hexagonal flat shape. Another interesting feature is that the tube is also flat-foldable in the longitudinal direction. But this also accounts for its poor stiffness.

Fig.4.3.18: half-collapsed model

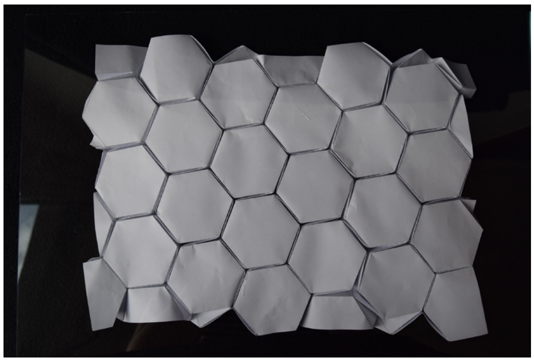


Fig. 4.3.19: fully-collapsed model

Fig. 4.3.20: Deformation

Fig. 4.3.21: Deformation

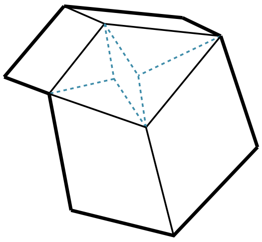


Fig.4.3.22: folding scheme
© Tomohiro Tachi

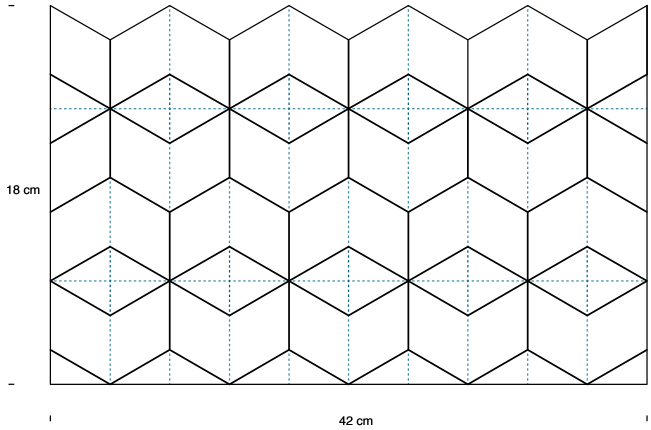


Fig. 4.3.23: flat sheet - folding pattern

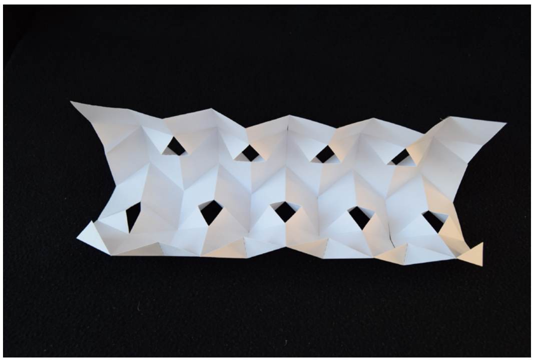


Fig.4.3.24: reverse side

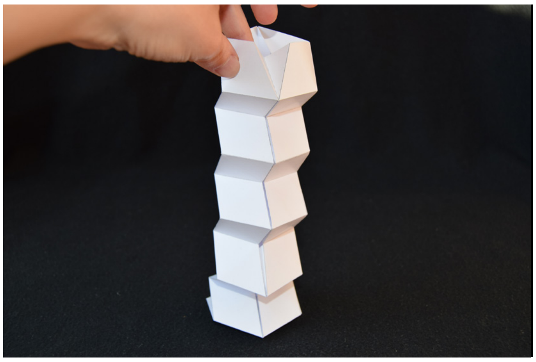


Fig.4.3.25: collapsing process 1/2

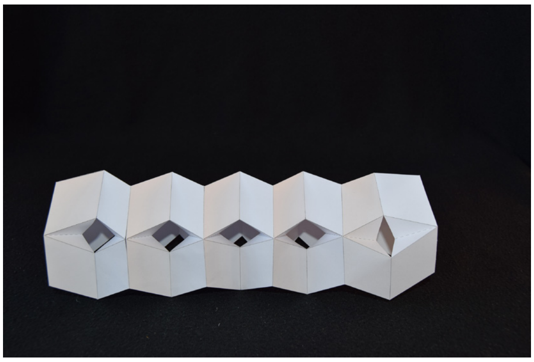


Fig.4.3.26: open cuts

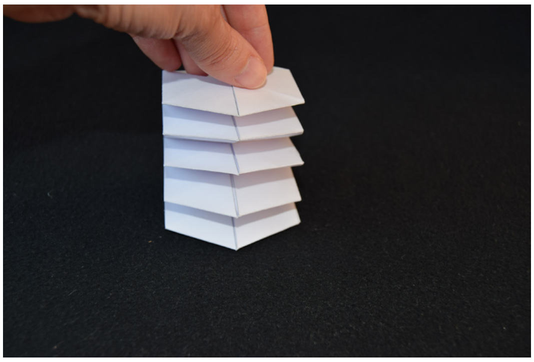


Fig.4.3.27: collapsing process 2/3

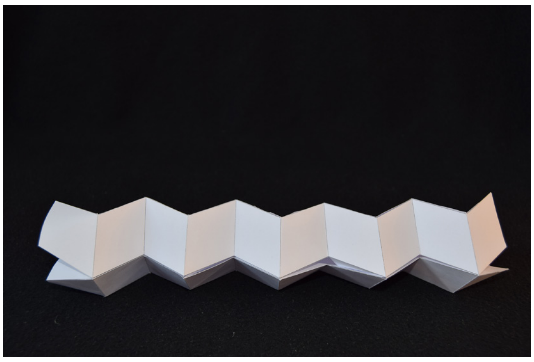


Fig.4.3.28: collapsed cuts

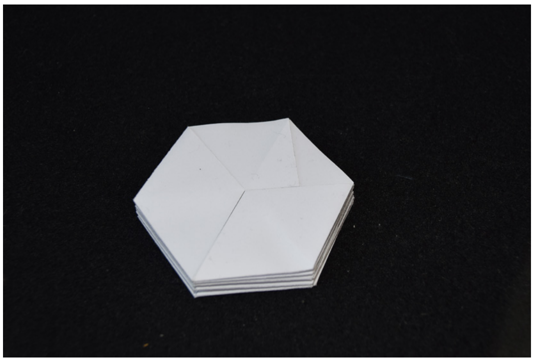


Fig.4.3.29: fully collapsed

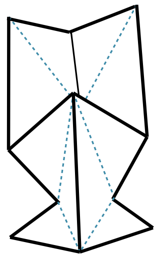


Fig.4.3.30: folding scheme 'magic ball'

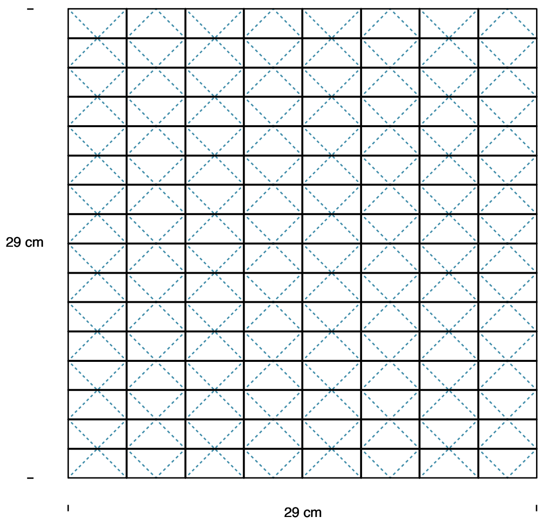


Fig.4.3.31: flat sheet - folding pattern

The 'magic ball' offers a lot of flexibility, when force is applied to it and depending on the scale of the grid (the finer - the more deformable), generating interesting configurations, but offers little stiffness and therefore it is not so favourable for a structural purpose.

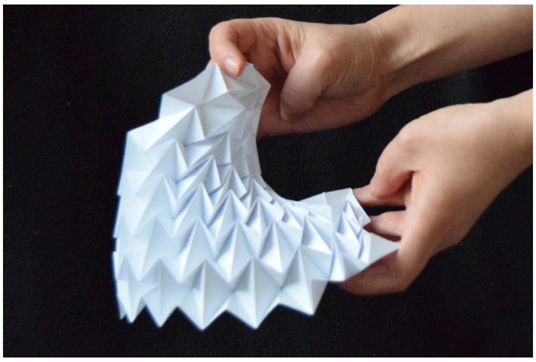


Fig. 4.3.33: Deformation

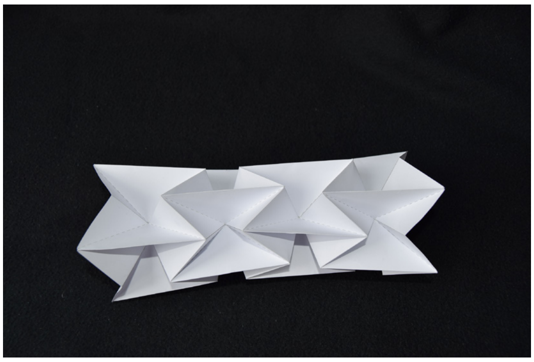


Fig. 4.3.32: cylindrical deformation-pattern scale

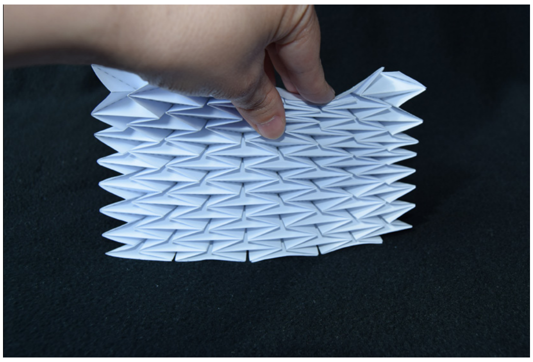


Fig. 4.3.34: collapsing modell

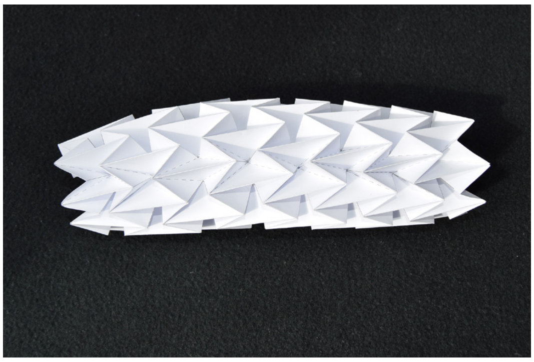


Fig. 4.3.35: cylindrical deformation

Fig.4.3.36: fully-collapsed model

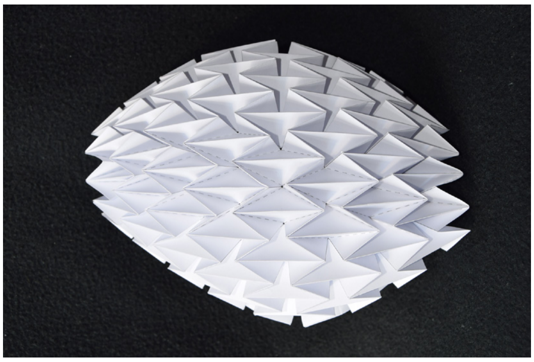


Fig.4.3.37: 'magic ball'

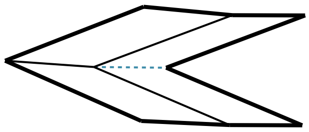


Fig.4.3.38: folding scheme 'Miura-or'
© Koryo Miura

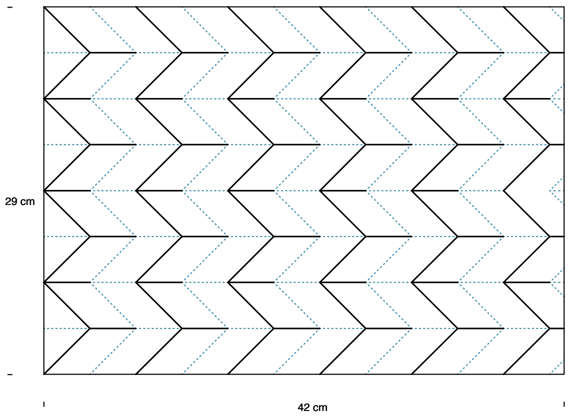


Fig.4.3.39: flat sheet -folding pattern

Miura-ori or Herringbone fold delivers a stiff surface with interesting properties. The patterns consists of parallel parallelograms with mirrored ones along the rows, creating a zig-zag pattern when folded. Deformation can be introduced locally or globally on the folded sheet. The pattern can collapse from a plate structure into a thin strip, making it an efficient fold in terms of deployed to collapsed surface ratio.

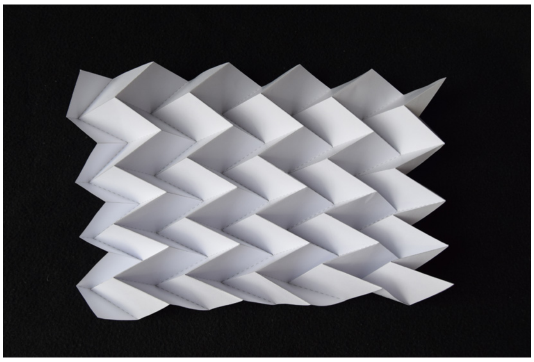


Fig. 4.3.40: corrugated sheet

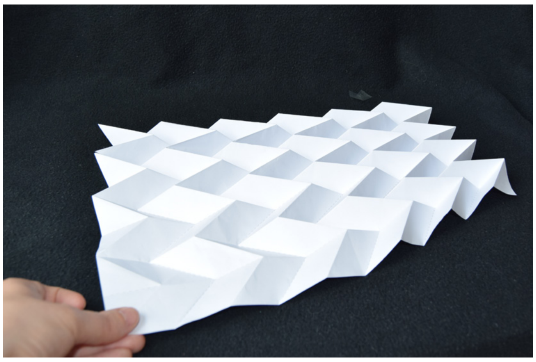


Fig.4.3.41: local deformation - edge

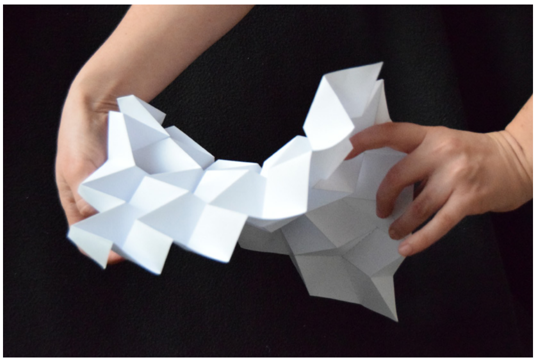


Fig.4.3.42: Deformation by bending both edges

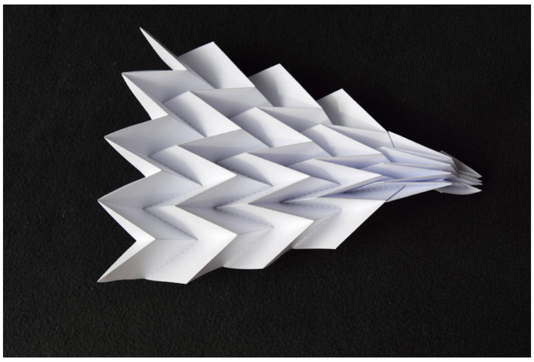


Fig.4.3.43: local deformation - side

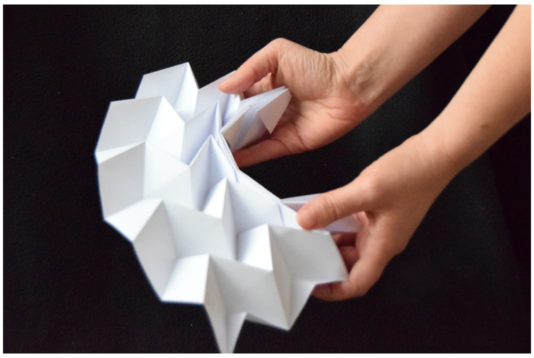


Fig.4.3.44: Deformation by bending one edge

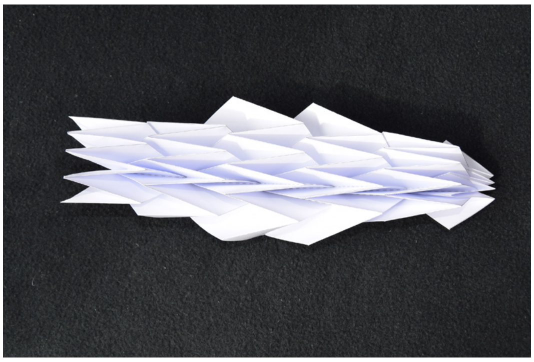


Fig.4.3.45: collapsing process 2/3

Accordion / Bellow pattern is capable of creating a tubular shape, with increased rigidity and creating movement along the axis of the tube. The tube can be flat-folded. Depending on the proportion of the trapezoids different prismatic shapes can be created. It is similar to the Yoshimura pattern and diagonal pattern, except there is no twisting motion involved in the folding process.

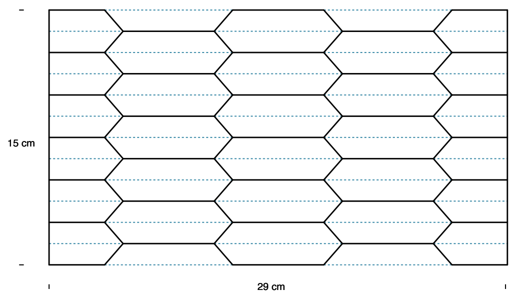


Fig.4.3.46: flat sheet -4-edges bellow folding pattern

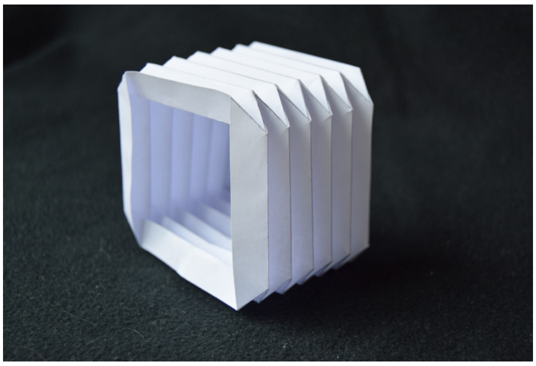


Fig.4.3.48: deployed state

Fig.4.3.47: collapsed state

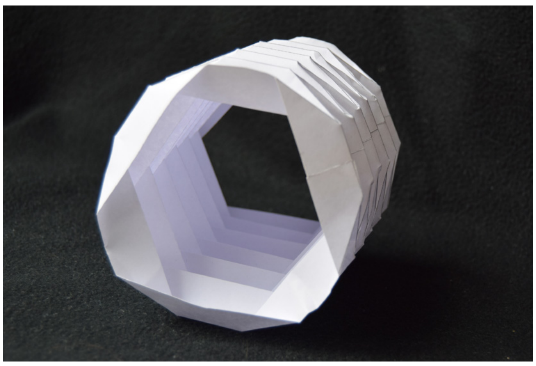


Fig.4.3.49: cylindrical shape

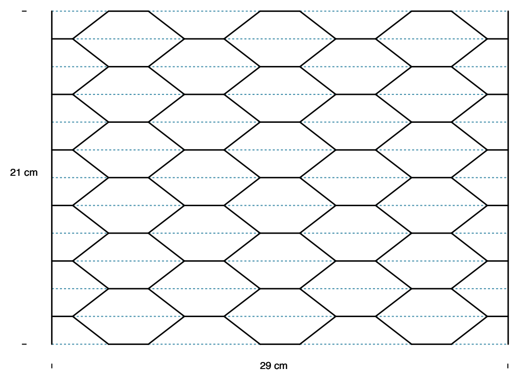


Fig.4.3.50: flat sheet - 6-edges bellow folding pattern

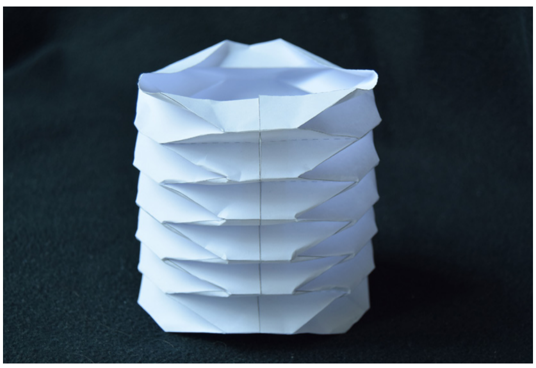


Fig.4.3.51: deployed state

Fig.4.3.52: collapsed state

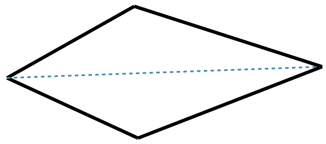


Fig.4.3.53: folding scheme © Yoshimura

Yoshimura or Diamond pattern features rhombuses with valley creases along the long diagonal. Depending on the ratio of the angles of the rhombuses it creates a cylindrical shape when folds. Elongated diamonds produce a flat arch and shorter diamonds produce a tubular enclosed structure. It has good stiffening properties. Variations of this pattern occur in thin (metal) cylinders under pressure load, being a self-structuring mechanism of the material.

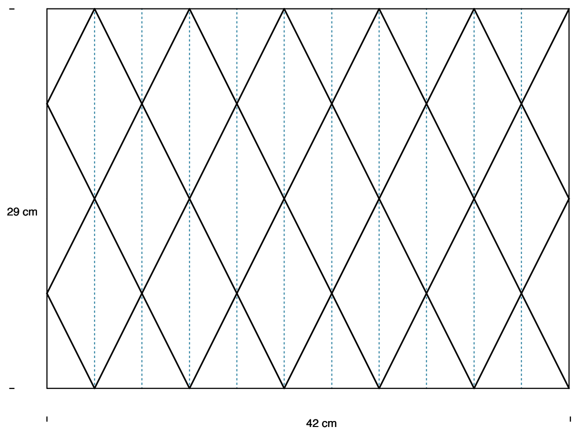


Fig.4.3.54: flat sheet -folding pattern - diamond pattern

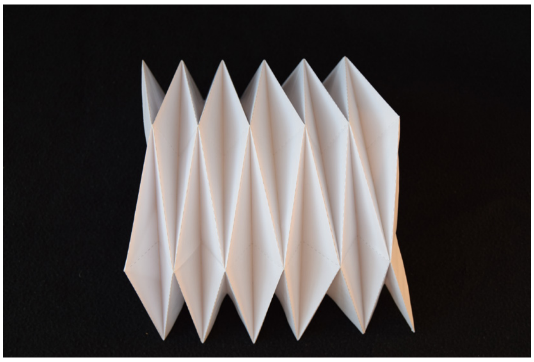


Fig. 4.3.56: corrugated sheet

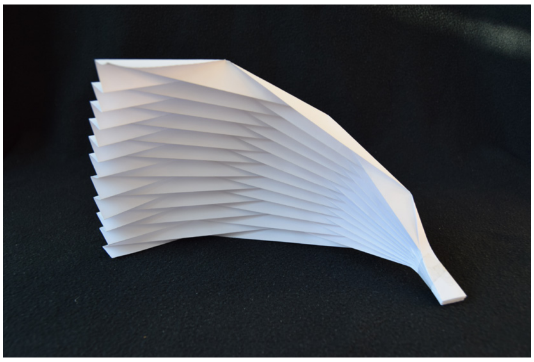


Fig.4.3.55: local deformation - end side

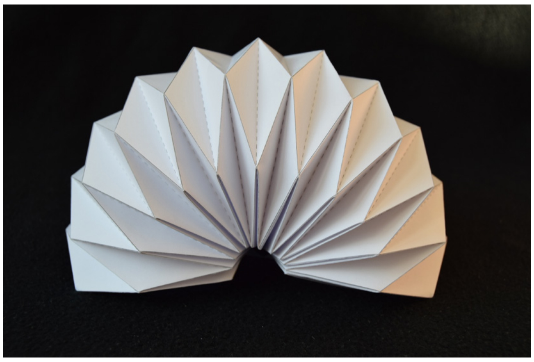


Fig.4.3.57: local deformation - both end sides

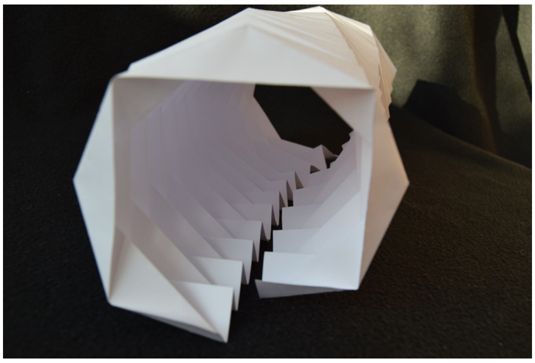


Fig. 4.3.58: corrugated sheet - tunnel

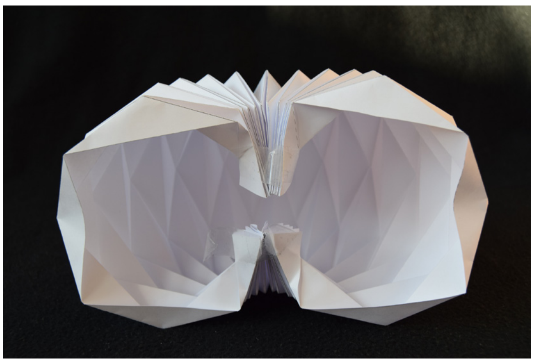


Fig. 4.3.59: half-collapsed model

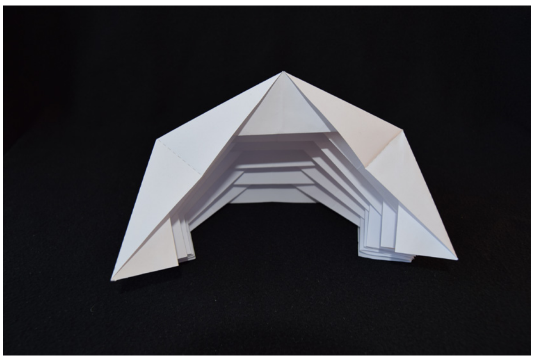


Fig. 4.3.60: fully-collapsed model

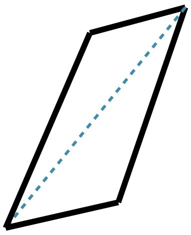


Fig. 4.3.61: folding scheme - diagonal pattern

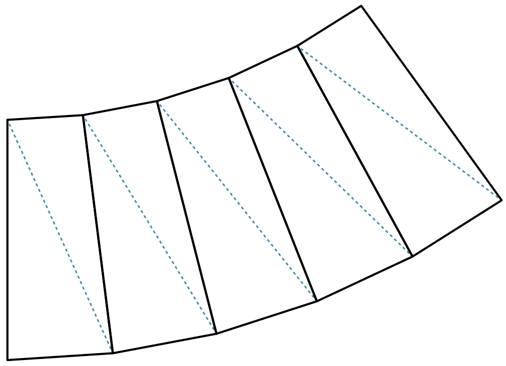


Fig. 4.3.62: . flat sheet -folding pattern- diagonal pattern

The diagonal pattern is similar to the Diamond pattern. The recurring shapes are parallelograms or trapezoids with long diagonals as valley folds. The relation between angles and side length ratio determine whether the pattern can create a tubular structure and / or be flat-folded. Long parallelograms can form a stiff prismatic shape, but which cannot be flat-folded because the valley creases block each other on the reverse side. Favourable side length ratio of the parallelograms from empirical observation in built test models ranges between 1,45 to 1,55 and angles about 80° respectively 100°. This pattern is also named Kresling-pattern and will be discussed at length in Chapter 4.4. Kresling Pattern and Chapter 5. Design Application.

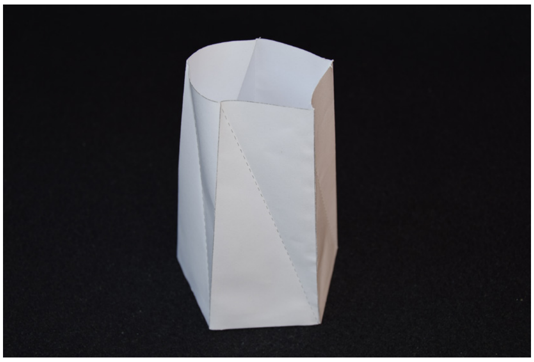


Fig. 4.3.63: deployed state - hexagonal base

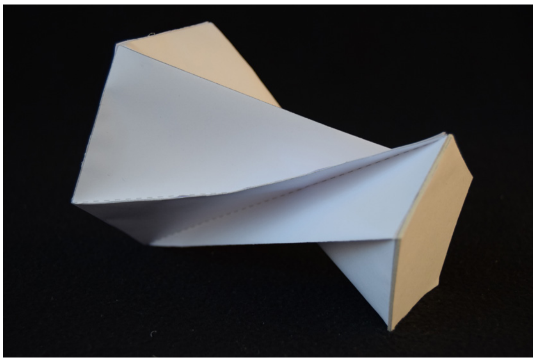


Fig. 4.3.64: folded state - not fully collapsible

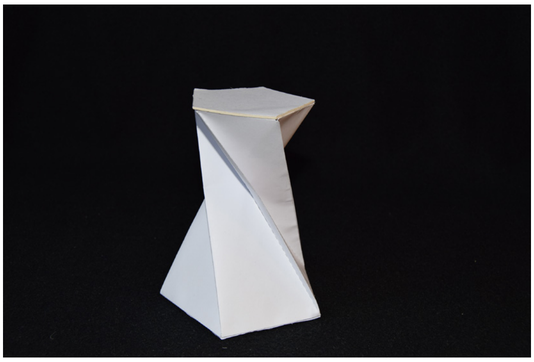


Fig. 4.3.65: folded state

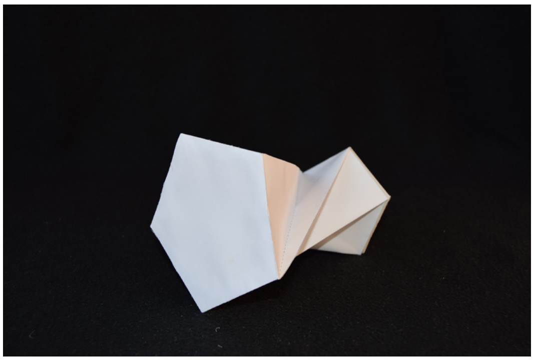


Fig. 4.3.66: folded state - base size scalable

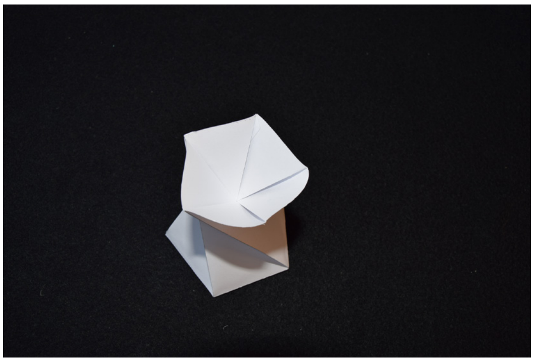


Fig. 4.3.67: collapsed state - hexagonal base

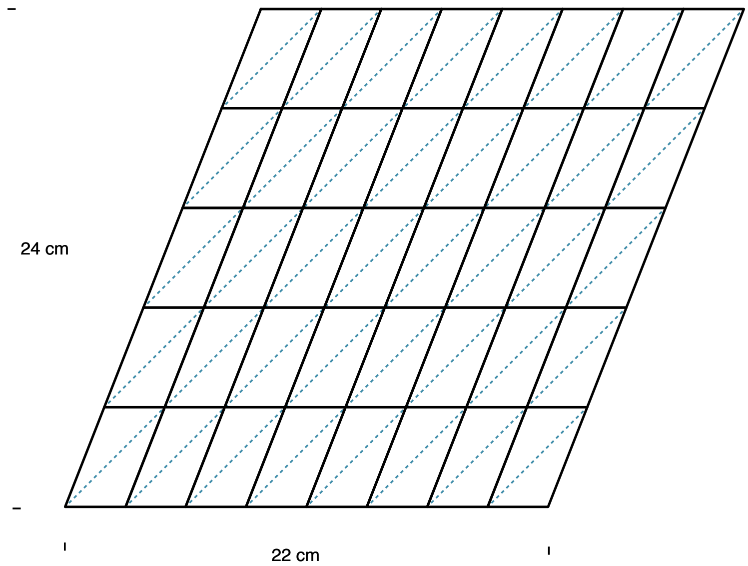


Fig. 4.3.68: flat sheet -folding pattern

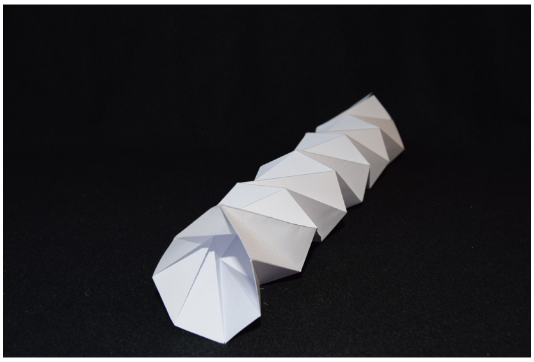


Fig. 4.3.69: tube - hexagonal base - not fully collapsible

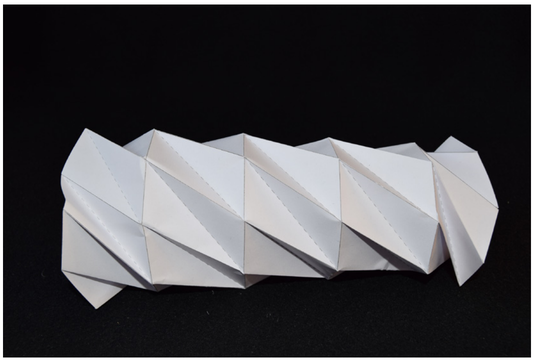


Fig. 4.3.70: deployed tube - octagonal base

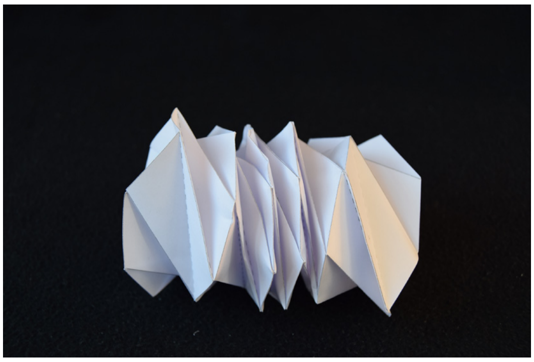


Fig. 4.3.71: collapsible units

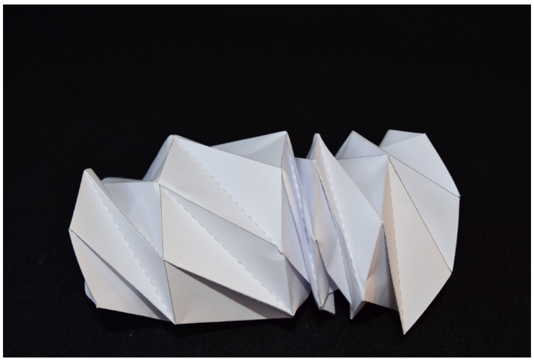


Fig. 4.3.72: individually collapsible units

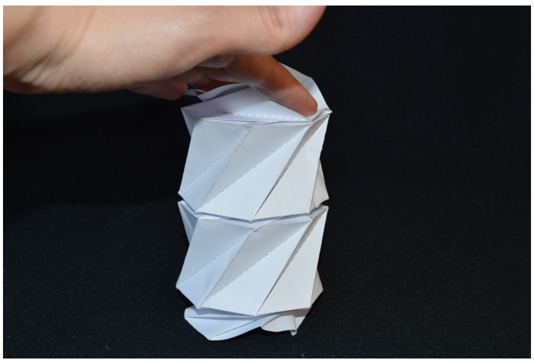


Fig. 4.3.73: individually collapsible units

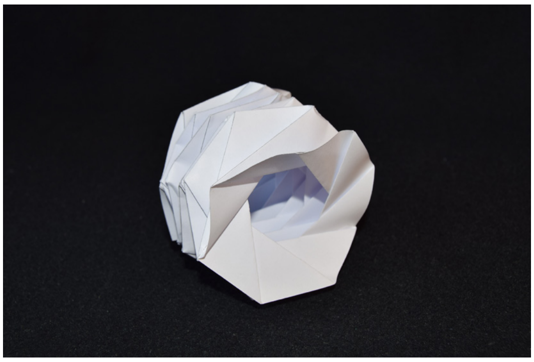


Fig.4.3.74: fully-collapsed model

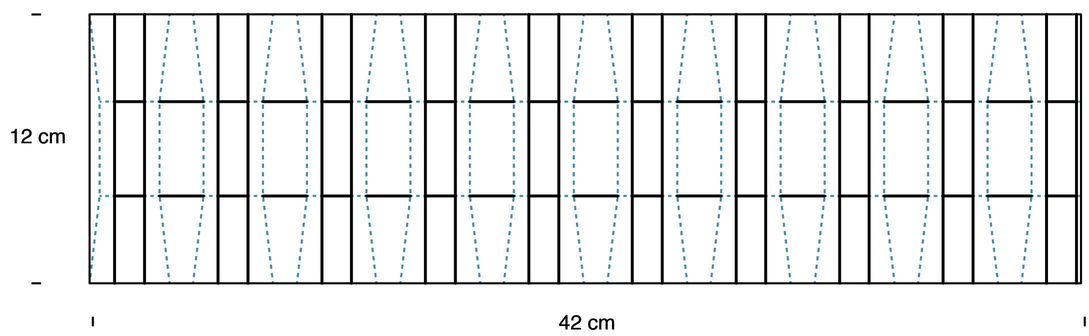


Fig.4.3.75: flat sheet -folding pattern © Jun Mitani

The origamist Jun Mitani developed a wide variety of different folding pattern, creating objects, which are an art of their own. From the impressive available collection on his website two seemed to offer relative simple folding pattern and create enclosed shapes.
The first, figure 4.3.75 is based on rectangles and triangles creating a cylindrical structure, which can be transformed into an arched structure with increased stiffness.
The second is a spherical shape which is foldable out of a flat sheet of paper figure 4.3.79.

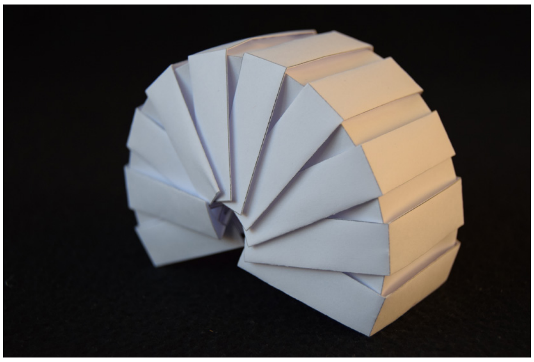


Fig.4.3.76: corrugated sheet in arch configuration

The patterns in figure 4.3.81 and 4.3.83 are more of corrugating technique to introduce stiffness in a thin sheet material from unknown authors.
The pattern in figure 4.3.85 is a variation on the bellow pleat but cannot be collapsed, due to the valley folds intersecting on the interior of the tube, evidencing once more how important geometry of the pattern is in ensuring deployability

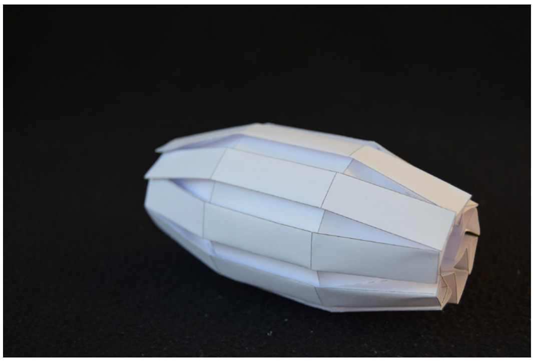


Fig.4.3.77: corrugated sheet in cylindrical configuration

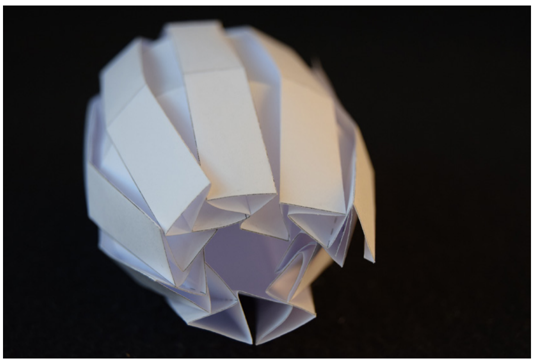


Fig.4.3.78: corrugated sheet close up

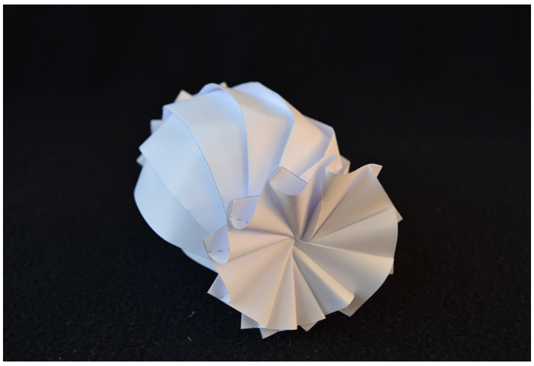


Fig. 4.3.79: folded spherical shape

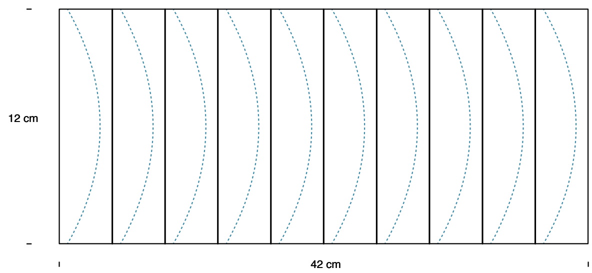


Fig.4.3.80: flat sheet -folding pattern © Jun Mitani

Fig. 4.3.82: local deformation by applying pressure

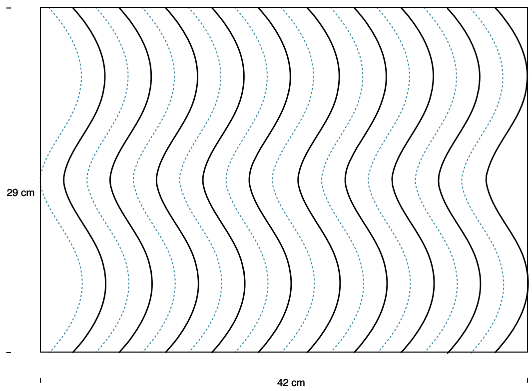


Fig. 4.3.81: flat sheet - curved folding pattern

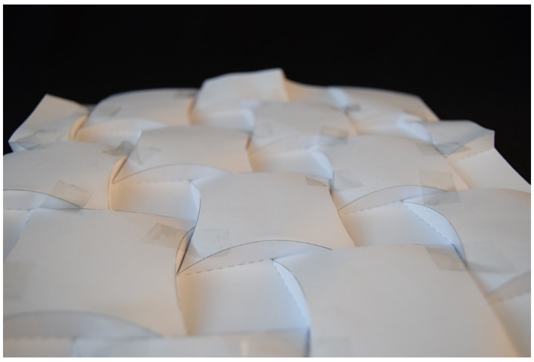


Fig. 4.3.84: corrugated sheet - close up

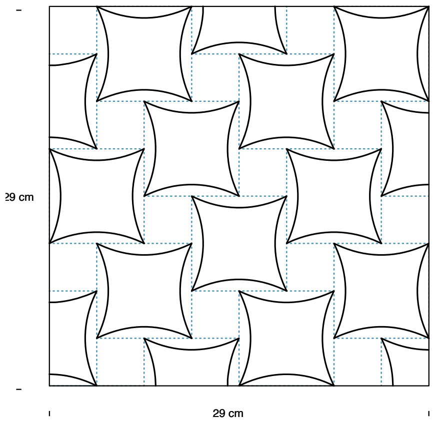


Fig. 4.3.83: flat sheet - curved tessellation

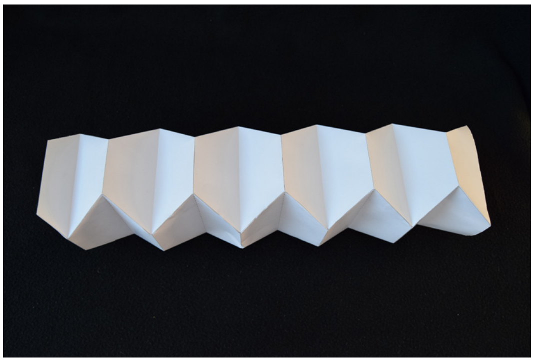


Fig. 4.3.86: prismatic shape - variation bellow fold

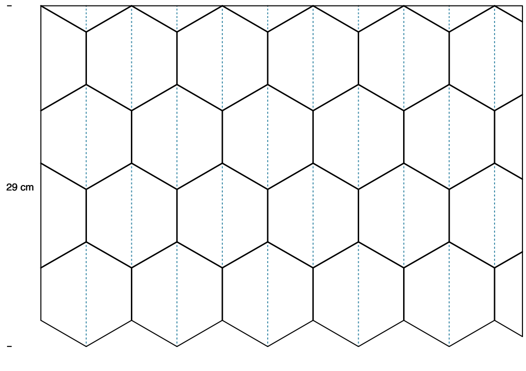
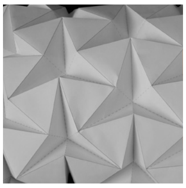
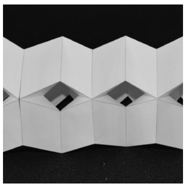
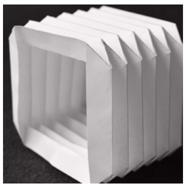
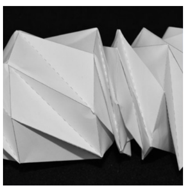


Fig. 4.3.85: flat sheet -folding pattern-bellow fold

PATTERN	DEPLOYABILITY	RIGIDITY	SEALABILITY	FOLDING PATTERN COMPLEXITY
 Ron Resch	+	++	–	+++
 Ron Resch	+	+	–	+++
 T. Tachi	+++	-	+ uses kirigami cuts in the folding pattern	++
 Magic Ball	+++	+	+	+++
 Koryo Miura	+++	+++	–	++
 Bellow	+++	+++	+++	+
 Yoshimura	+++	+++	+	+
 Kresling	+++	+++	+++	+

Tab.4.3.01: Evaluating qualities of presented origami patterns

DESIGN APPLICATION
folding wall or roof structure
roof structure, partially enclosed space
enclosed space, modular
folding roof or wall structure, partially enclosed space
folding roof, floor, wall structure
enclosed space , modular
arched roof, canopy, partially enclosed space
enclosed space , modular

Evaluating paper folded models

It must be emphasized that even though many of the patterns bear interesting deployment features, what in paper models seems very easy to achieve is at a larger scale and using sheet material with thickness a real challenge. Manipulating the paper model generated fascinating surface features like double curvature, springs, which the plane sheet of paper would not be able to attain on its own, evidencing the correlation between geometry and material. The last 3 patterns bellow-fold, Yoshimura and Kresling in the comparative table created an enclosed interior space consisted of one single repetitive geometrical shape to achieve folding. Also the fact that they provided modularity was considered as being advantageous for the design process. The Kesling pattern was chosen as the most suitable patter due to its high ratio of compression, meaning that the relatively large surface could be flat-folding using minimal crease, which at an architectural scale means less hinging elements between the plates, and therefore less weak elements in the system. Also the fact that the folding pattern could be applied to different polygonal shapes made the choice for this pattern easy. However the twisting motion was deemed as a shortcoming for designs intended to be placed on the ground, as the panels need to perform a rotation in order to be folded and deployed. This can however be overcome by slightly heightening the structure from the ground ensuring that the rotation can be performed.

4.4. Digital tools

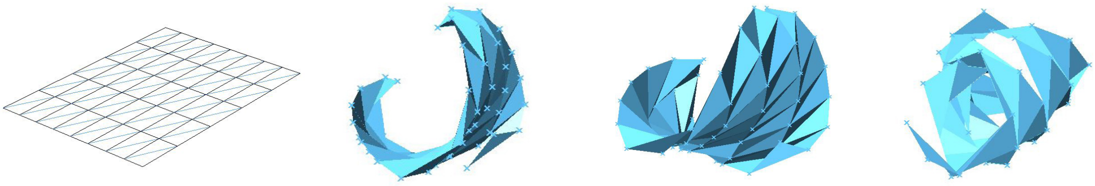


Fig. 4.4.01. Diagonal pattern simulation using Daniel Piker's Grasshopper definition

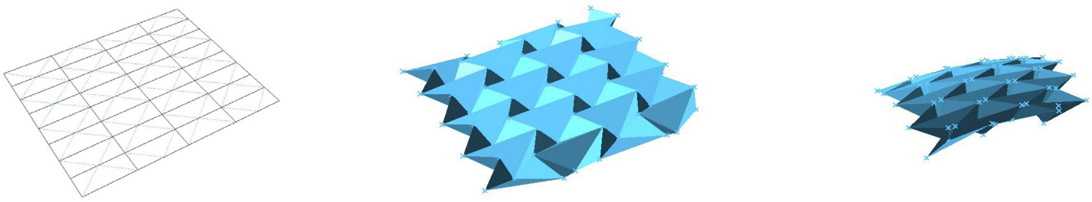


Fig. 4.4.02. 'Water bomb' pattern simulation using Daniel Piker's Grasshopper definition

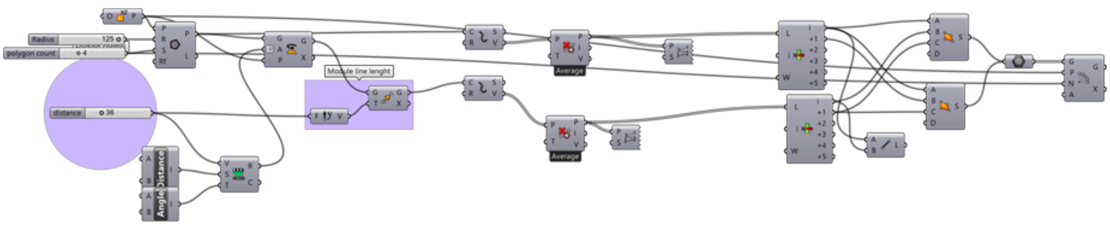


Fig. 4.4.03. Grasshopper definition for Kresling pattern

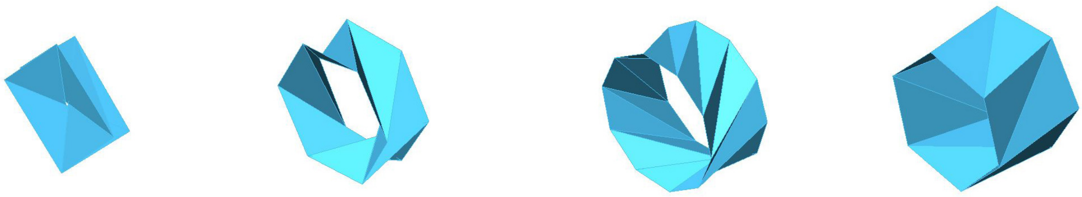


Fig. 4.4.04. Grasshopper definition -variable polygon count- Kresling pattern

The process of creating the models differed from the traditional origami folding since the patterns were created in a CAD-program (Rhinoceros) as a line work printed and cuts were placed on both sides, black lines (mountain folds) on the front side and blue hidden lines (valley creases) on the reverse side of the paper sheet. This method delivered more accurate models, and paper quality was not such defining as opposed to folding. Moreover the digitally created line work could be used as input for a Grasshopper definition to simulate the folding process, even though not all patterns could be digitally simulated. Especially problematic proved the patterns containing curved lines. Regarding the digital simulation of the folding process 2 approaches were tested using the plug-in Grasshopper and different components available in its environment. The first attempt was by using a definition created by Daniel Piker using the physics engine Kangaroo, which enables the simulation of different forces. While this method was relatively fast to test out a large number of patterns as line inputs were in most cases sufficient to generate a mesh, that could be folded, it was also inaccurate as the simulation transformed the input mesh and the initial side lengths of the line patterns deviated slightly in the folded state. Also the definition did not retrieve any results, when attempting to use curved lines. The second method was by using relative geometry transformations between the input parameters. While this method is somehow more difficult since the geometrical transformations have to be carefully studied and translated into Grasshopper components it was more accurate. It was used for the geometrical pattern chosen for the design, the Kresling-pattern. This method could be enhanced by using the exact node functions, which define the geometrical transformations.

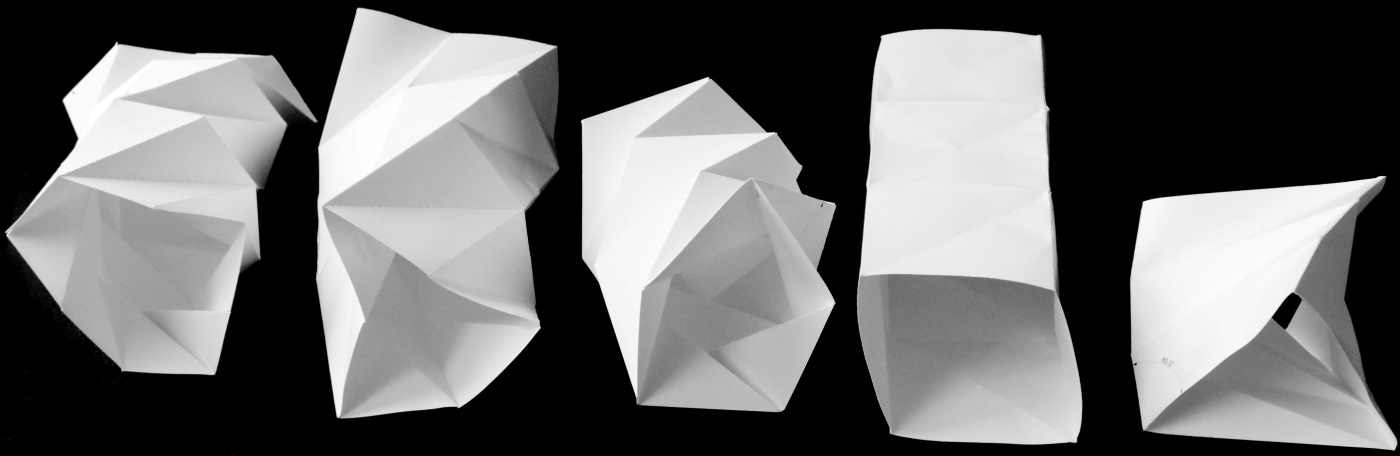


Fig. 4.5.01: a) Kresling pattern with different polygonal shapes - deployed state

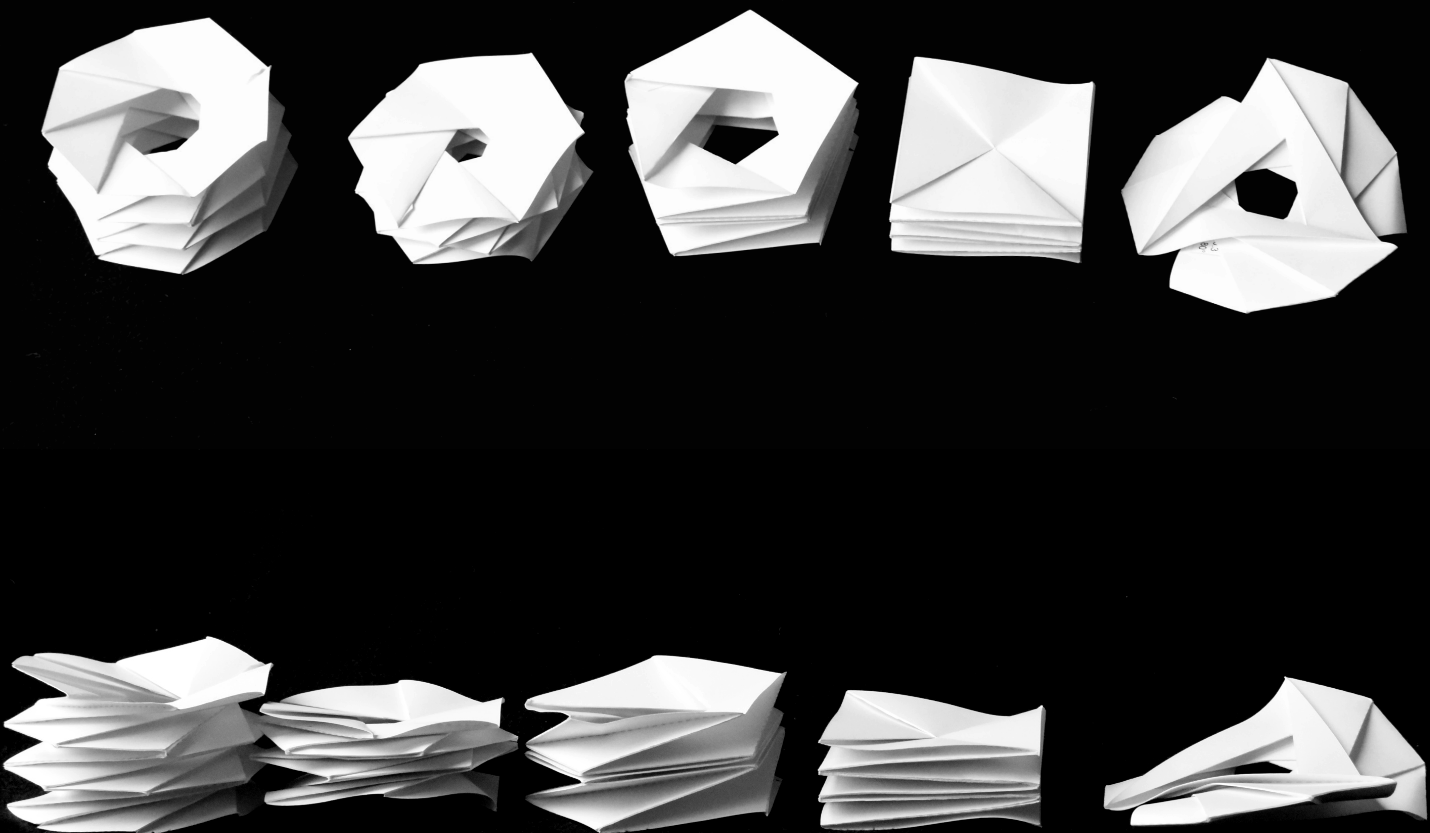


Fig. 4.5.01: b) Kresling pattern with different polygonal shapes - flat folded tubes

4.5. Kresling pattern

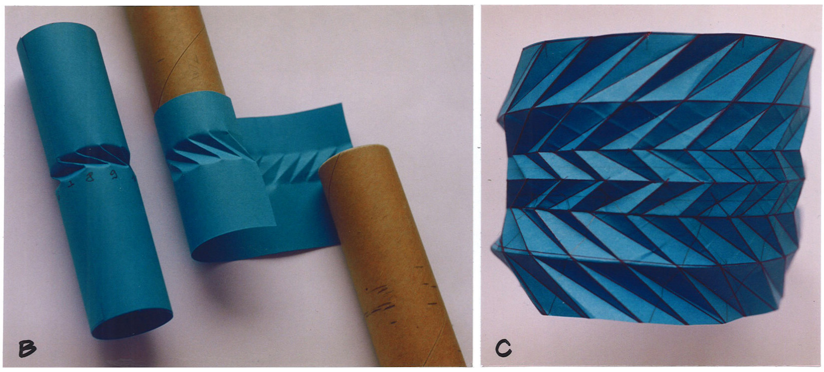


Fig.4.5.02: Self-structuring pattern of paper tube under torsion

Fig. 4.5.03: Surface texturing through cylindrical buckling

The form finding process, where different folding patterns were tested, revealed that different patterns provide different spatial configuration possibilities and structural properties, which bare both high potential but also design limitation and structural challenges. For the design intention the most favourable shapes were tubular flat-folding shapes, which would provide an enclosed deployable space. Further the Diagonal or Kresling pattern / cylinder origami will be explained.

The Kresling pattern is actually a self-structuring process of thin wall cylinders under torsion load. The pattern can be generated without the manual creasing process of valley and hill folds. For this purpose a sheet of paper is wrapped around two cylinders e.g. paper rolls, or any cylindrical tube, leaving a gaping distance between them. The cylinders are twisted against each other resulting in elongated parallelogram pattern with valley folds along the long diagonal. This phenomenon is named *"twist buckling"* [68], which represents a failure state induced by a torsion force in a system (in the exemplified case the cylinder shaped paper).

This pattern, named Kresling pattern after architect Biruta Kresling, can also be induced artificially for design purpose generating deployable structure, which provide a stress-reduced folding mechanism due to its 'natural' occurring oblique compression and tension lines crossing at 90° angles. The folding-unfolding produce a pop-up effect in single or multiple twisting units. The pattern is also favourable for modular configurations. The cylindrical units can fold on its own or in combination with multiple units. A herringbone pattern is obtained when mirroring one unit row resulting in a cylindrical Miura-ori fold (figure 4.6.03 middle).[69]

The Kresling pattern is similar to Yoshimura fold. However the parallelogram width to height ratio and angels result in different folding motion, not only a translation operation occurs but also rotation around the internal axis. Kresling pattern parallelograms are elongated and the valley fold along the long diagonal results in the accentuated twisting motion. The triangles which make up the pattern are all identical, a phenomenon called *"cyclic symmetry"* [70]. Also the cross section of the tube generates a regular polygon.

Concluding it is interesting to observe that naturally occurring phenomenons researched in-depth can provide design tools and applications, not only formally but also structurally, opening new perspectives of design strategies and research topics.

Geometry

The geometrical transformations of a belt unit Kresling pattern are exemplified on hexagonal cross-section. The presented mathematical relations in this chapter are based on a scientific research article on "*Bistable Behaviour of the Cylindrical Origami Structure with Kresling Pattern"* [71]. The graphical schemes were recreated by the author of the thesis using the same source.

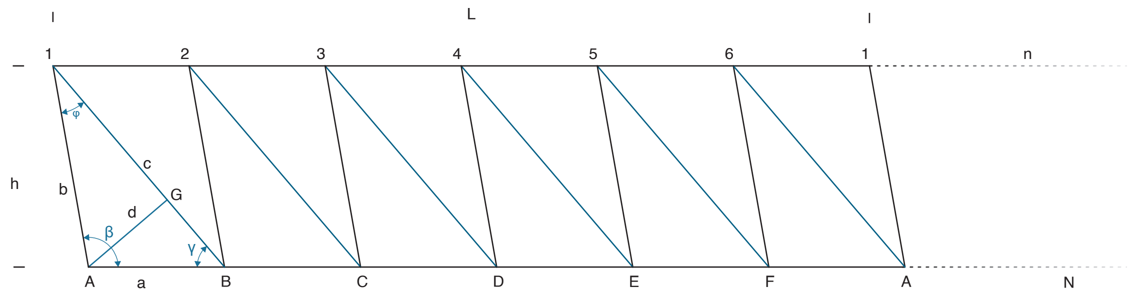


Fig.4.5.04: Folding pattern of a paper strip

Fig. 4.5.05: Movement of the adjacent triangles
a) deployed state

b) folded state

The angle relation of the folding triangular elements is defined as follows:

$$\measuredangle 1'0C = \measuredangle 1'20 + \measuredangle 21'0 = \measuredangle 1'20 + \measuredangle BC0 = \measuredangle 1'20 + \measuredangle C23 = \measuredangle 1'20 + \measuredangle 3'2C = \measuredangle 1'23'$$

In the deployed state results in $\measuredangle 1'0C$ and $\measuredangle 1'23'$ being equal

$$\measuredangle 1'0C = \measuredangle 1'23' = \pi - 2\varphi$$

The sum of the inner angles of the regular polygon formed by the upper lines of the strip of paper is:

$$n \times \measuredangle 1'23' = n \times (\pi - 2\varphi) = (n-2)\pi$$

Resulting in:

$$\varphi = \frac{\pi}{n}$$

The length of the line a as the side of the regular polygon is obtained by division of the length l of the paper strip to the number of sides n of the regular polygon

$$a = \frac{l}{n}$$

The triangle $1AB$ contains following relations:

$$l1G = d \times \cot\varphi$$

$$lGB = \sqrt{a^2 - d^2} = \sqrt{\left({}^{l}/_{n}\right)^2 - d^2}$$

$$l1G + lGB = c$$

The angles of the triangle $1AB$ are defined as:

$$\gamma = \sin^{-1}\frac{d}{a} = \sin^{-1}\frac{nd}{l}$$

$$\beta = \pi - \varphi - \gamma = \frac{n-1}{n}\pi - \sin^{-1}\frac{nd}{l}$$

During the deployment process one of the regular polygons is rotated around the central axes of the cylindrical shell. This results in a relative rotation angle θ of the upper lines of the polygon [12],[23],[34]… to the lower lines [AB],[BC],[CD]… The radius of the circumscribed circle of the two regular polygons R results in:

$$R = \frac{\frac{a}{2}}{\sin\left(\frac{\pi}{n}\right)}$$

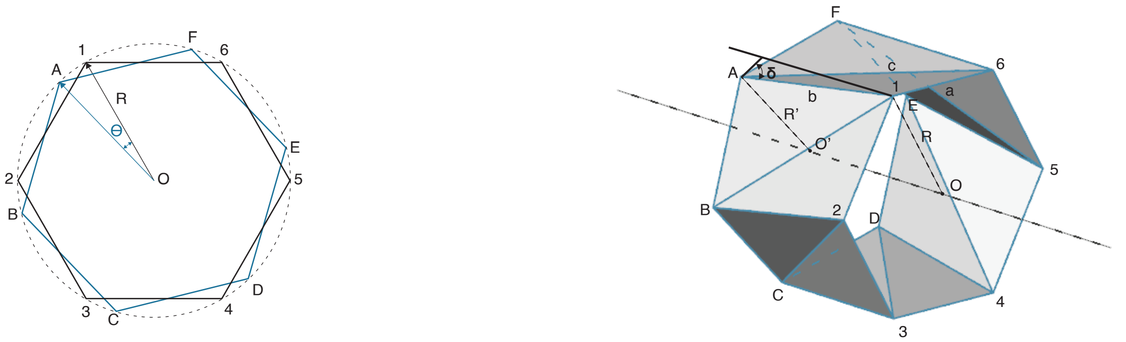


Fig. 4.5.06: a) Relation between the two initial state

b) Cylindrical shell in deployed state

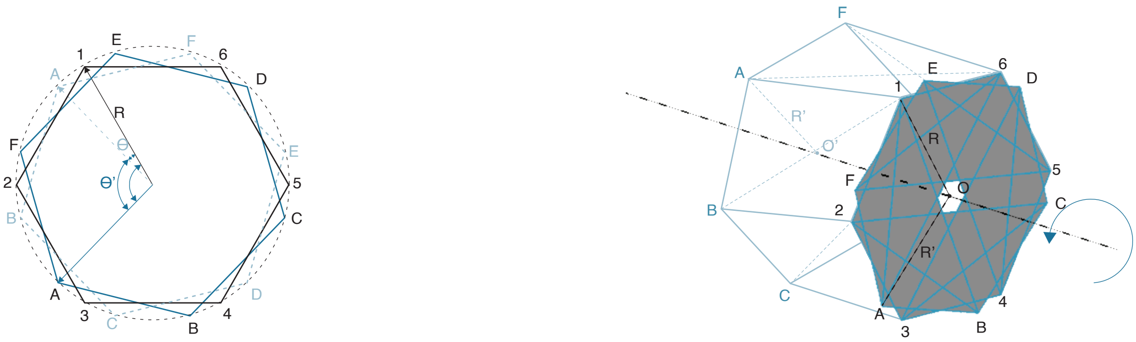


Fig. 4.5.07: a) Relation between the two polygons during the folding process

b) Cylindrical shell during motion

The perpendicular distance from point 1 to point A defines the height of the cylindrical shell in the undeployed state and can be obtained with the following equation:

$$H = b\sin\delta$$

H is also the distance between the two centres O, O' of the rotated regular polygons and is located on the rotation axis. The coordinates for point 1 are (R,$\frac{2\pi}{n}$,O) respectively for point A (R',O', $b\sin\delta$)

The distance between point 1 and A is defined by the edge b:

$$b = \sqrt{\left[2R\sin\left(\frac{2\pi/n-\theta}{2}\right)\right]^2 + (b\sin\delta)^2}$$

The relation between angle θ and δ is obtained as

$$\theta = \frac{2\pi}{n} - 2\sin^{-1}\frac{b\cos\delta}{2R}$$

$$\frac{b\cos\delta}{2R} \leq 1$$

$\frac{b}{a}$ defines geometry length ratio

$$\frac{b}{a} \leq \frac{1}{\cos\delta\sin\left(\frac{\pi}{n}\right)}$$

Fully folded configuration

$$\frac{b}{a} \leq \frac{1}{\sin\left(\frac{\pi}{n}\right)}$$

The coordinates for point 2 are (R, 4π/n, O) and the distance between 1 and B is represented by diagonal c resulting in:

$$c = \sqrt{\left[2R\left(\sin\frac{\pi}{n} + \sin^{-1}\frac{b\cos\delta}{2R}\right)\right]^2 + (b\sin\delta)^2}$$

The ratio between the diagonal c and the edge a of the regular polygon is described as:

$$\frac{c}{a} = \sqrt{\left[\frac{1}{\sin\frac{\pi}{n}}\sin\left(\frac{\pi}{n} + \sin^{-1}\left(\frac{b}{a}\cos\delta\sin\left(\frac{\pi}{n}\right)\right)\right)\right]^2 + \left(\frac{b}{a}\sin\delta\right)^2}$$

In fully folded configuration

$$\frac{c}{a} = \frac{1}{\sin\left(\frac{\pi}{n}\right)}\sin\left(\frac{\pi}{n} + \sin^{-1}\left(\frac{b}{a}\sin\left(\frac{\pi}{n}\right)\right)\right)$$

In the particular case of n=6

$$\frac{c}{a} = \sqrt{\left[2\sin\left(\frac{\pi}{6} + \sin^{-1}\left(\frac{b}{2a}\cos\delta\right)\right)\right]^2 \left(\frac{b}{a}\sin\delta\right)^2}$$

Folding base shapes

Fig. 4.5.08: Shape functionality

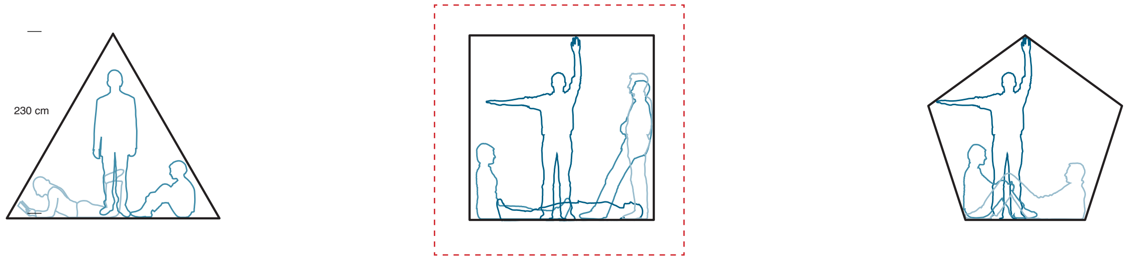


Fig. 4.5.09: Connecting modules

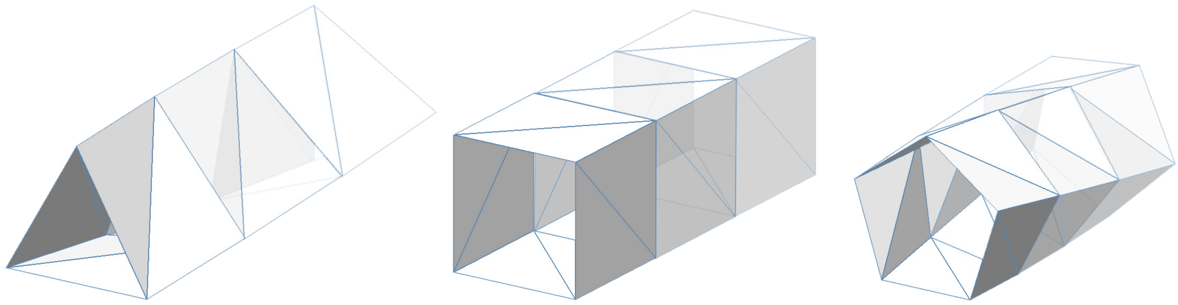


Fig. 4.5.10: Folding process of individual units

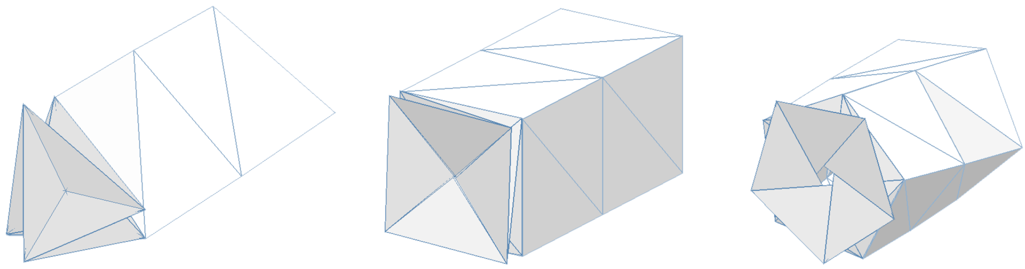


Fig. 4.5.11: 1st unit folded

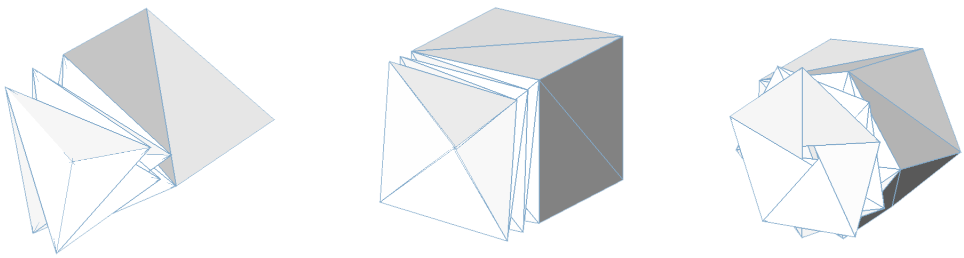


Fig. 4.5.12: 2nd unit folded

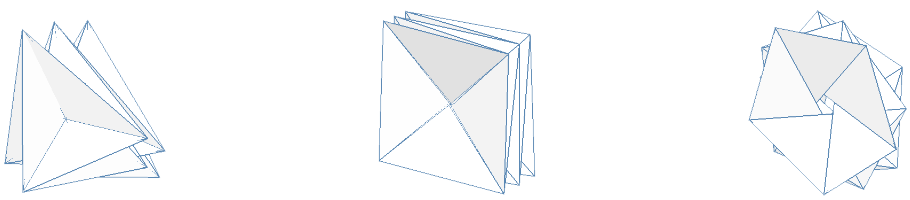
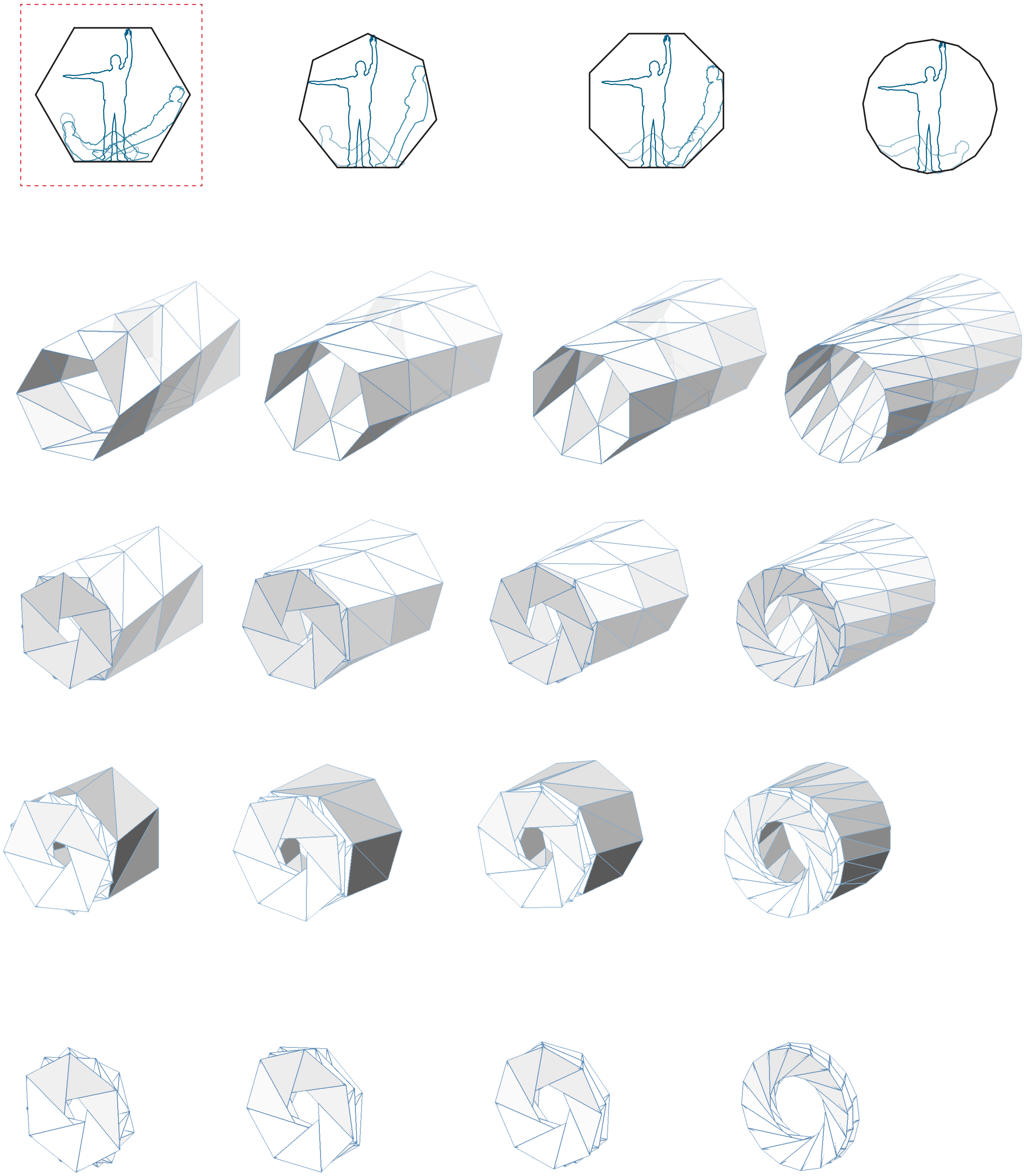


Fig. 4.5.13: 3rd unit folded...



5. DESIGN APPLICATION

5.1. Facade add-on
5.2. Folding Pod
5.3. Mock-up photos

5.1. Facade Add-on

In this first design application the folding principle of the Kresling pattern is put into practice by translating it to a cantilevering aluminium and glass structure with the function of a closed balcony. It consist of a cube with 2,4 m side length.

The folding facade add-on imagines the potential of the deployable system to extend the living space in an block of apartments for instance. The project exemplifies how the cube shaped structure can be mounted on an existing facade and function as an additional enclosed space for an existing apartment. From building typology it can be considered similar to a closed balcony hanging from the facade. The facade plane can be preserved in order not to damage and weaken the structural and thermal function of the facade.
From a structural point of view it can be attached to the slab floor in a building by means of anchoring profiles, which are fastened to the slab. A reinforced concrete structure would be suited for the anchors to provide proper load transfer. Two slab anchors supporting the lower platform and 2 wall anchors for the roof panels are needed. To these anchors 4 custom-made structural nodes with a swinging beam mechanism are attached. Each swinging beam has 1 degree of freedom (DOF), being able to perform a 90° angle rotation around the axis of the pivoting joint. Every two beams are swinging downwards respectively upwards and sidewards left and right. When reaching the deployed state the beams are locked in place and function as cantilevering beam to ensure the stability of the structure. The beams are pipe profiles with 8 cm diameter encased into a second pipe profile which rotates around the first, to which the platform, lateral and top triangular panels are attached. While the bottom platform is designed with laminated walk-on insulating glazing panels, to ensure safety, the lateral and top panel consist of insulated framed glass triangles.
Since the folding element was not designed for a specific location and it can be mounted to different locations on buildings with different functionality, the structural design needs to be adapted to the required safety regulations.
The deployment and folding of the structure is performed by electric motors which control the pivot joints. The triangular panels are connected to each other trough a hinged strut enabling a 180° angle of rotation. The front panel consists of 2 sections: a fixed one in 0.9 m height functioning as a parapet, and the upper section which is openable to ensure ventilation. When folded the structure collapses into a protective case mounted around the structure with the purpose of storing and protecting the structure while not in use.

Fig. 5.1.01: Facade Add-on - folding process overlay

Fig.5.1.02: Facade add-on in different deployment states
Facade reconstruction after Eberlgasse 1-5, 1020 Vienna

Facade add-on attached to type A apartment

The net internal area of the apartment is 47 m^2 with an additional 5 m^2 provided by the facade add on element.

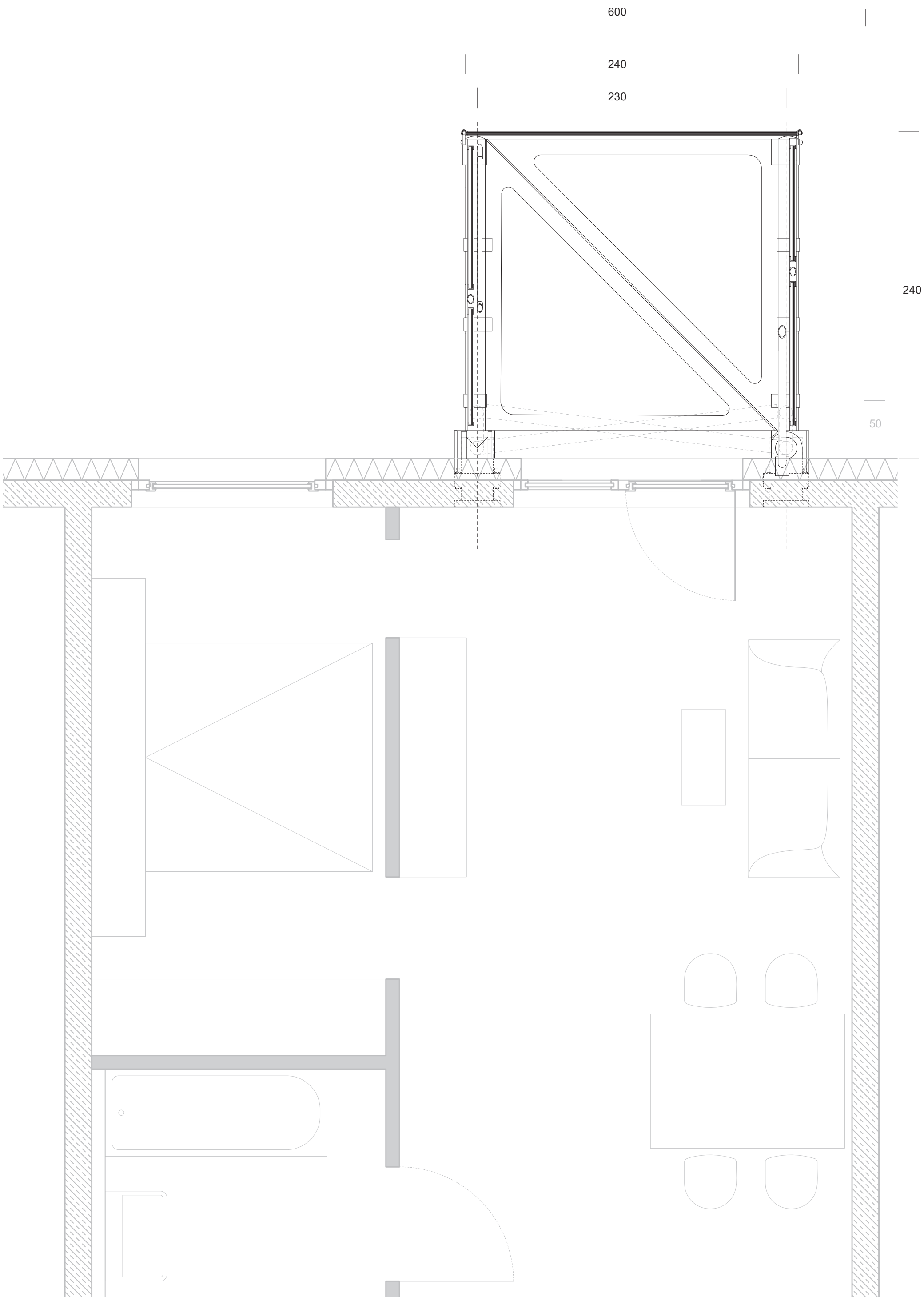


Fig. 5.1.03: Floor plan - scale 1:50

Fig. 5.1.04: Isometric view

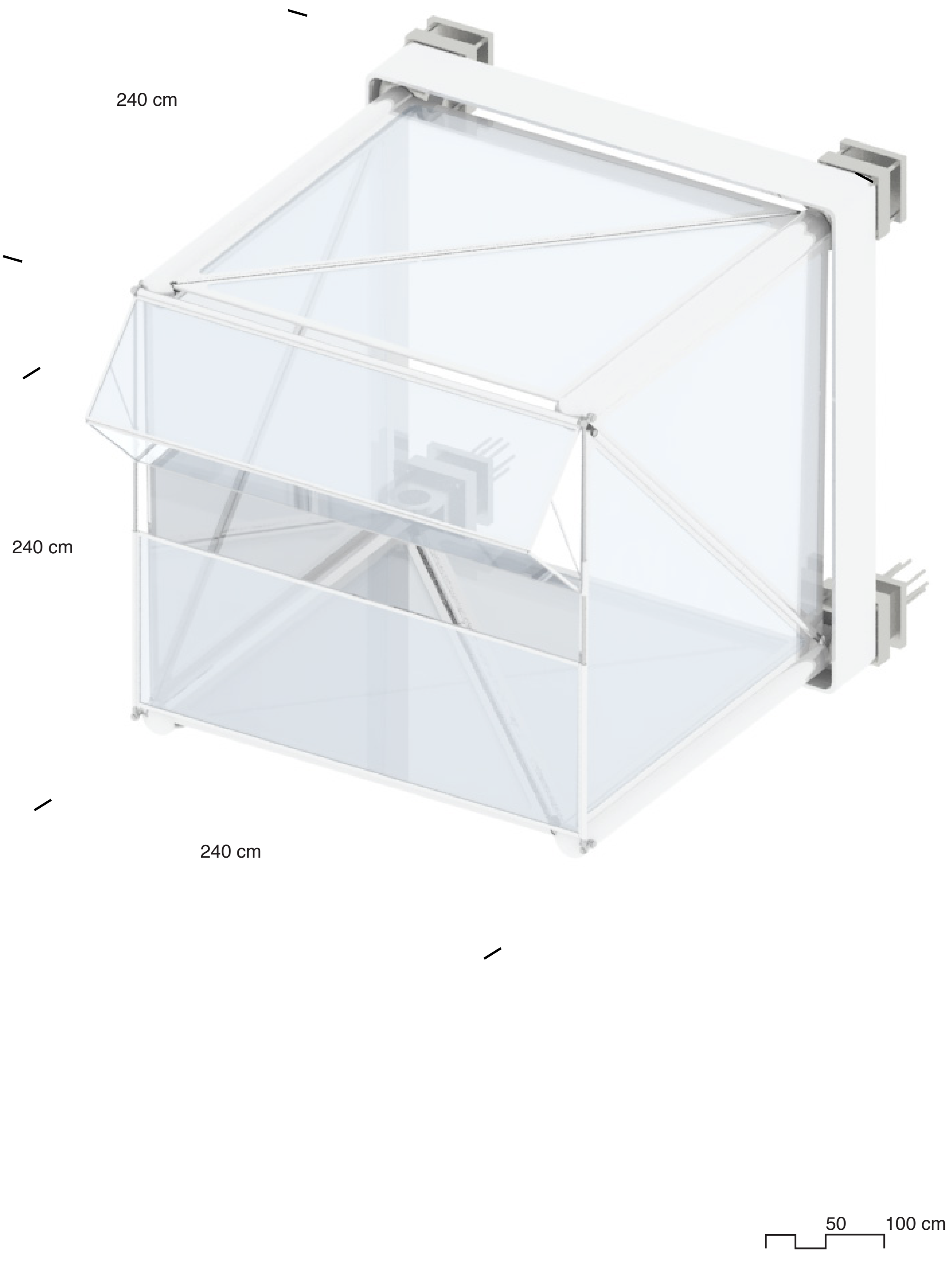


Fig. 5.1.05: Floor plan - scale 1:20

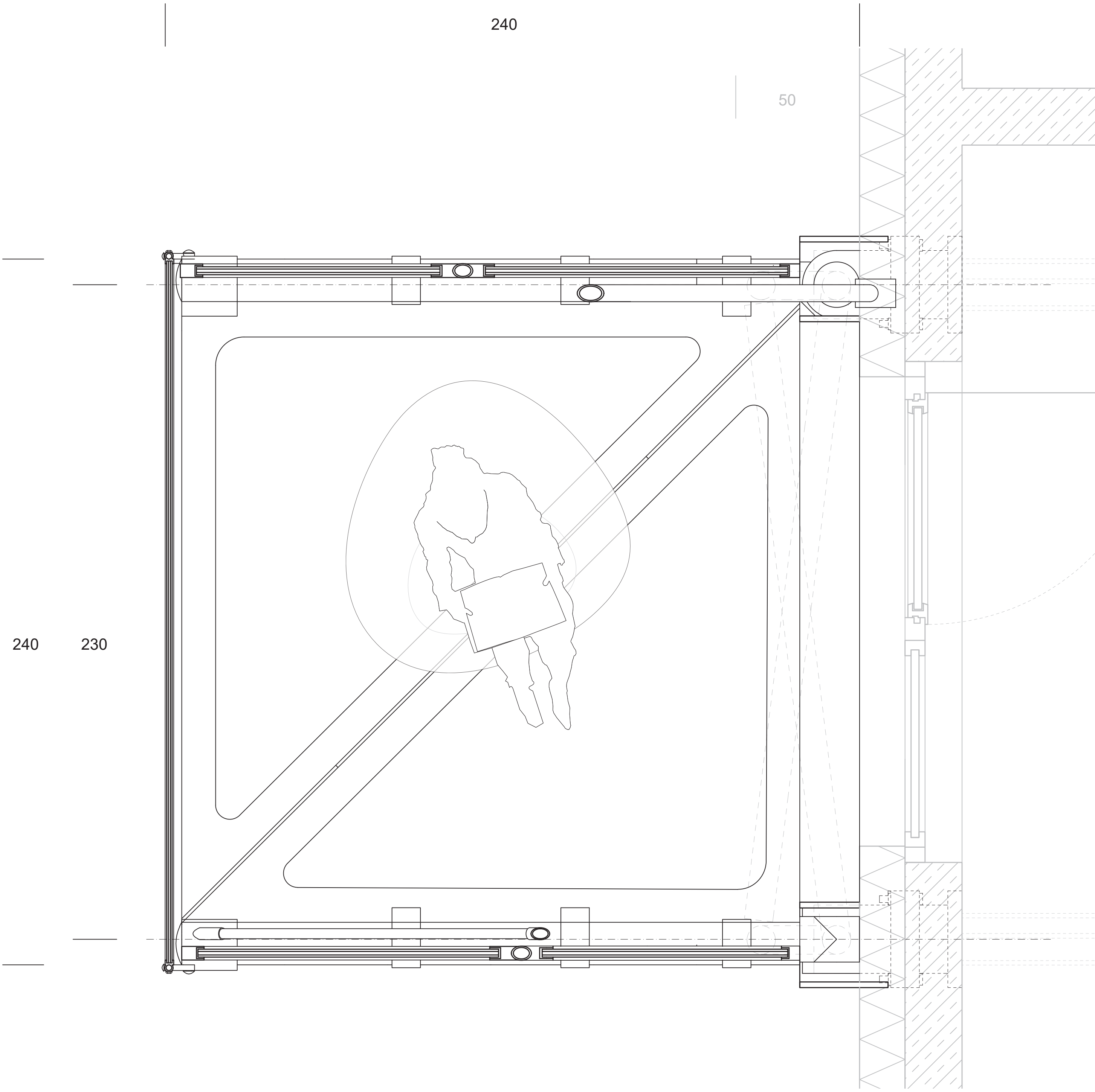


Fig. 5.1.06: Interior rendering

Fig. 5.1.07: Section - scale 1:20

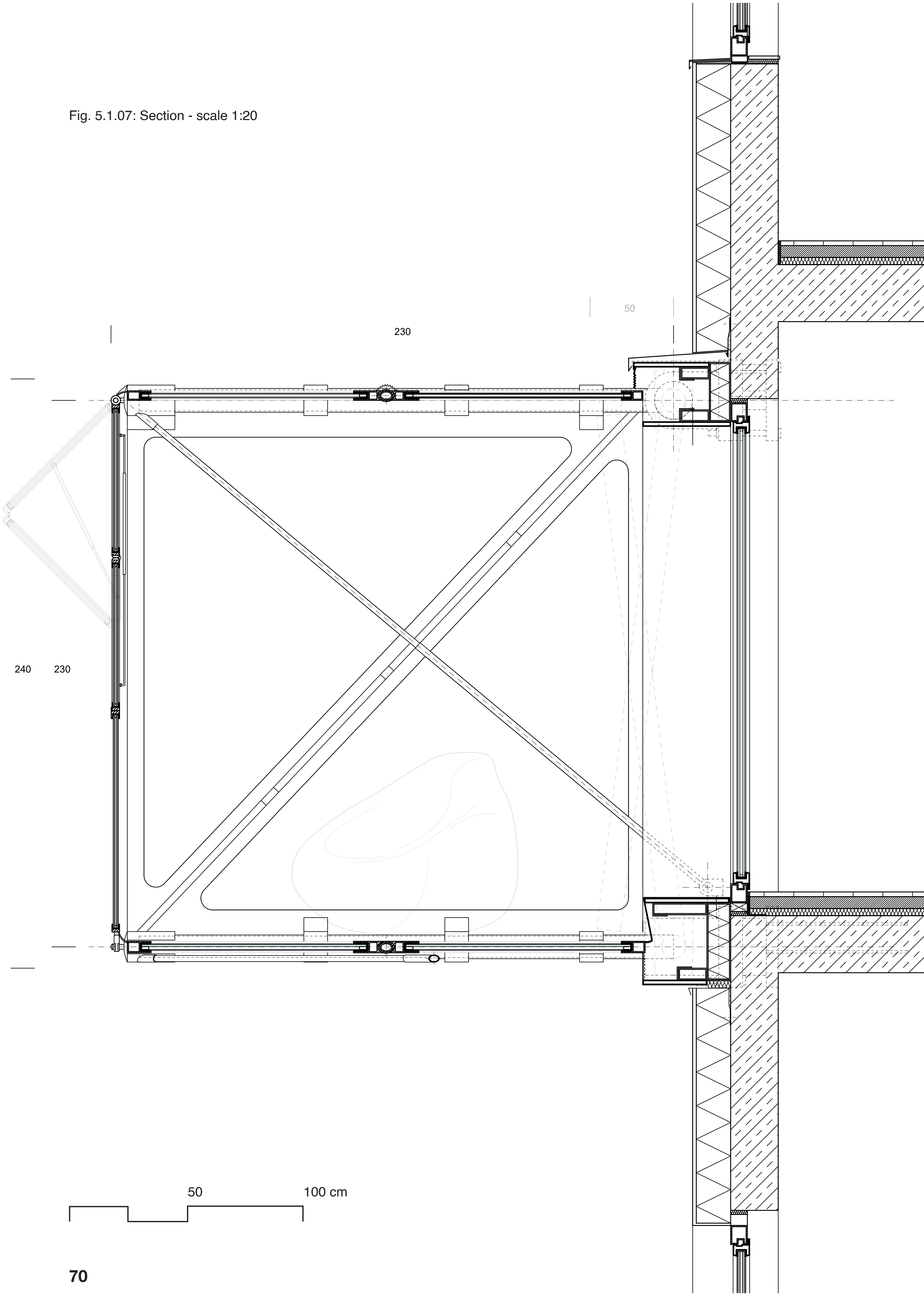


Fig. 5.1.08: Facade add-on deployed state

Folding scheme of beam structure

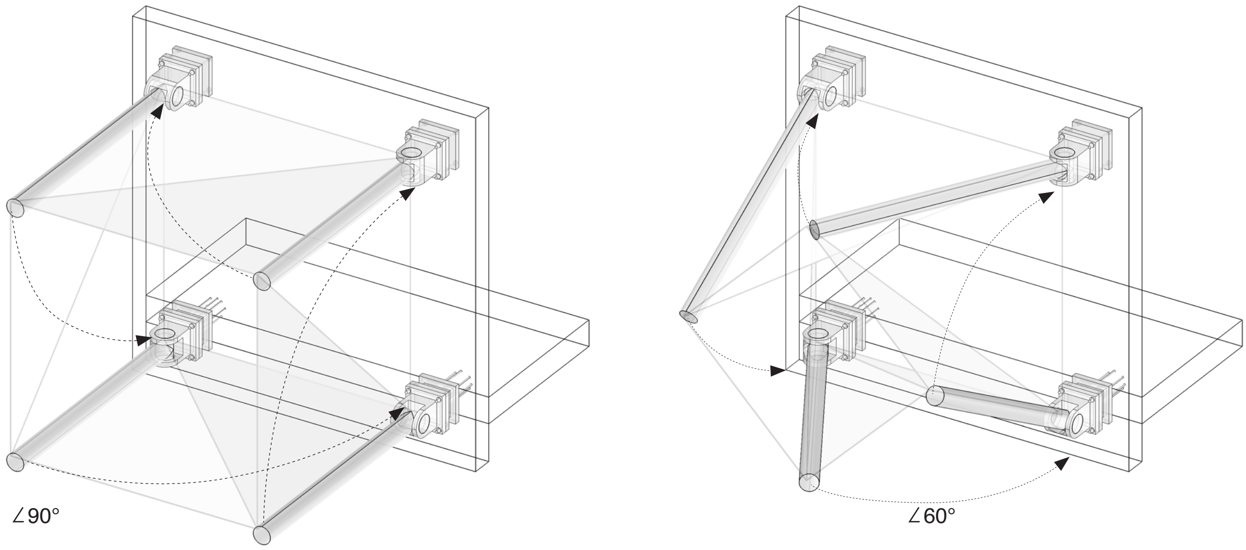


Fig. 5.1.09: a) deployed structure 90° angle
path movement

b) folding process 60° angle

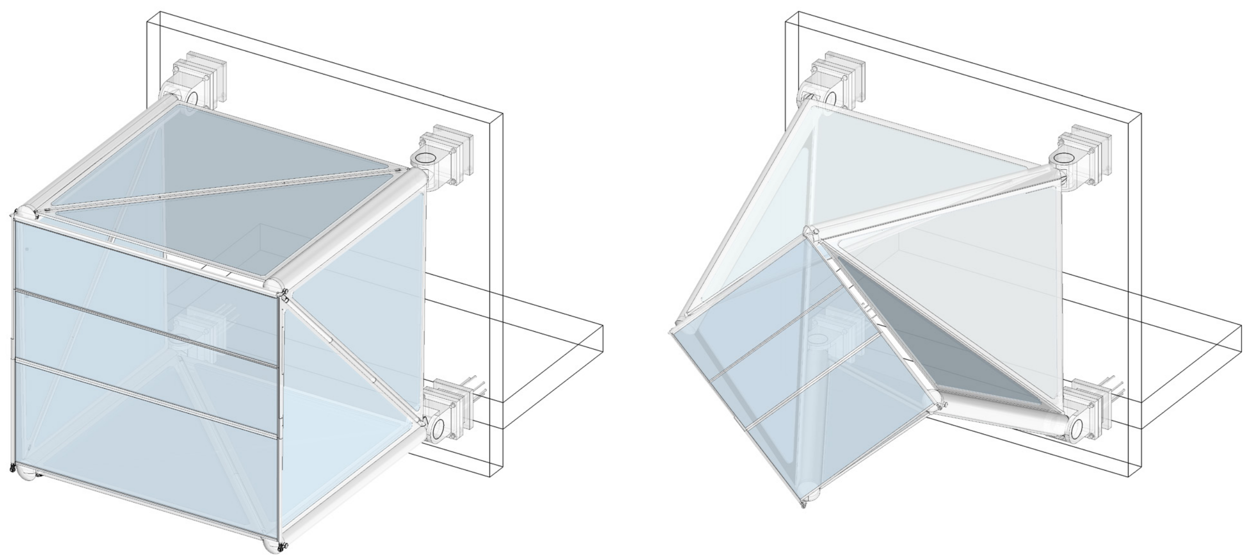
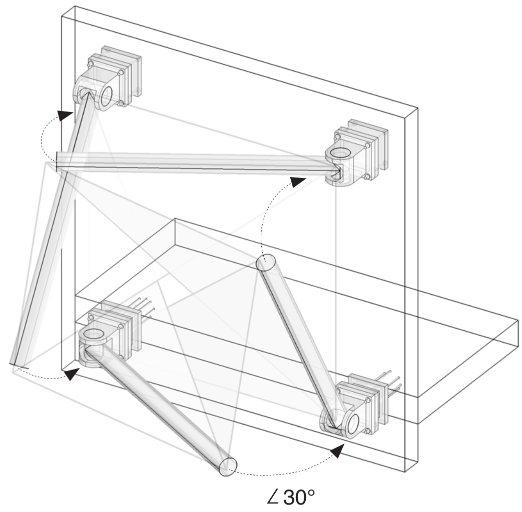
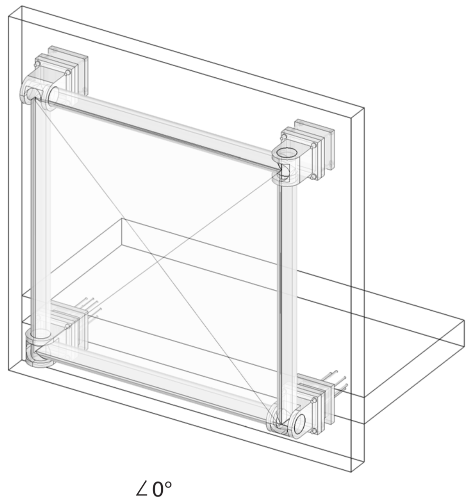


Fig. 5.1.10: a) deployed oriel 90° angle

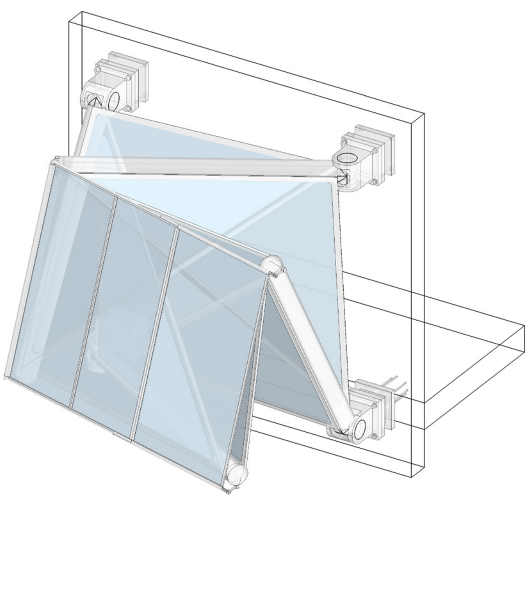
b) oriel - folding process 60° angle

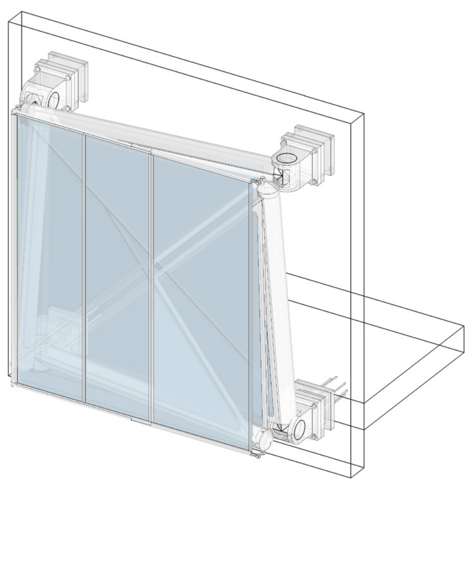




c) folding process 30° angle

d) folded structure 0° angle - only works for the beams without cladding panels





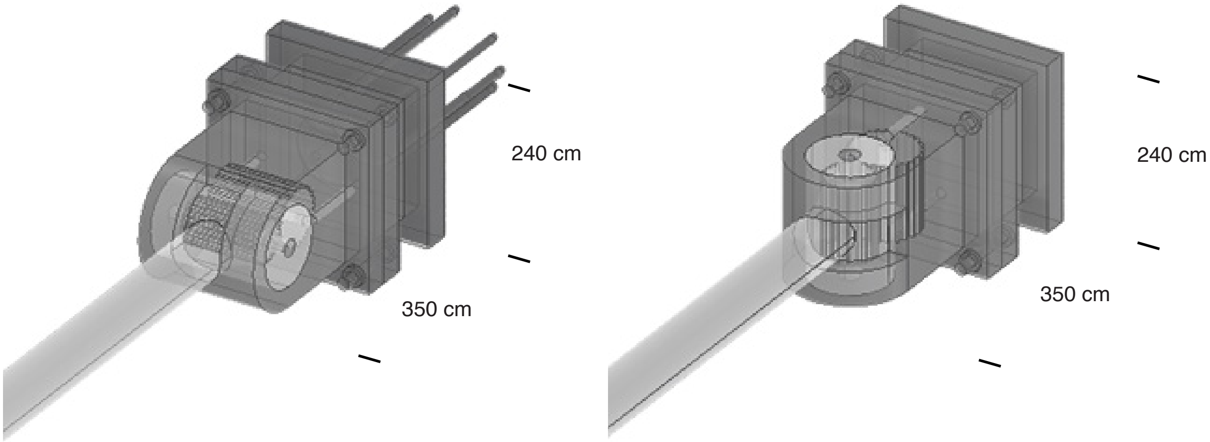
c) oriel folding process 30° angle

d) folded oriel aprox. 5° angle - with cladding panels the structure cannot be folded completely due to the overlapping diagonal struts

Structure

Fig. 5.1.11: a) slab anchor - steel plate with steel rods with rotary joint actuated by electric motor 1-DOF 85° angle - vertical movement

b) wall anchor with rotary joint actuated by electric motor 1-DOF 85° angle - vertical movement



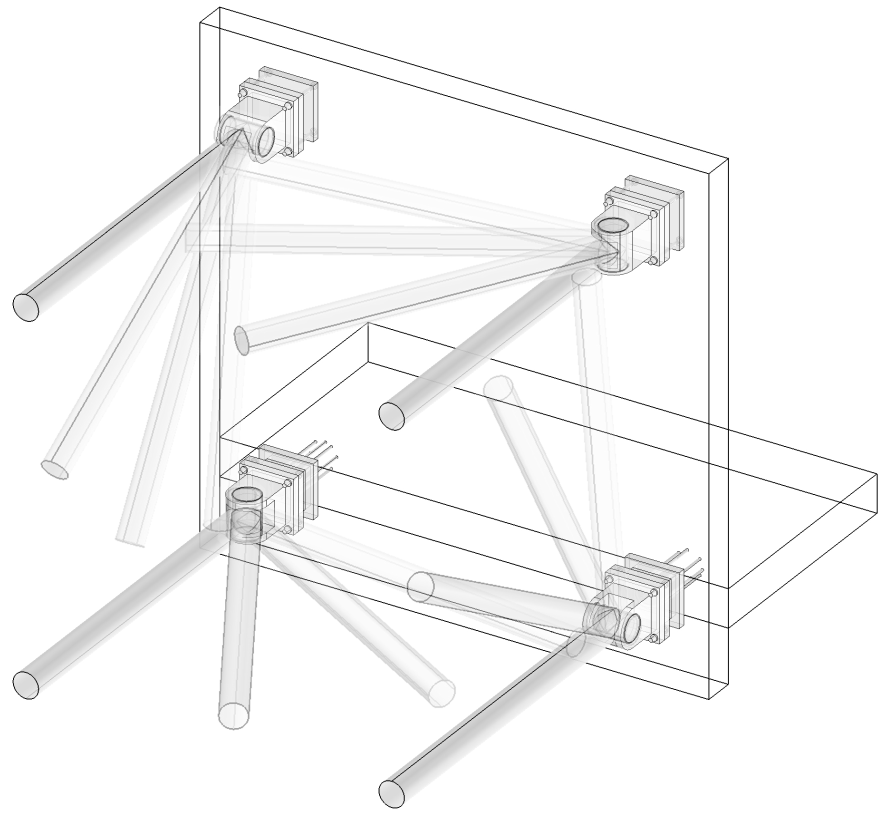
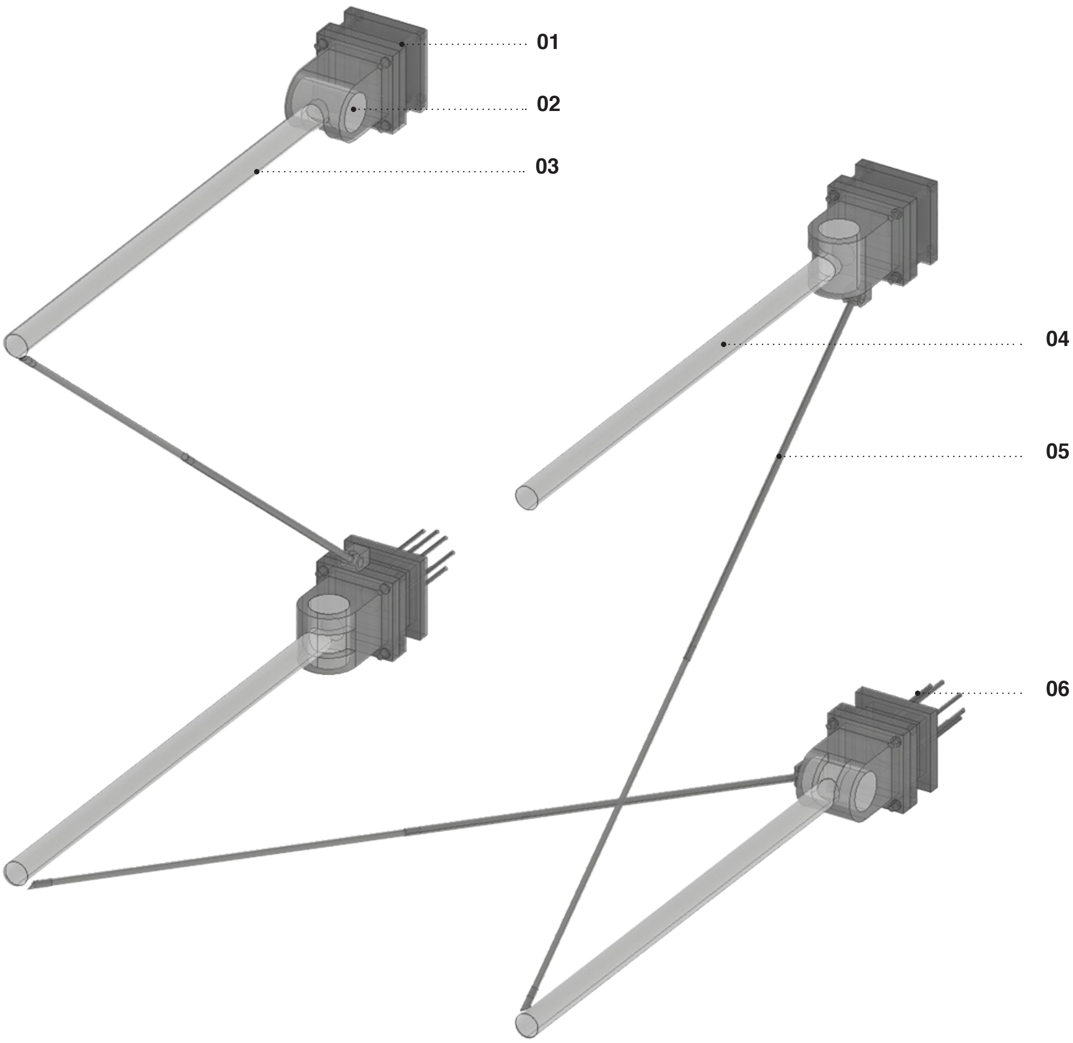


Fig. 5.1.12: Structure - folding process

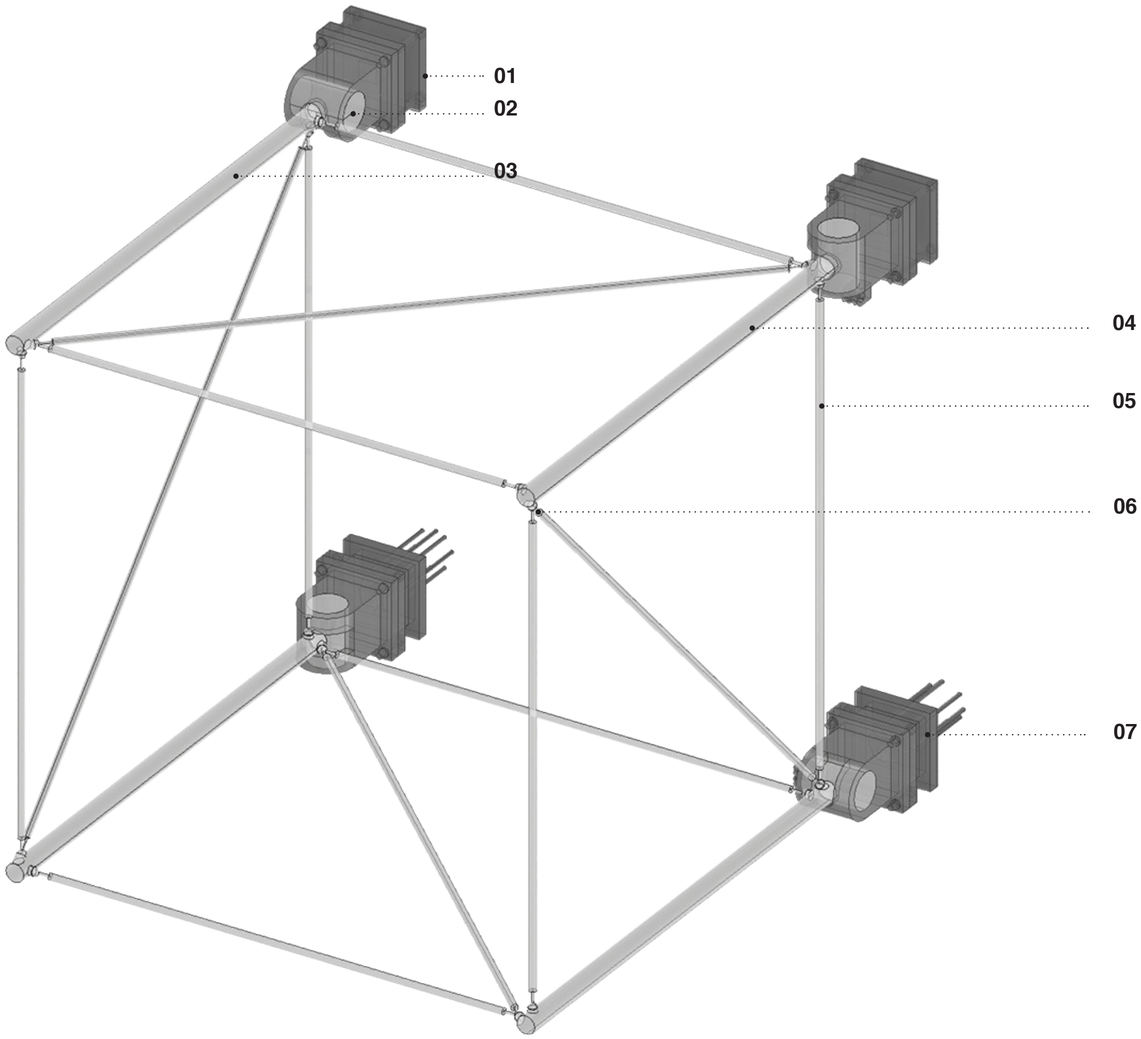
Fig. 5.1.13: Load bearing structure
Beams and retractable wind bracing elements



Legend

01	Isolated wall anchor - steel plate bolted to reinforced concrete wall
02	Rotary joint actuated by electric motor 1-DOF 85° angle
03	Vertically swinging beam - structural aluminium Ø 80, s5 mm
04	Horizontally swinging beam - structural aluminium Ø 80, s5 mm
05	Retractable wind bracing beam support Linear actuator Ø30 mm aluminium pipe with rotary joint
06	Slab anchor node - steel plate with steel rods

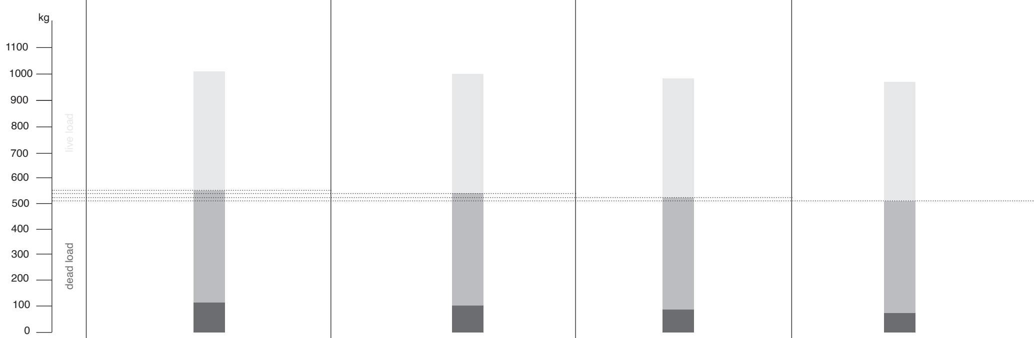
Fig. 5.1.13: b) Load bearing structure
Beam pipes with spherical joints



Legend

01	Isolated wall anchor - steel plate bolted to reinforced concrete wall
02	Rotary joint actuated by electric motor 1-DOF 85° angle
03	Vertically swinging beam - structural aluminium Ø 60, s5 mm
04	Horizontally swinging beam - structural aluminium Ø 60, s5 mm
05	Steel strut Ø30 mm
06	Spherical steel joint
07	Slab anchor node - steel plate with steel rods

Tab 5.01.01: Facade Add on - Structural materials comparison

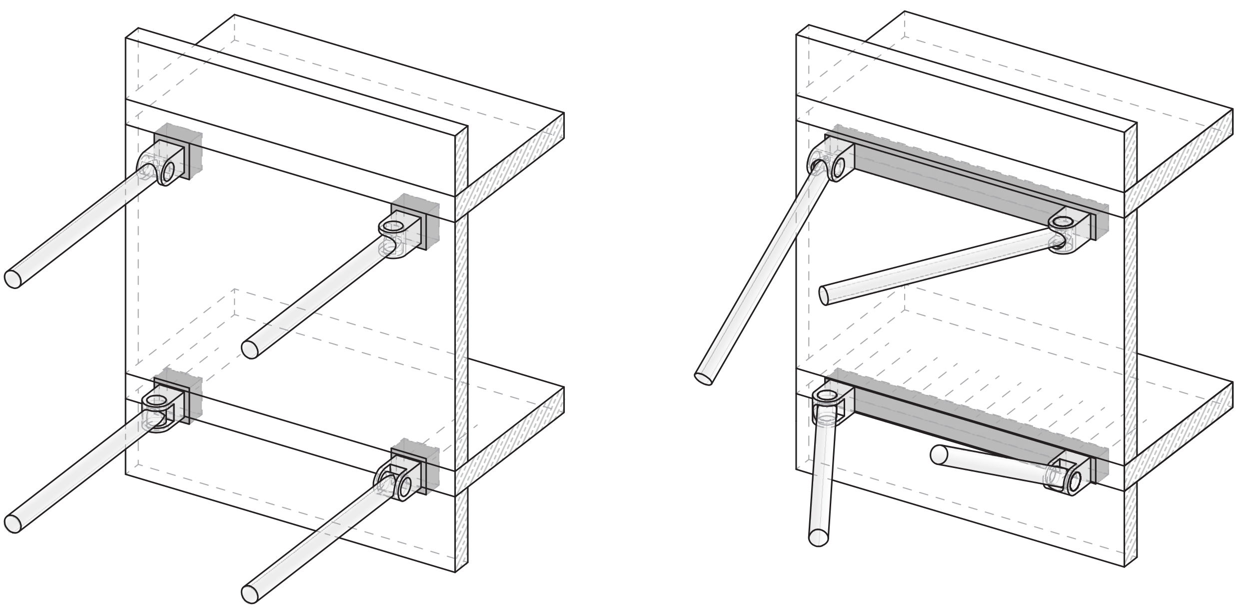
	Steel S235		Aluminium 6061-T6 alloy	
	Structure 01	Structure 02	Structure 01	Structure 02
Beam Dimension [mm]	ø 71 s 2,9	ø 51 s 2,6	ø 80 s 5	ø 60 s 5
Weight structure [kg]	78	62	52	43
Anchor nodes [kg]	40			
∑ Structure [kg]	118	102	92	82
Glass panels [kg]	300			
Alu frame [kg]	132			
Alu hinge pipes [kg]	7,2			
∑ cladding [kg]	439,2			
Unit weight comparison [kg] 				
Total weight [kg] 	557,2	541,2	531,2	521,2

The above table juxtaposes the 2 structural models for which both steel and aluminium pipe were considered as possible load bearing structural material. While structure 01 consists of 4 main beams and 3 secondary supporting struts it requires larger cross-section dimensioning for the pipes. Structure 02 consists of truss structure with smaller cross-sections for the pipes as there are more load bearing elements which improve the load transfer.

Reinforcement types

Depending on the construction material of the building the add-on structure will be installed on, different reinforcement types can be used to ensure the load transfer from the cantilevering structure to the existing one.

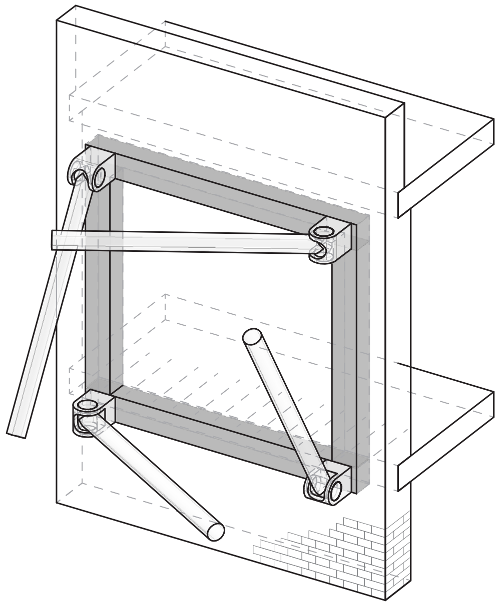
Fig. 5.1.14: Reinforcement types
a) Isolated reinforcement for each beam suitable for reinforced concrete structures
b) Linear reinforcement along the slab



Steel reinforcement element

50 100 cm

c) Frame reinforcement



d) Column reinforcement

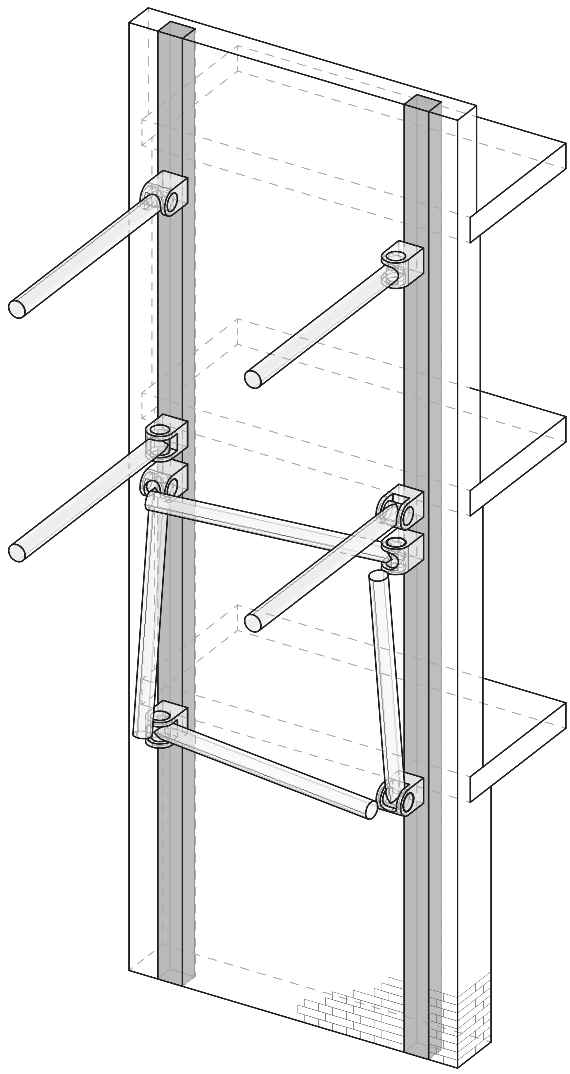
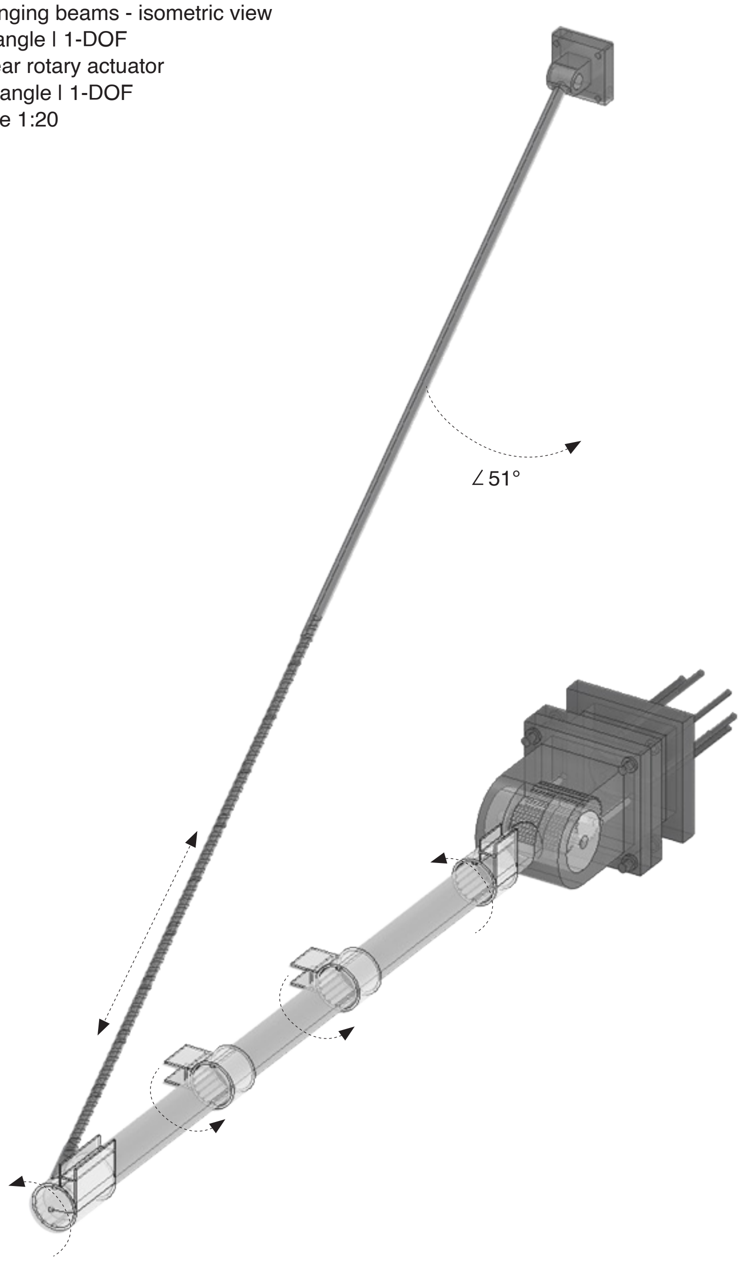
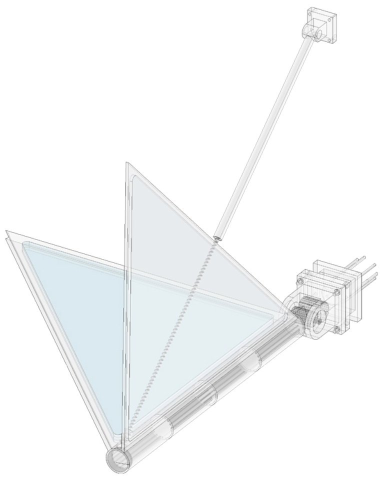


Fig. 5.1.15: a) Swinging beams - isometric view
90°angle | 1-DOF
Linear rotary actuator
53 °angle | 1-DOF
scale 1:20



Panels in deployed position
90° angle



Panels in folding process
60° angle

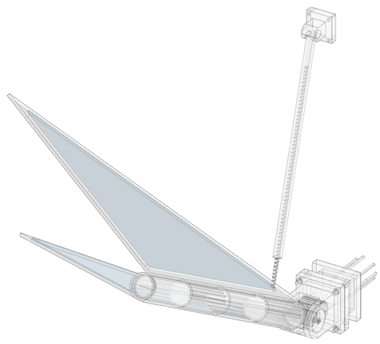
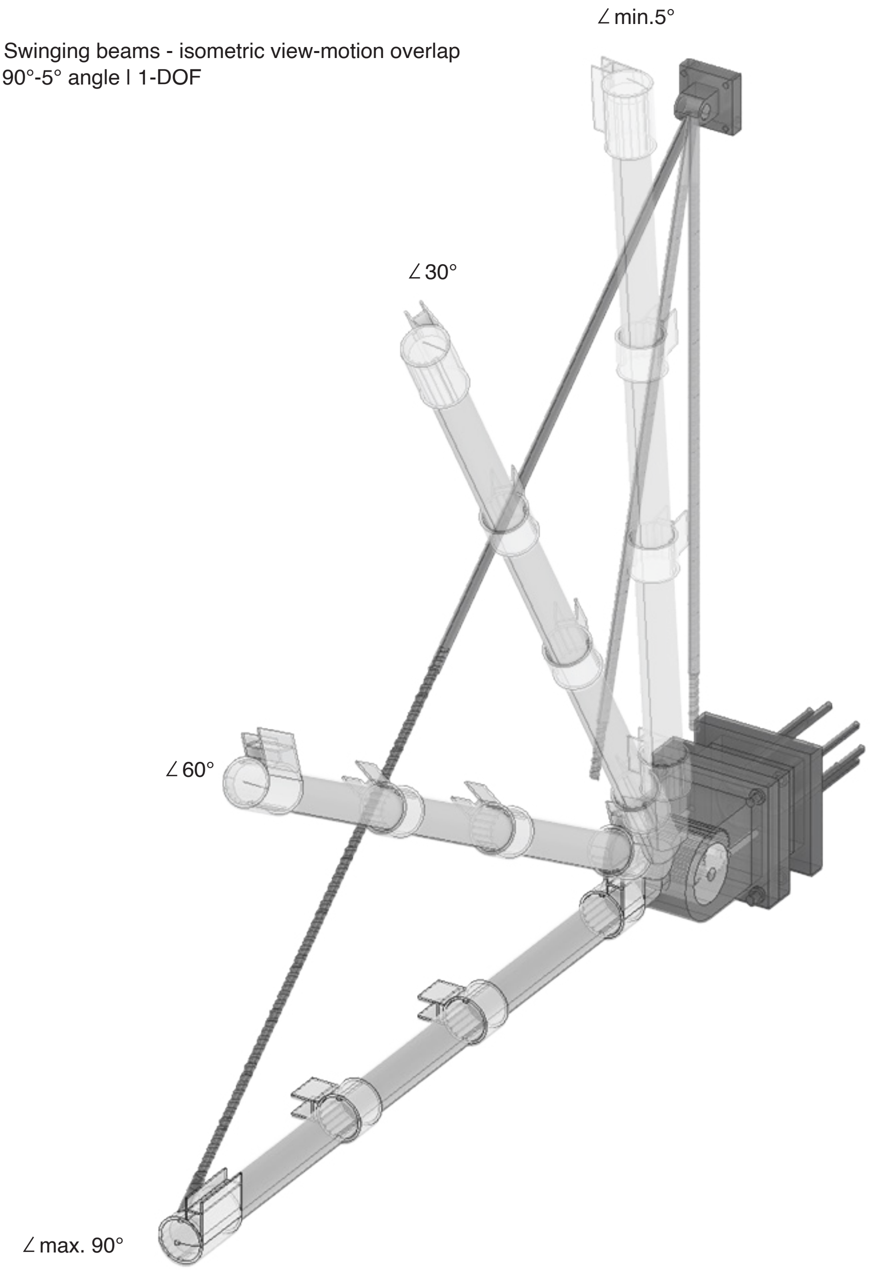
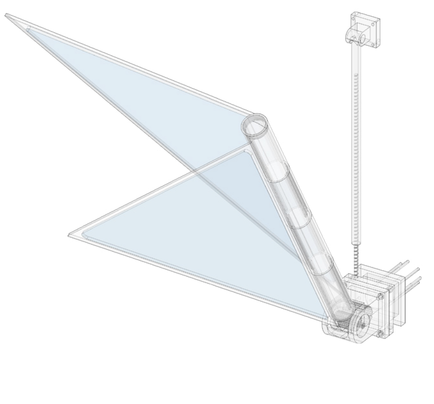


Fig. 5.1.15: b) Swinging beams - isometric view-motion overlap
90°-5° angle | 1-DOF



Panels in folding process
30° angle



Panels in folded state
5° angle

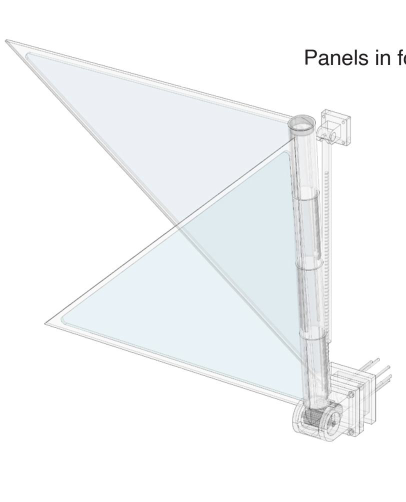


Fig. 5.1.16: a) Swinging beam | retractable wind bracing element - section - deployed state
90°angle | 1-DOF
Scale 1:20

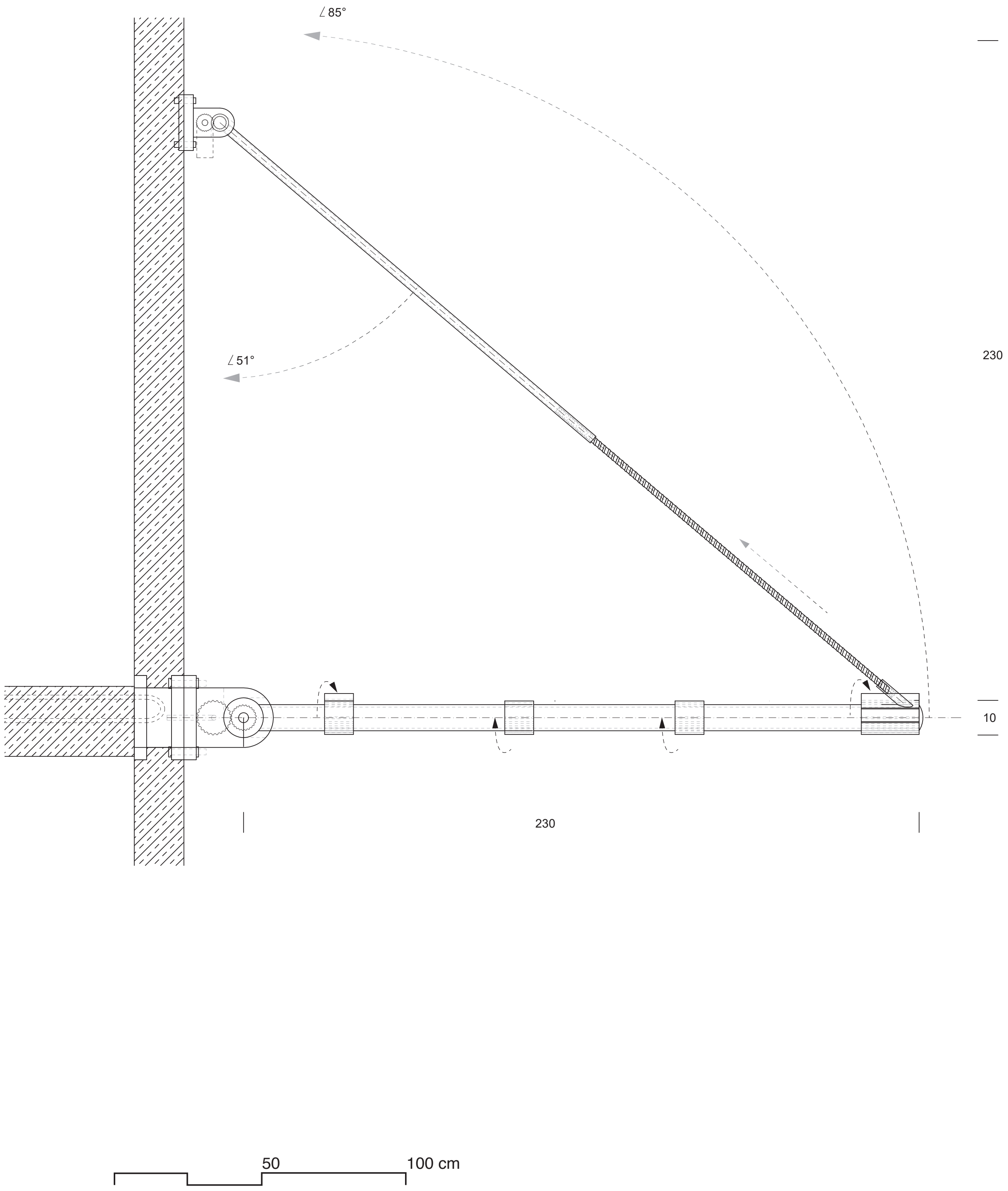


Fig. 5.1.16: b) Swinging beam I retractable wind bracing element - section - movement overlay
90°, 60°, 30°, 5° angle
Scale 1:20

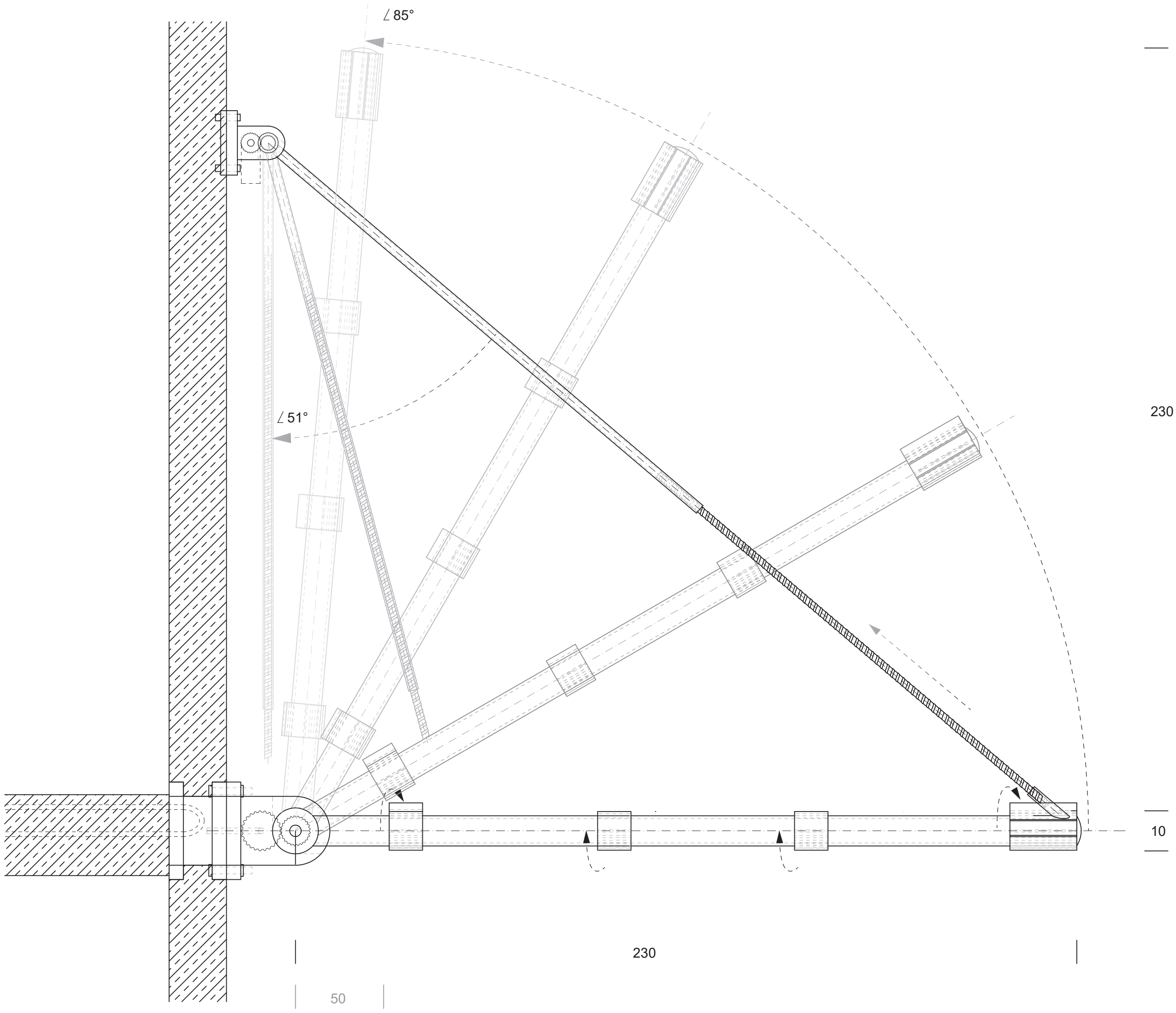


Fig. 5.1.17: Reference - Linear actuator

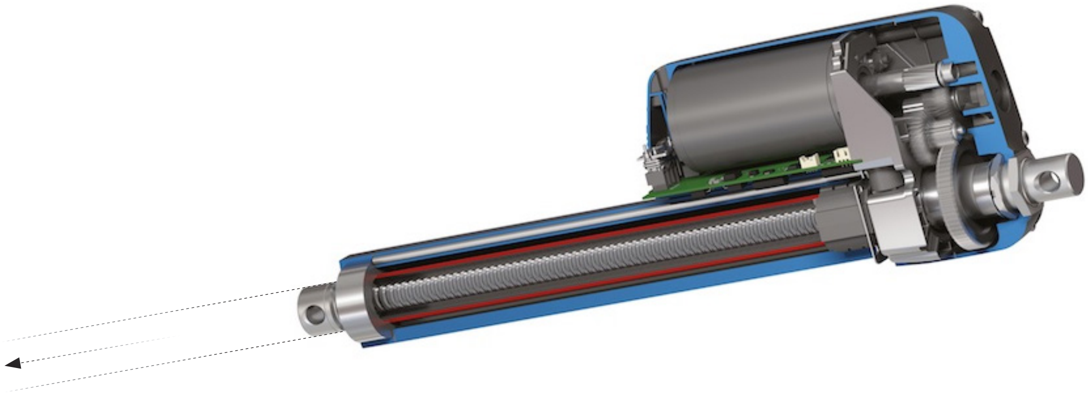
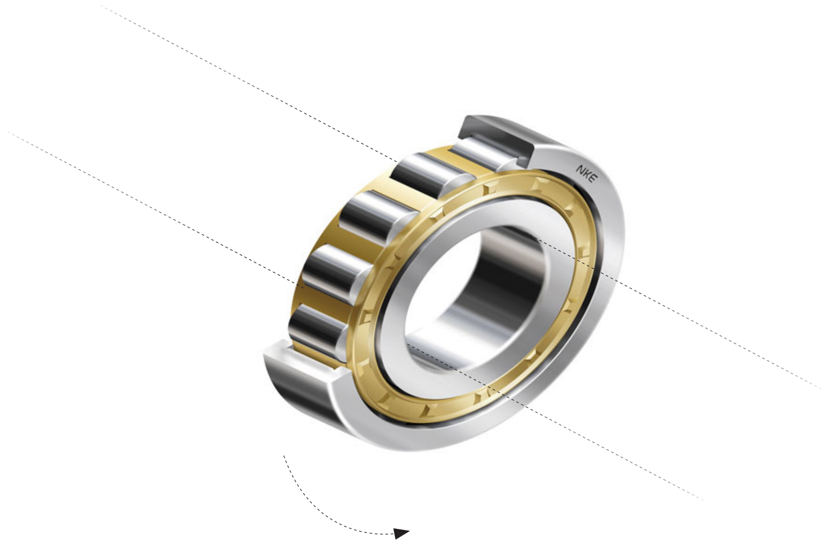


Fig. 5.1.18: Reference - Cylinder bearing



Legend

01 Wall anchor - steel profile
02 Swinging node of wind bracing element
03 Retractable wind bracing beam support - linear rotary actuator Ø 40mm
04 Insulation glass panels 4mm tempered glass I12 mm spacing I 4mm tempered glass
05 Rotating hinge pipe for the framed glass panels with cylinder bearing
06 Load bearing vertically swinging beam Ø 80mm
07 Rotation lock
08 Ribbed rubber profile - weather proof
09 Slab anchor - steel profile
10 Rubber profile
11 Walk-on aluminium framed insulation glazing
Laminated glass with top layer anti-slip texture: 4 mm tempered glass
0,76 PVB-foil
8 mm tempered glass
12 mm spacing
4 mm tempered glass

Fig. 5.1.19: Beam | retractable wind bracing element | hinged aluminium & glass elements
Detail cross-section
Scale 1:5

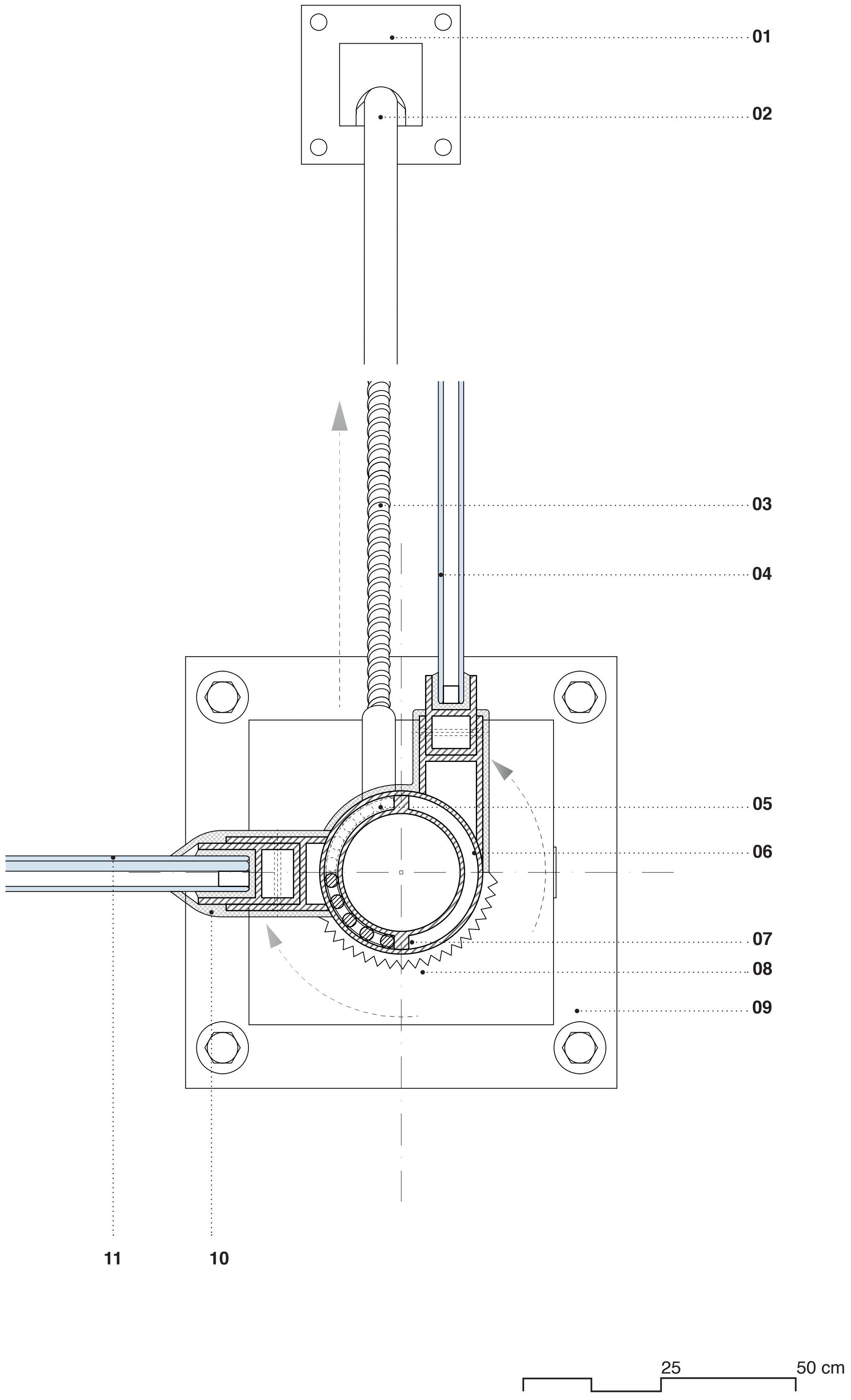
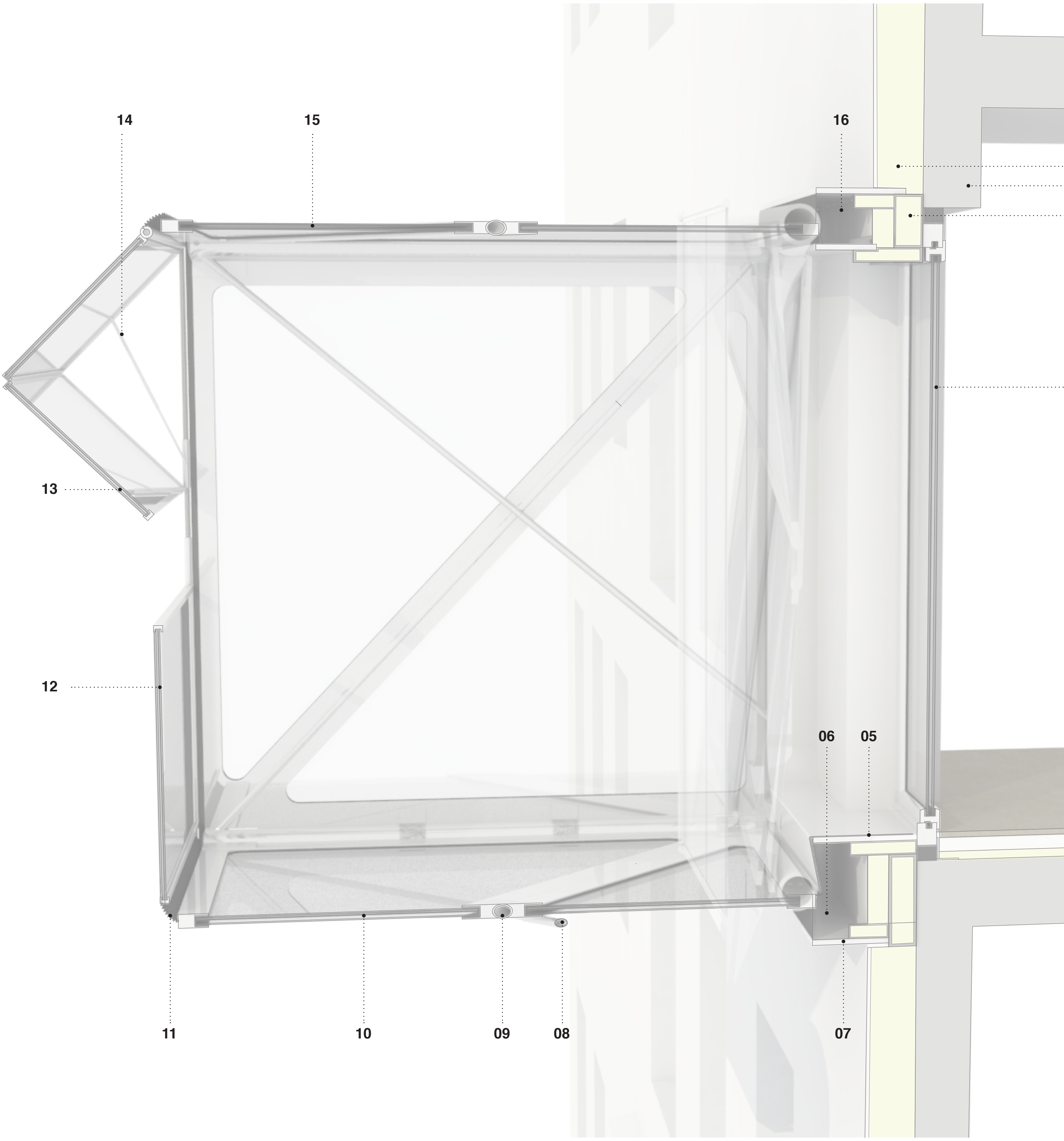
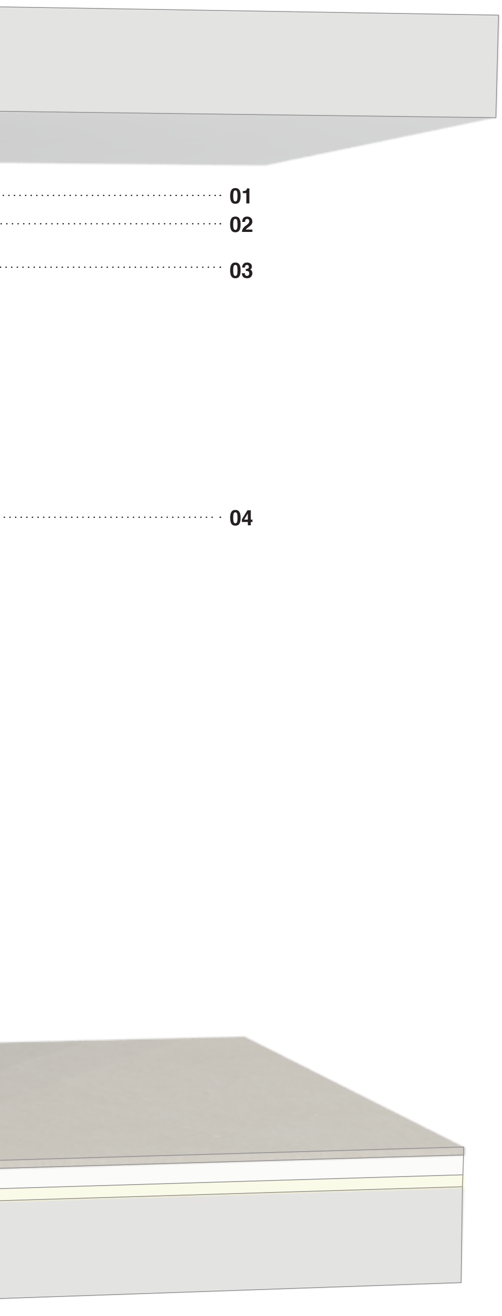


Fig. 5.1.20: 3D cross-section



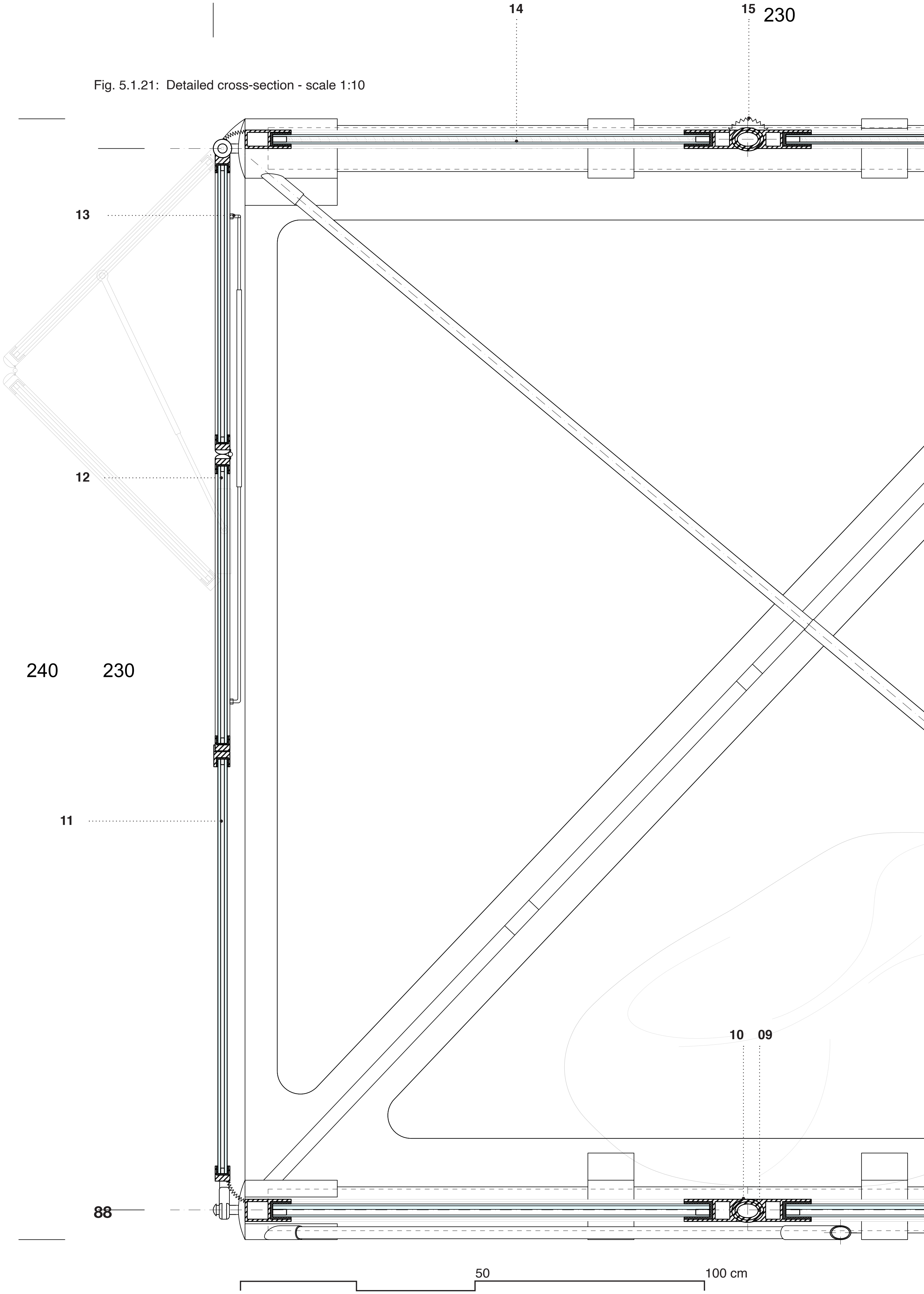


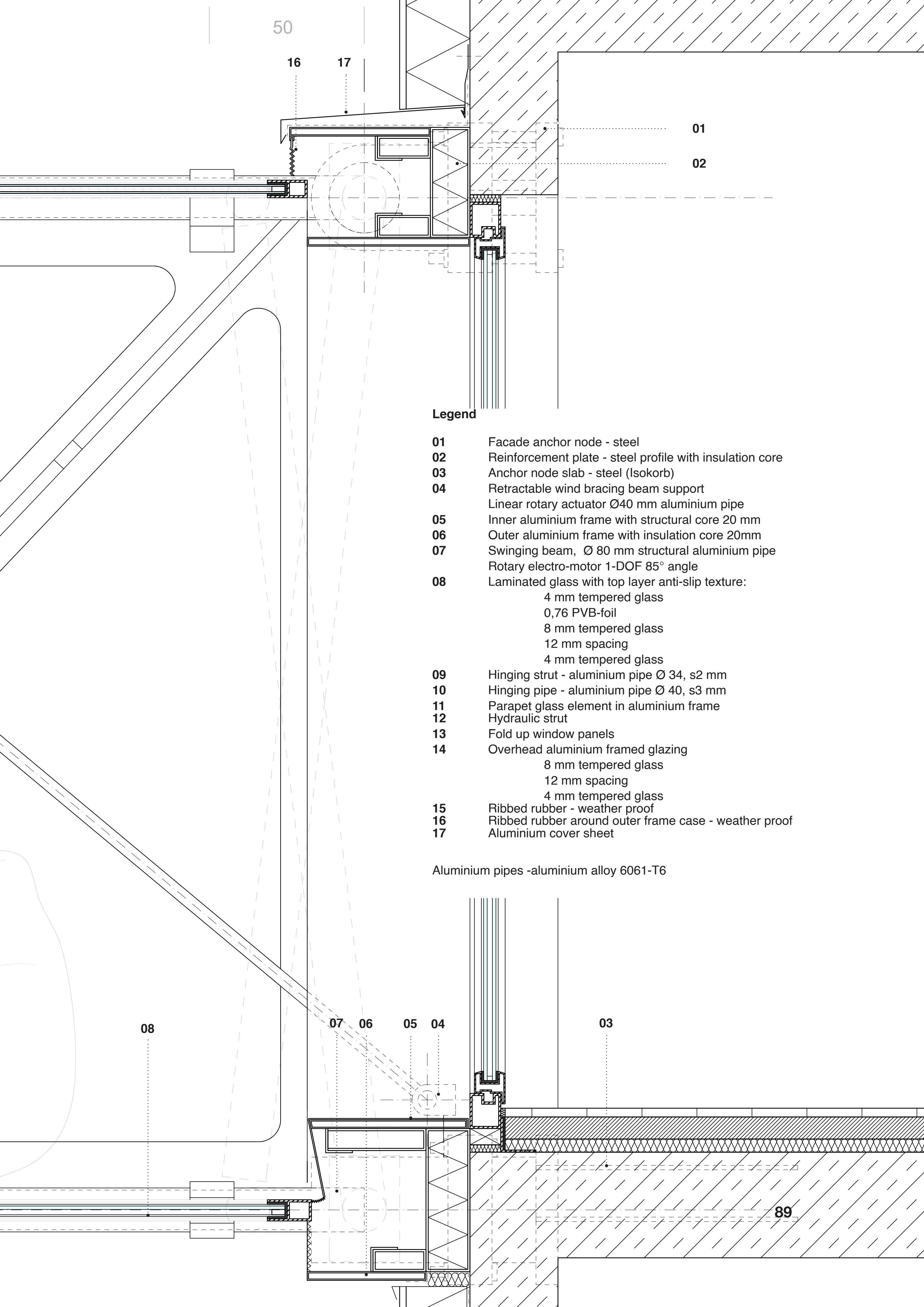
Depending on the national regulations regarding the use of structural glazing variations for the laminated glass panels can be used depending on the safety requirements. For the case of residential use of the add-on regulations regarding walk-on structural glazing from the ÖNORM B 3716-4 Austrial National Standards were considered. According to DIN 18008-5 German national Standards however the walk on glazing is required to consist of 3 panels of laminated glass.

Legend

01	Thermal insulation existing facade 160 mm
02	Existing load bearing wall - reinforced concrete
03	Anchor plate - steel profile
04	Door
05	Inner aluminium frame with structural core 20 mm
	Step - 160 mm height
06	Protection case for folding beam
07	Outer aluminium frame with insulation core 20mm
08	Retractable wind bracing beam support
	Linear rotary actuator Ø40 mm aluminium pipe
09	Hinging aluminium pipe 40 mm
10	Laminated glass with top layer anti-slip texture:
	4 mm tempered glass
	0,76 PVB-foil
	8 mm tempered glass
	12 mm spacing
	4 mm tempered glass
11	Ribbed rubber profile - weather proof
12	Parapet glass element in aluminium frame
13	Up-folding window panels
14	Hydraulic strut
15	Overhead aluminium framed glazing
	8 mm tempered glass
	12 mm spacing
	4 mm tempered glass
16	Protection case for folding beam

Fig. 5.1.21: Detailed cross-section - scale 1:10





Legend

01	Facade anchor node - steel
02	Reinforcement plate - steel profile with insulation core
03	Anchor node slab - steel (Isokorb)
04	Retractable wind bracing beam support Linear rotary actuator Ø40 mm aluminium pipe
05	Inner aluminium frame with structural core 20 mm
06	Outer aluminium frame with insulation core 20mm
07	Swinging beam, Ø 80 mm structural aluminium pipe Rotary electro-motor 1-DOF 85° angle
08	Laminated glass with top layer anti-slip texture: 4 mm tempered glass 0,76 PVB-foil 8 mm tempered glass 12 mm spacing 4 mm tempered glass
09	Hinging strut - aluminium pipe Ø 34, s2 mm
10	Hinging pipe - aluminium pipe Ø 40, s3 mm
11	Parapet glass element in aluminium frame
12	Hydraulic strut
13	Fold up window panels
14	Overhead aluminium framed glazing 8 mm tempered glass 12 mm spacing 4 mm tempered glass
15	Ribbed rubber - weather proof
16	Ribbed rubber around outer frame case - weather proof
17	Aluminium cover sheet

Aluminium pipes -aluminium alloy 6061-T6

5.2. Folding Pod

The folding pod is a modular structure based on the Kresling folding pattern. The primary structure is composed of 2 hexagonal frames to which the secondary folding structure is attached. The triangular cladding panels are designed with a hinging tube which runs to the middle of each side and connect to the neighbouring panel using ball joints to perform the deployment of the system and lock in place to ensure the load transfer, when used. The cladding panels can be also designed with glass panels, which can be opened. The proposed material for the cladding panel is insulated aluminium panels, which would provide durability. The structure can be designed from different materials like steel, aluminium or carbon fibre composite.

The proposed unit can be connected to multiple units by fixing two adjacent frames with nut and bolt fixtures. One unit offers an area of 5 m^2. A sanitary unit was designed that could be attached to the folding modules and provide more functionality. The sanitary unit contains a cooking top, an enclosed bathroom with shower toilet and water tanks for fresh, grey and waste water. The unit is also cladded with solar panels to be able operate self-sufficiently and provide electricity, water preparation or heating. The units could be configured to operate as a mobile office space, kiosk or sleeping pod. It could be place anywhere in the city, depending on the configuration 2 folding units attached to a sanitary unit can easily fit on a parking lot or narrow plots. It would be also ideal as a self-sufficient structure to be placed in remote area and function as a get-away retreat for adventurous users, who like to escape the city on weekend and explore nature as an alternative form of accommodation to conventional of hotel or hostel.

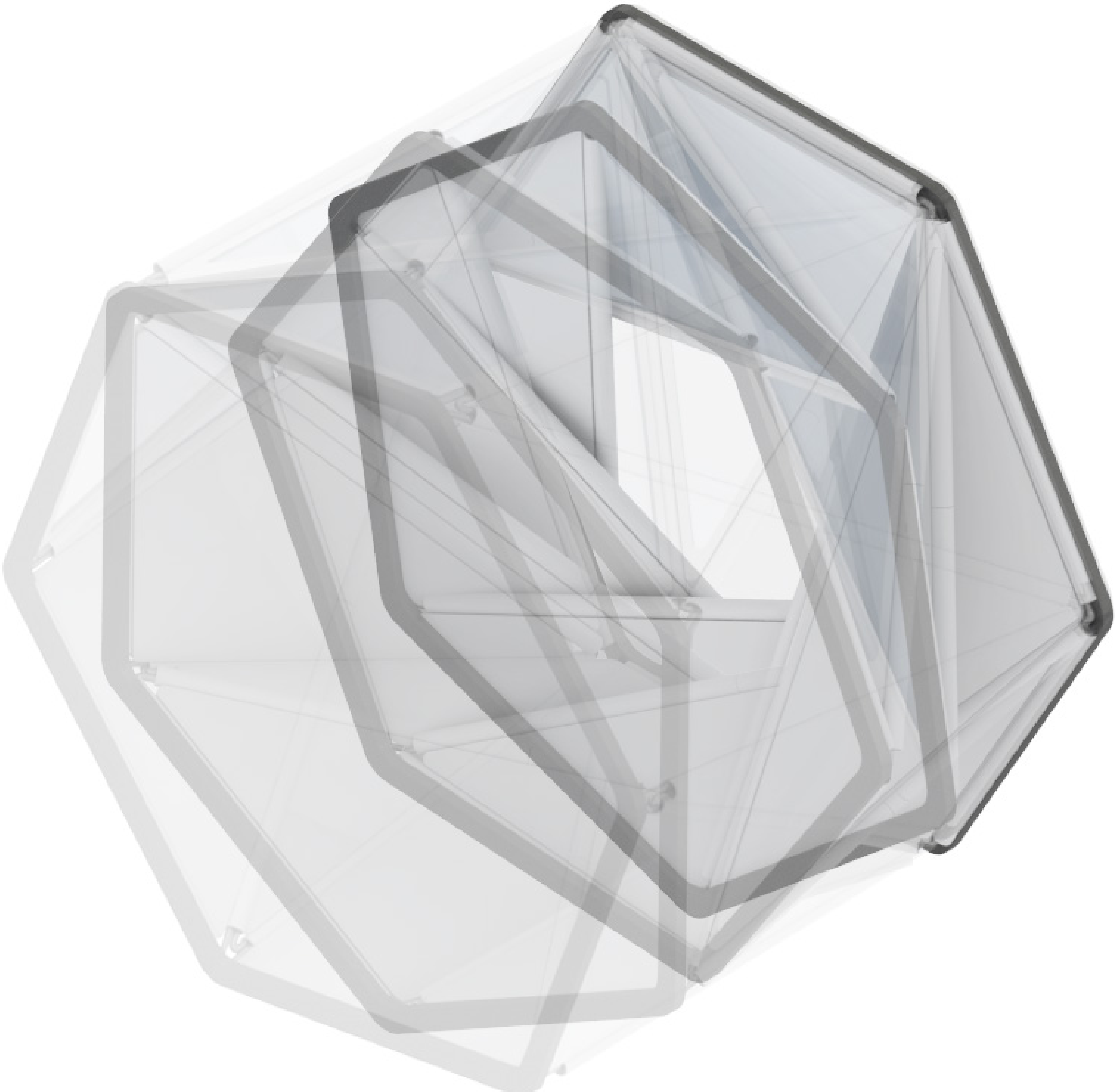


Fig. 5.2.01: Pod unit - folding process overlay

The Folding Pod units are intended as modular structures which can be connected to units with different functionality. It can function as temporary working or dwelling space as an alternative form of retreat accommodation. The functionality of the pods can be extended by automating the folding process. To make the experience user-friendly an app can be designed by which the pods can be booked online and unlocked at the destination via smart phone.

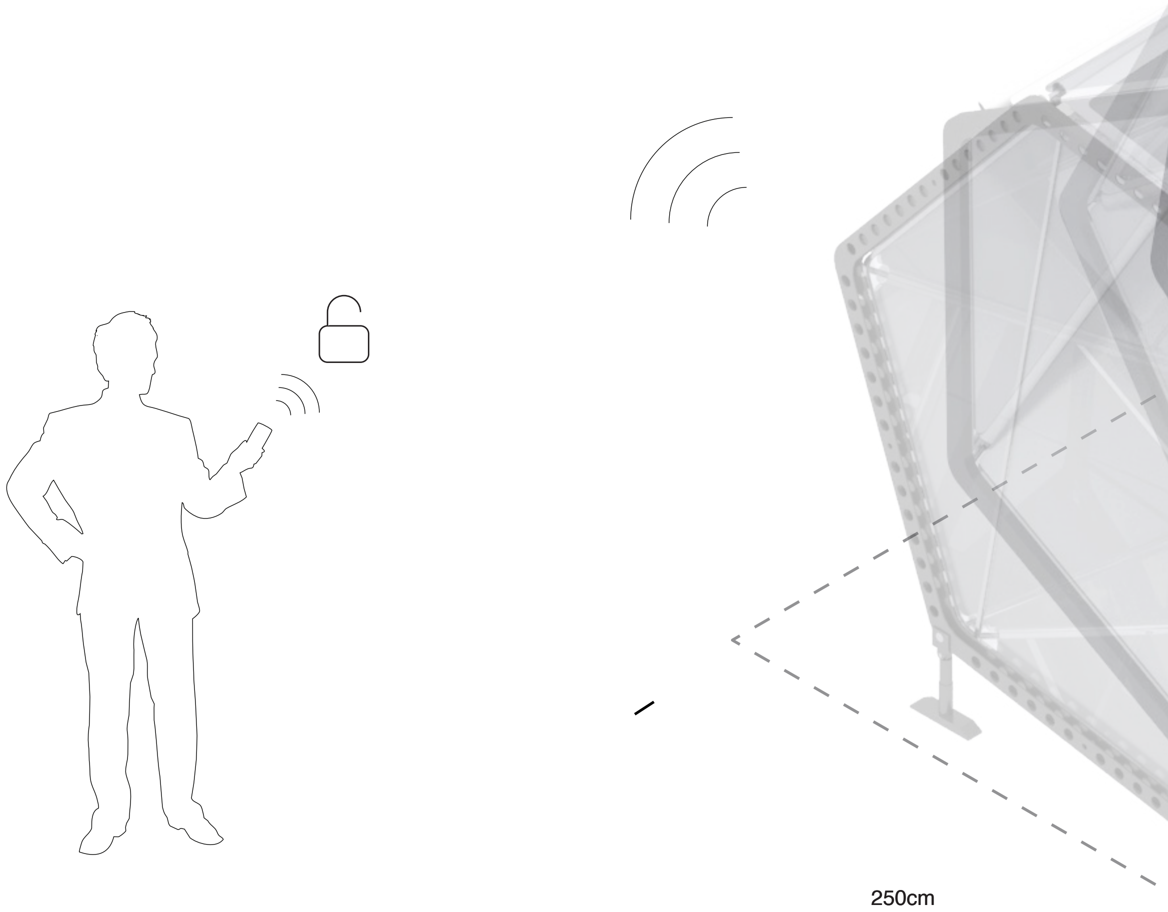
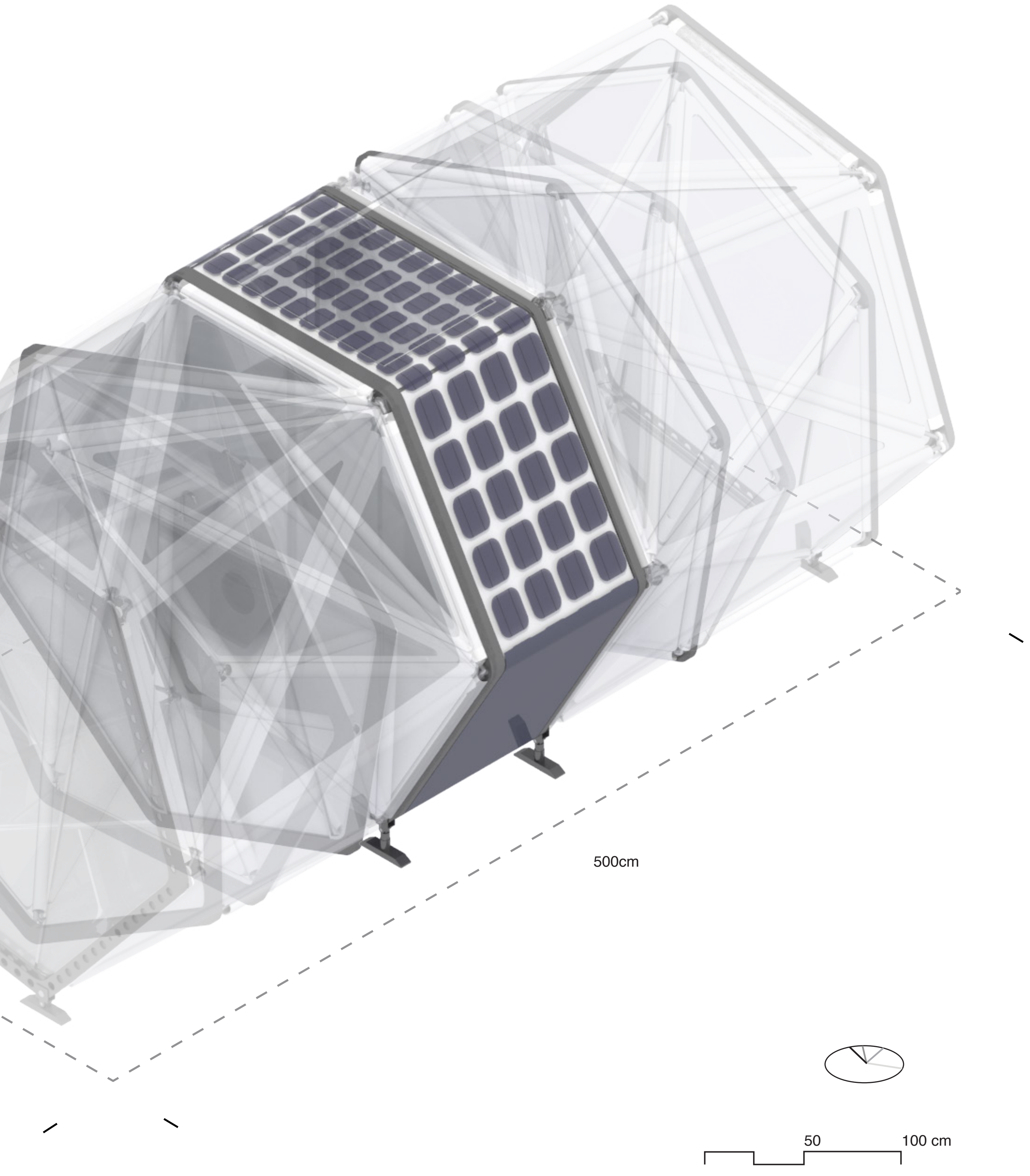


Fig. 5.2.02: Pod units configuration - deployment process overlay when unlocked by user via mobile app


500cm
50
100 cm

Folding structure scheme

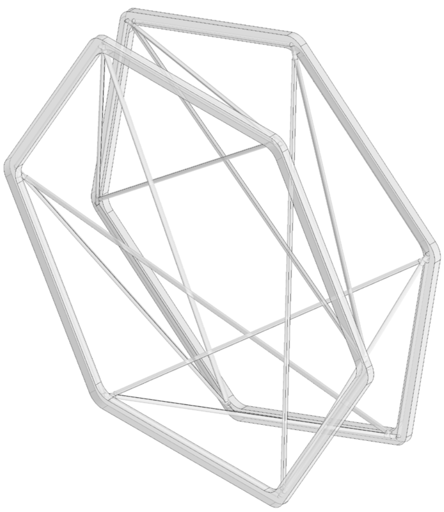
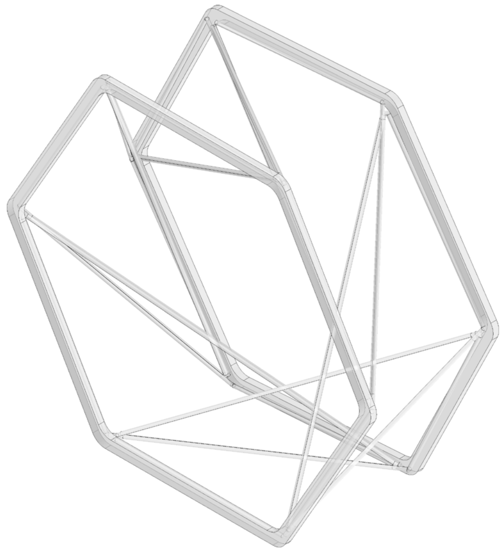


Fig. 5.2.03: a) folded structure aprox.5° angle



b) folding process 35° angle

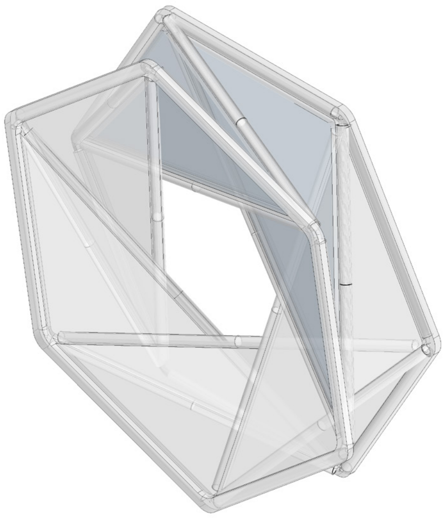
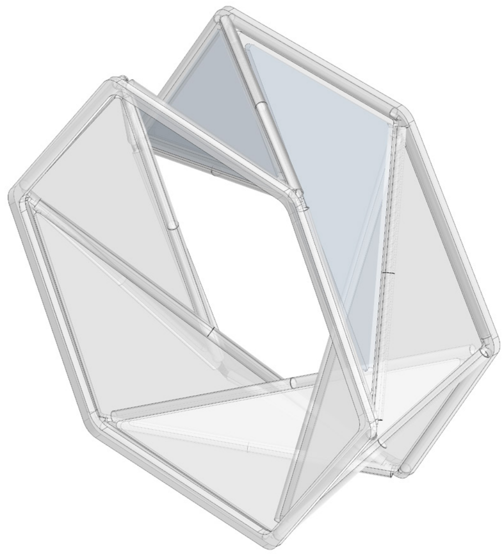
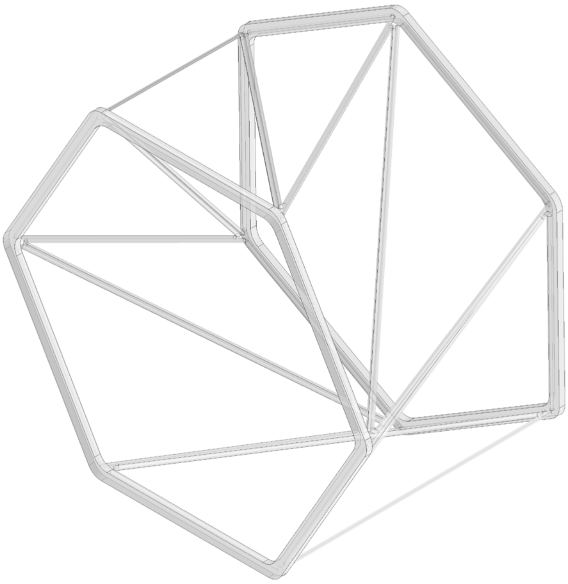


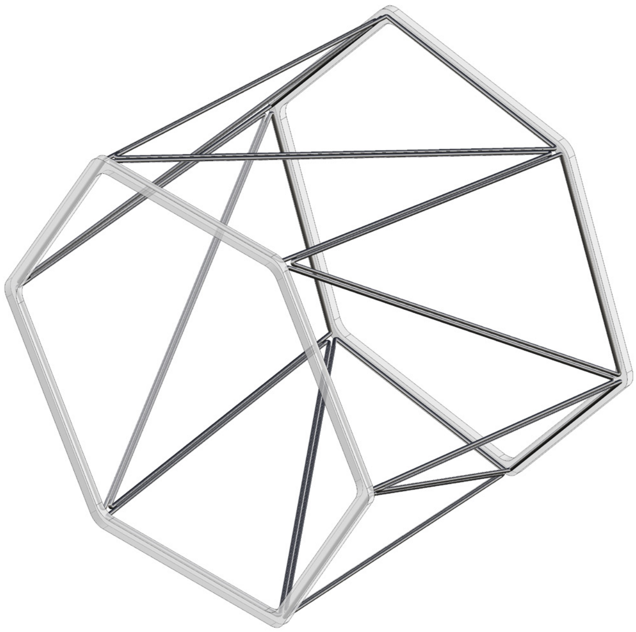
Fig. 5.2.04: a) folded pod unit aprox.5° angle



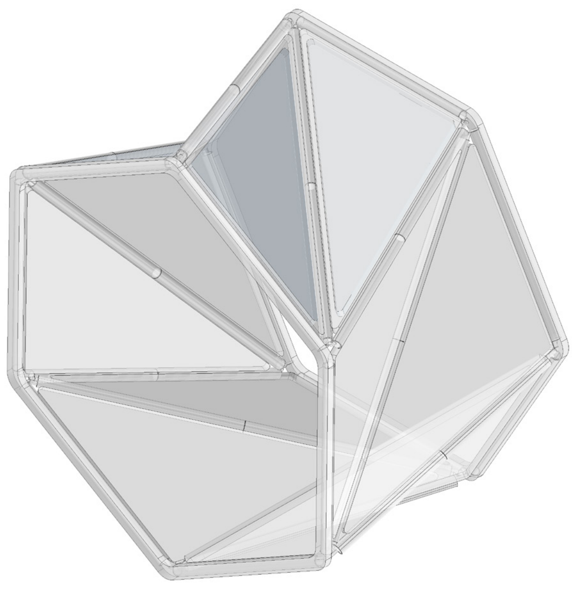
b) folding process 35° angle



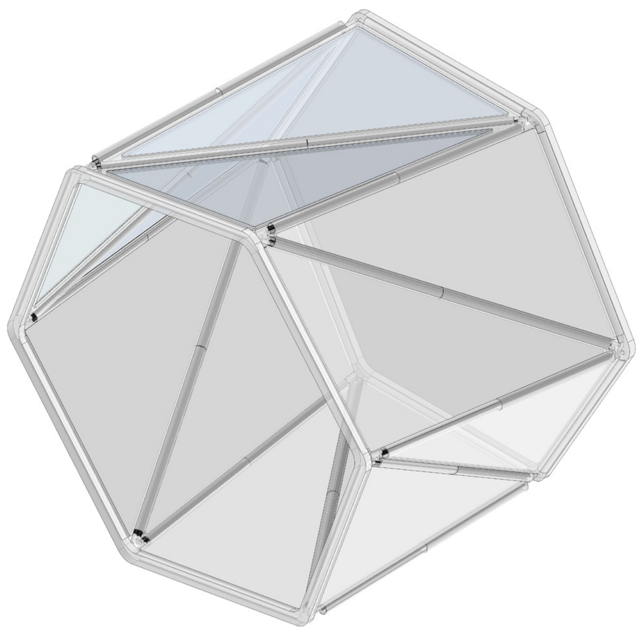
c) folding process 65° angle



d) deployed structure 85° angle



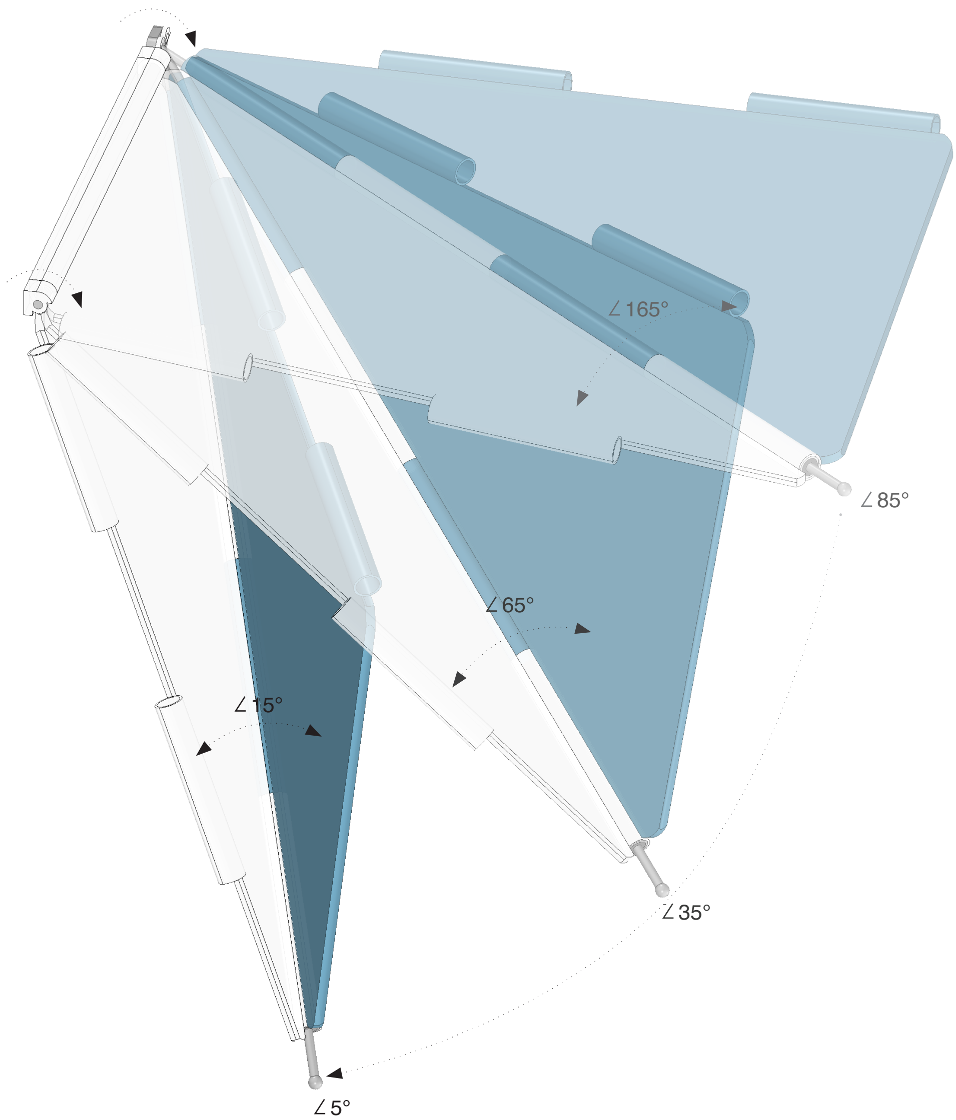
c) folding process 65° angle



d) deployed pod unit 85° angle

Fig. 5.2.05: Deployed pod unit with integrated foldable furnishing elements

Fig. 5.2.06: Folding panels - overlay



Folding unit structure

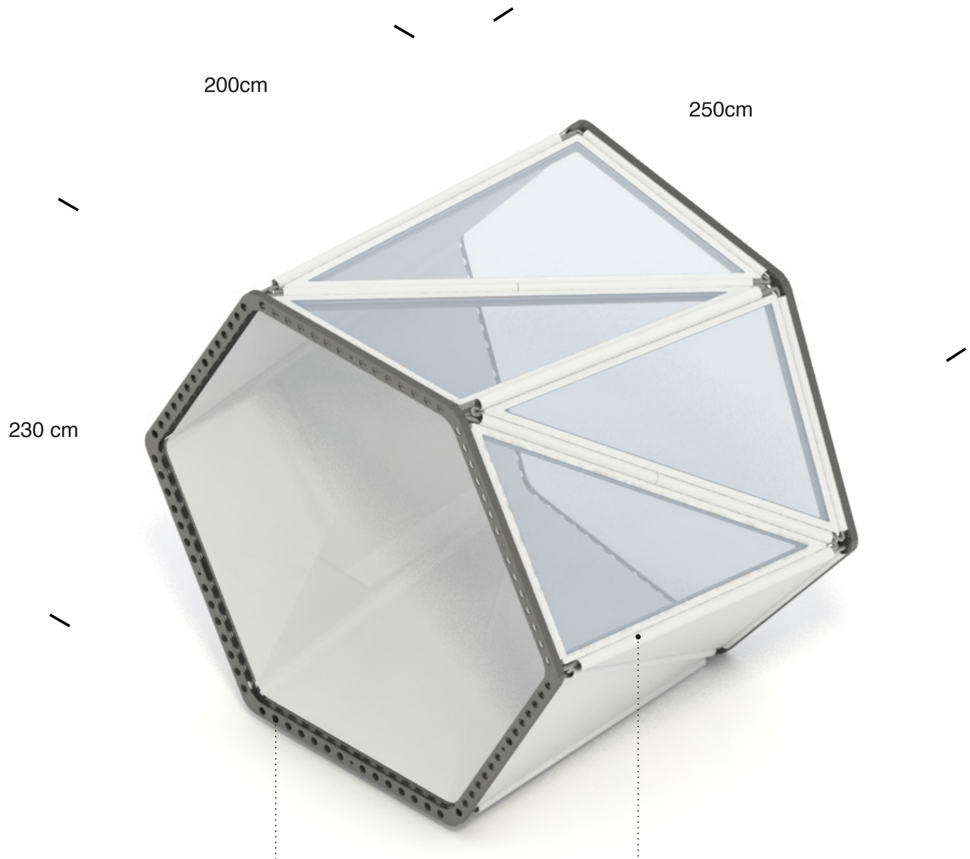


Fig. 5.2.07: Deployed pod unit
isometric view

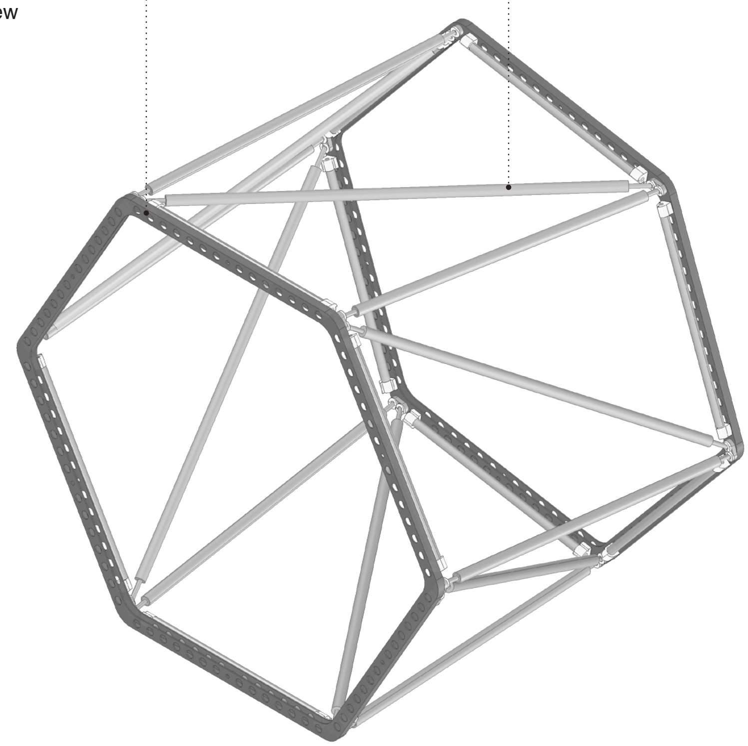
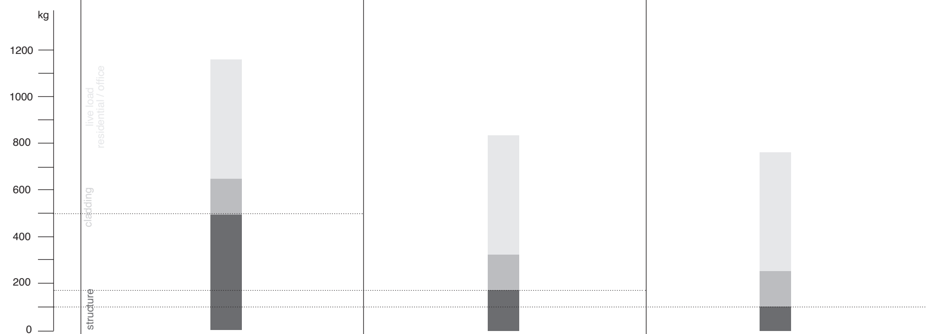


Fig. 5.2.08: Deployed pod structure
isometric view

50 100 cm

Tab 5.02.01: Pod module - structural materials comparison

Structure material	Steel S235	Aluminium 6061-T6 alloy	Carbon fibre (one-direction)
			
Density [kg/m³]	7850	2700	1700
E-Module [N/mm²]	210000	69000	240000
Yield strength [N/mm²]	235	270	700
Weight structure module [kg]	500	170	100
Module weight comparison [kg]			
Total weight [kg]	650	320	250

The unit can be fabricated from different materials depending on the requirements. However taking into consideration that the units should be easily moved around a lightweight high-performance material would be best suited for the structure. Carbon fibre composite profiles for the load bearing profiles would be optimal material as it is 5x lighter than steel and 2x as structural aluminium providing a higher performance.

Structure assembly - joining 2 frames

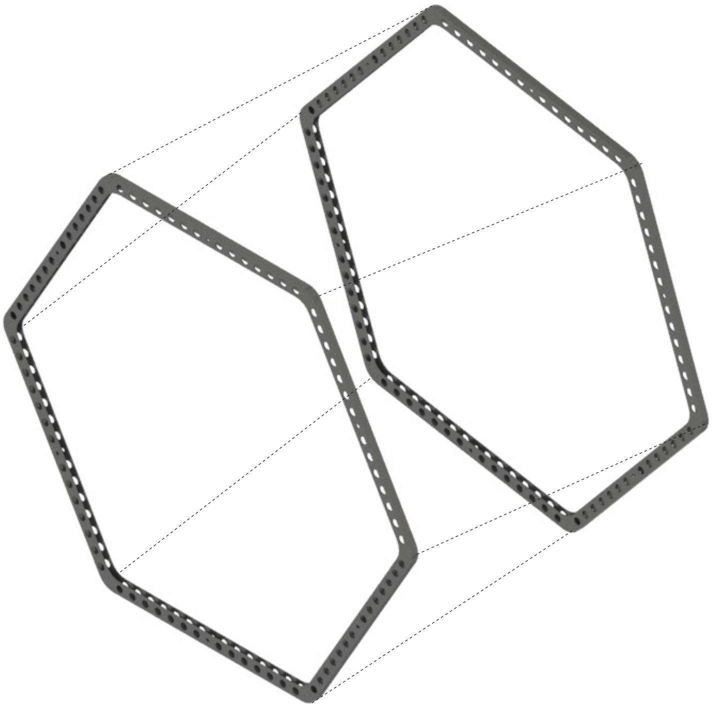


Fig. 5.2.09: Hexagonal structural aluminium / carbon fibre composite frames

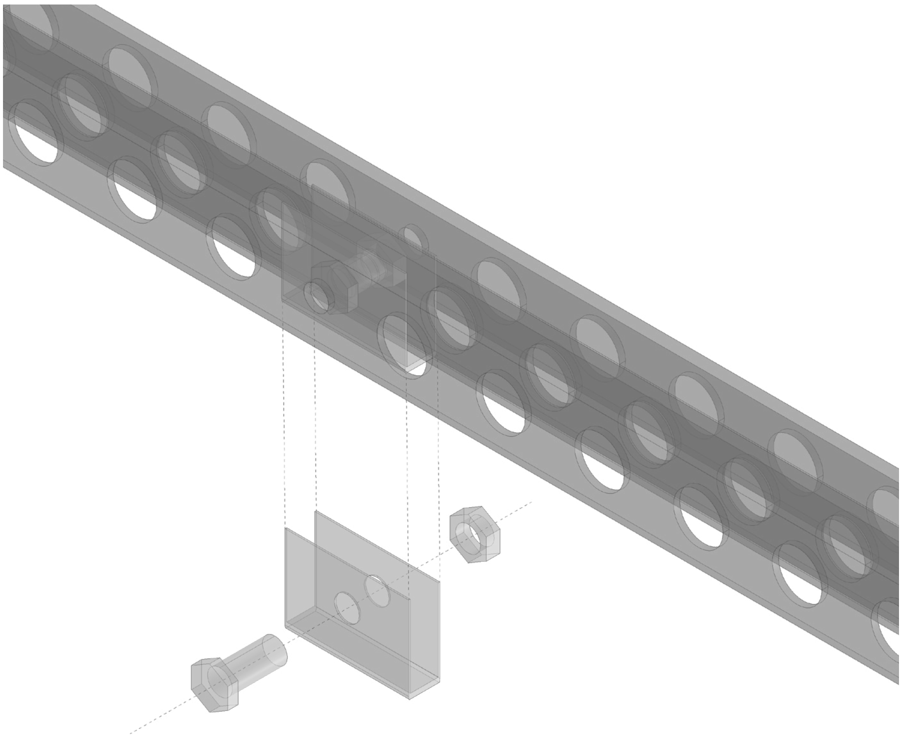


Fig. 5.2.10: Connecting frames - bolt and nut fixture

The individual folding units can be interconnected by bolt-and-nut fixings and a C-shape profile to hold in place the frames. In this way the structure can be extended with additional units.

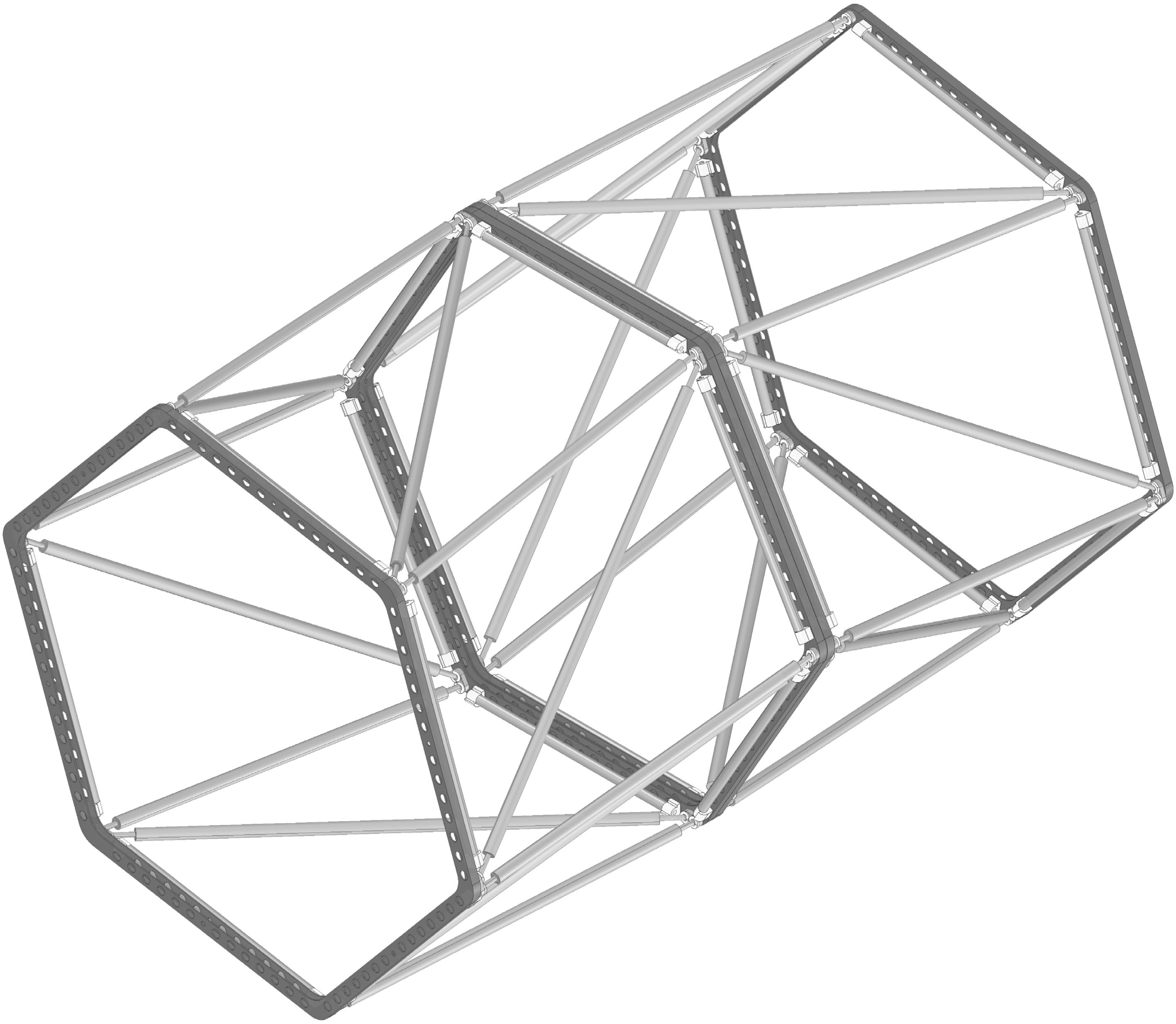
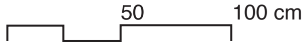


Fig. 5.2.11: Connecting structure units with bolt and nut fixing



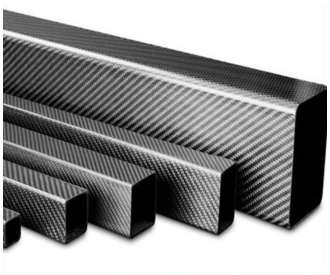


Fig. 5.2.12: Carbon fibre rectangle pipes

01, 05 The optimal material for the supporting frame and pipe structure is carbon fibre tubes with a rectangular and cylinder profiles.

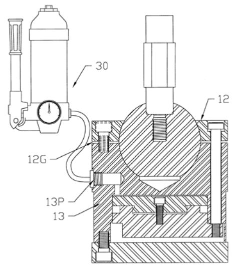


Fig. 5.2.13: Spherical joint with hydraulic lock

02 For the spherical joints there are different systems available which ensure the locking in place once the system is deployed and movement is constricted in all directions while the structure is in use.

Fig. 5.2.14: Spherical joint with grip lock

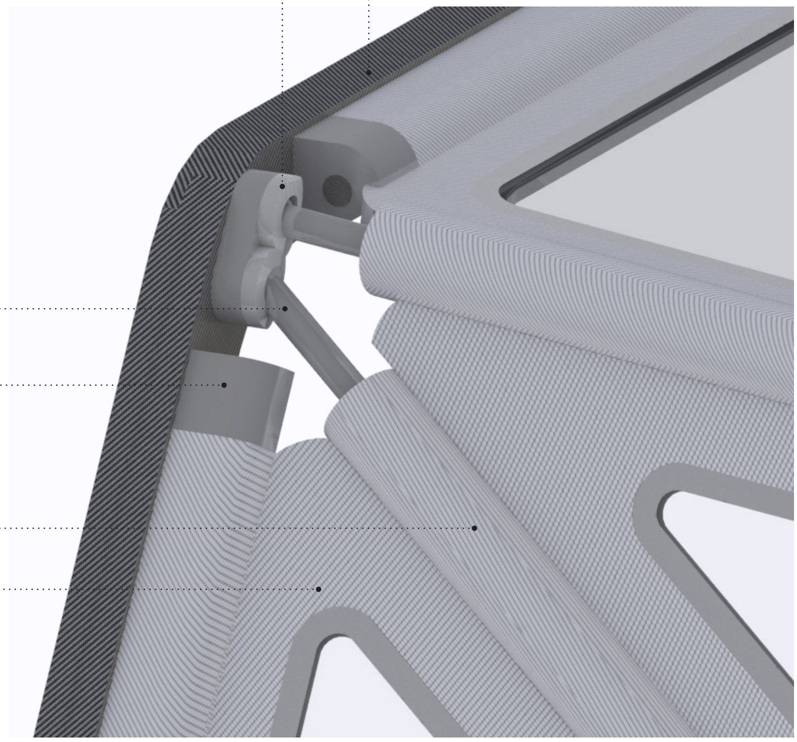
Fig. 5.2.15: Carbon fibre pipes with steel spherical joint

03 Due to the fact that carbon fibre parts cannot be welded together the joining elements are made of steel or aluminium and act as linking elements between structural elements.

Fig. 5.2.16: Electro-motor

04 In order to actuate the movement of the triangular plates an electro-motor is needed which rotates the panels attached to the frame structure and generates the movement of its constituent parts.

Fig. 5.2.17: Detail of folding mechanism and materials



Legend

01	Carbon fibre composite frame 70/40 mm
02	Spherical joint with grip lock
03	Pipe with ball joint ø 40 mm carbon fibre
04	Rotary electro-motor 85° angle
05	Hinging pipe ø 50 mm carbon fibre
06	Structural carbon fibre panel with aluminium honey comb core 20-40 mm

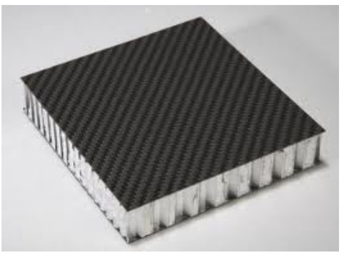


Fig. 5.2.18: Carbon fibre-aluminium panels with honey comb structural core

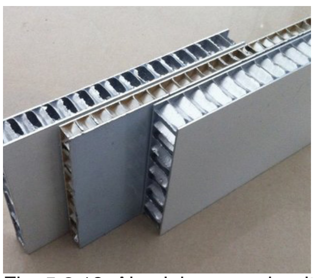


Fig. 5.2.19: Aluminium panels with honey comb structural core panel

06 The triangular cladding elements can be fabricated using carbon fibre composite material with an aluminium core consisting of a honey comb structure for the floor parts of the unit and for the lateral cladding panels with a foam core for insulation can be used.

Structural insulated aluminium frame with polycarbonate panel

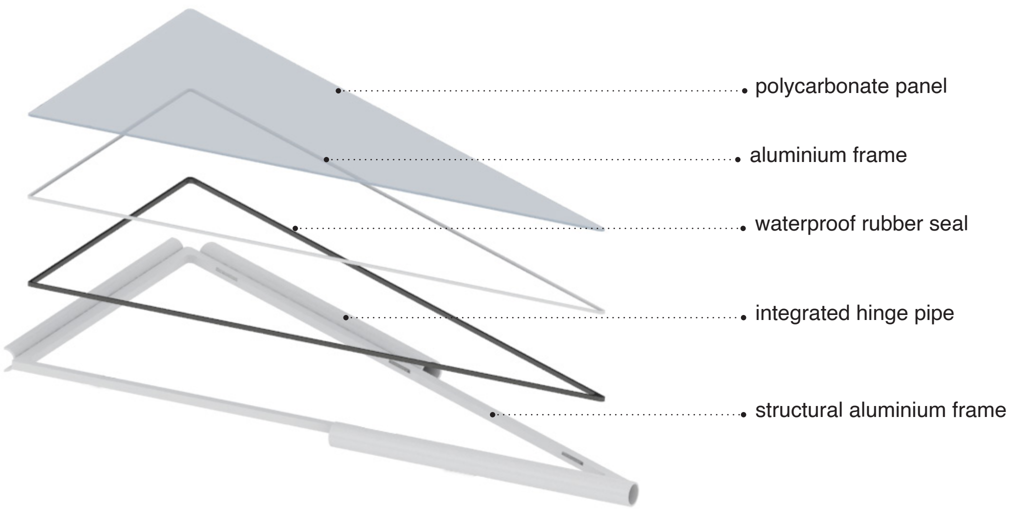


Fig. 5.2.20: Triangular folding panel - explosion drawing

Fig. 5.2.21: triangular folding panel

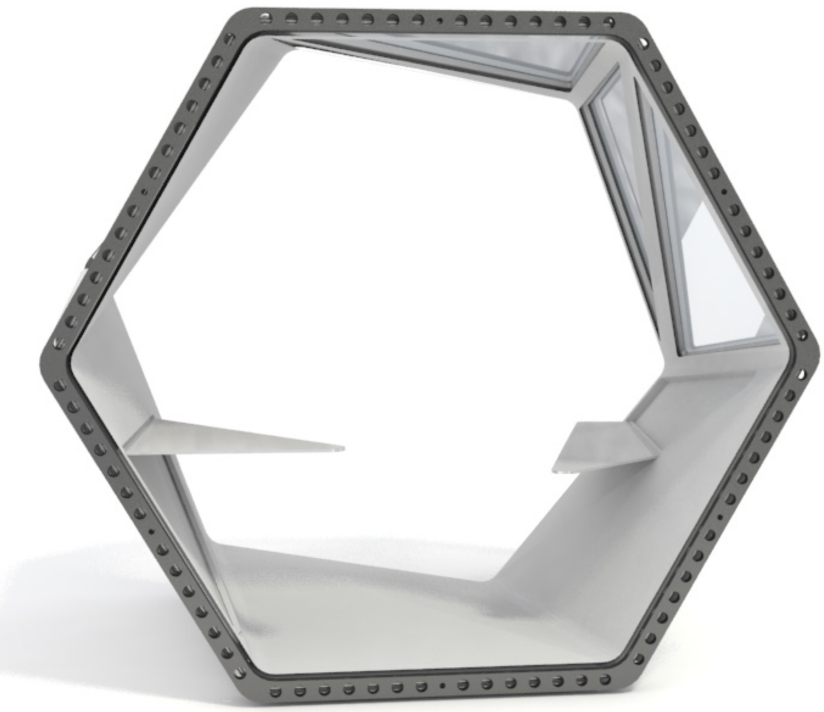


Fig. 5.2.22: Pod unit - convertible table tops

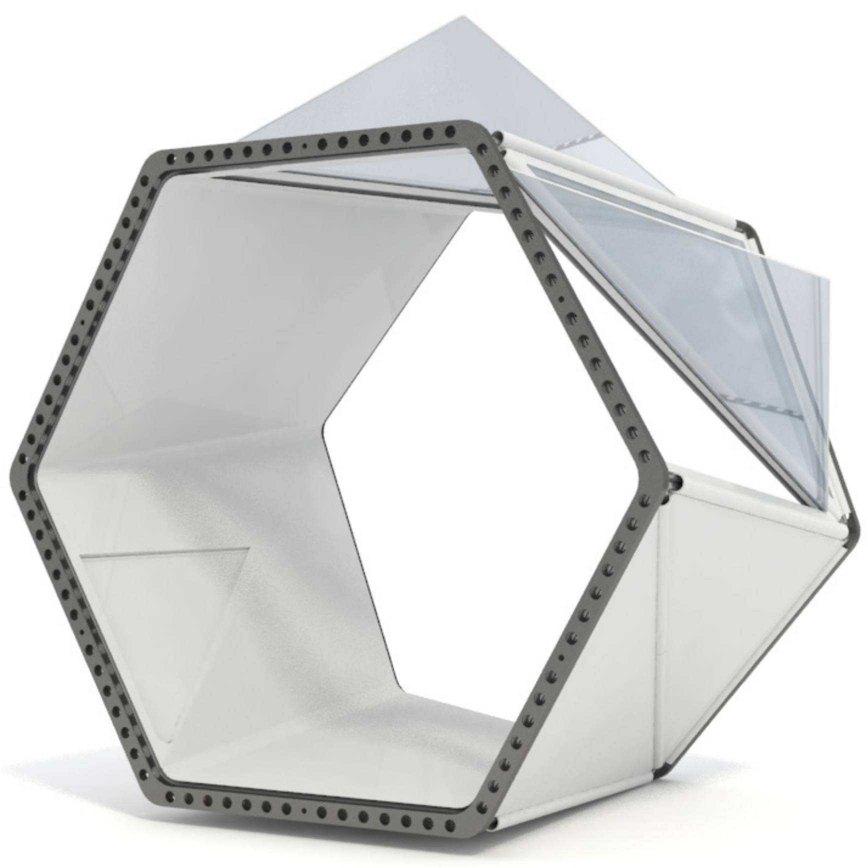
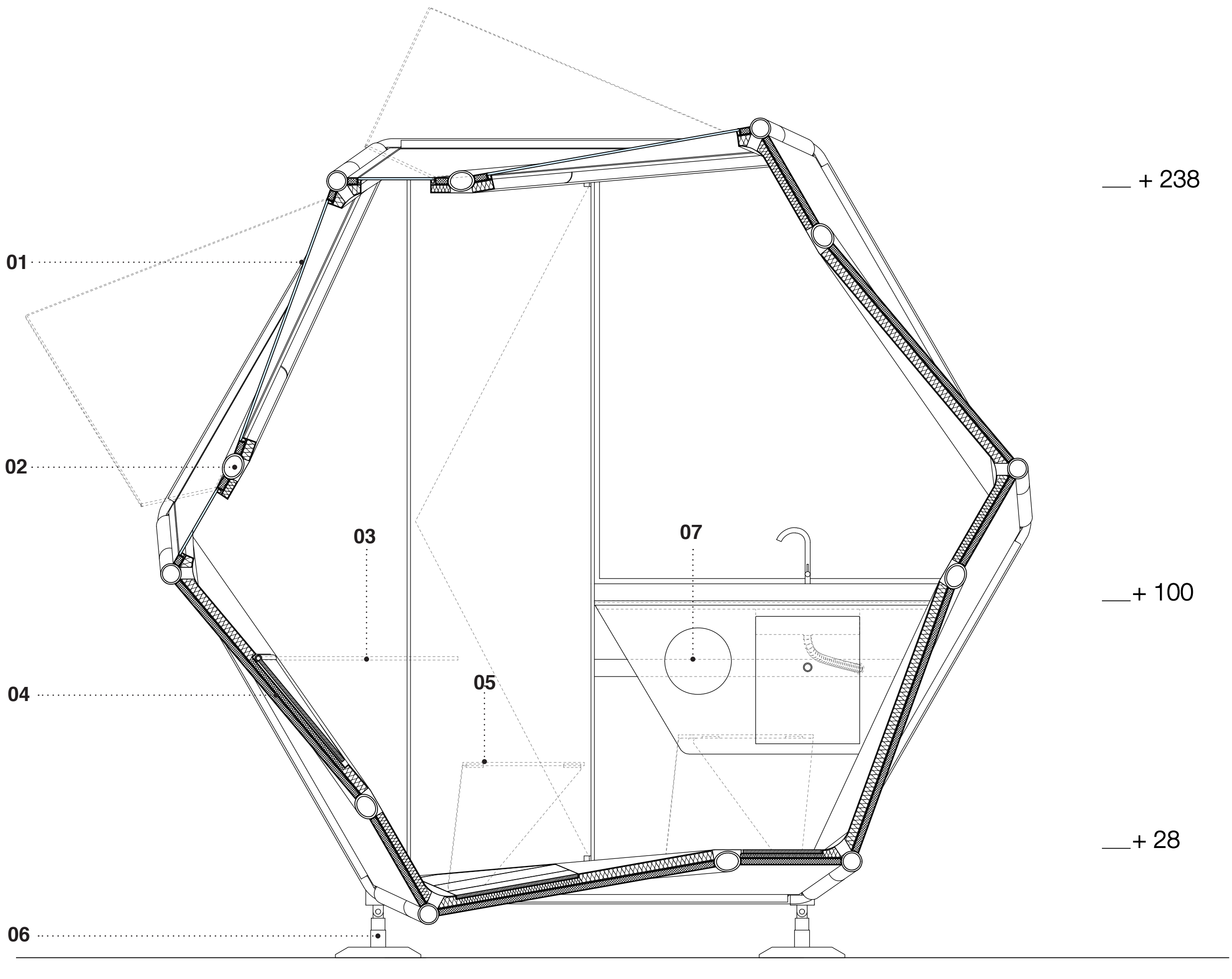


Fig. 5.2.23: Pod unit - openable windowpanes

Fig. 5.2.24: Cross-section - folding unit

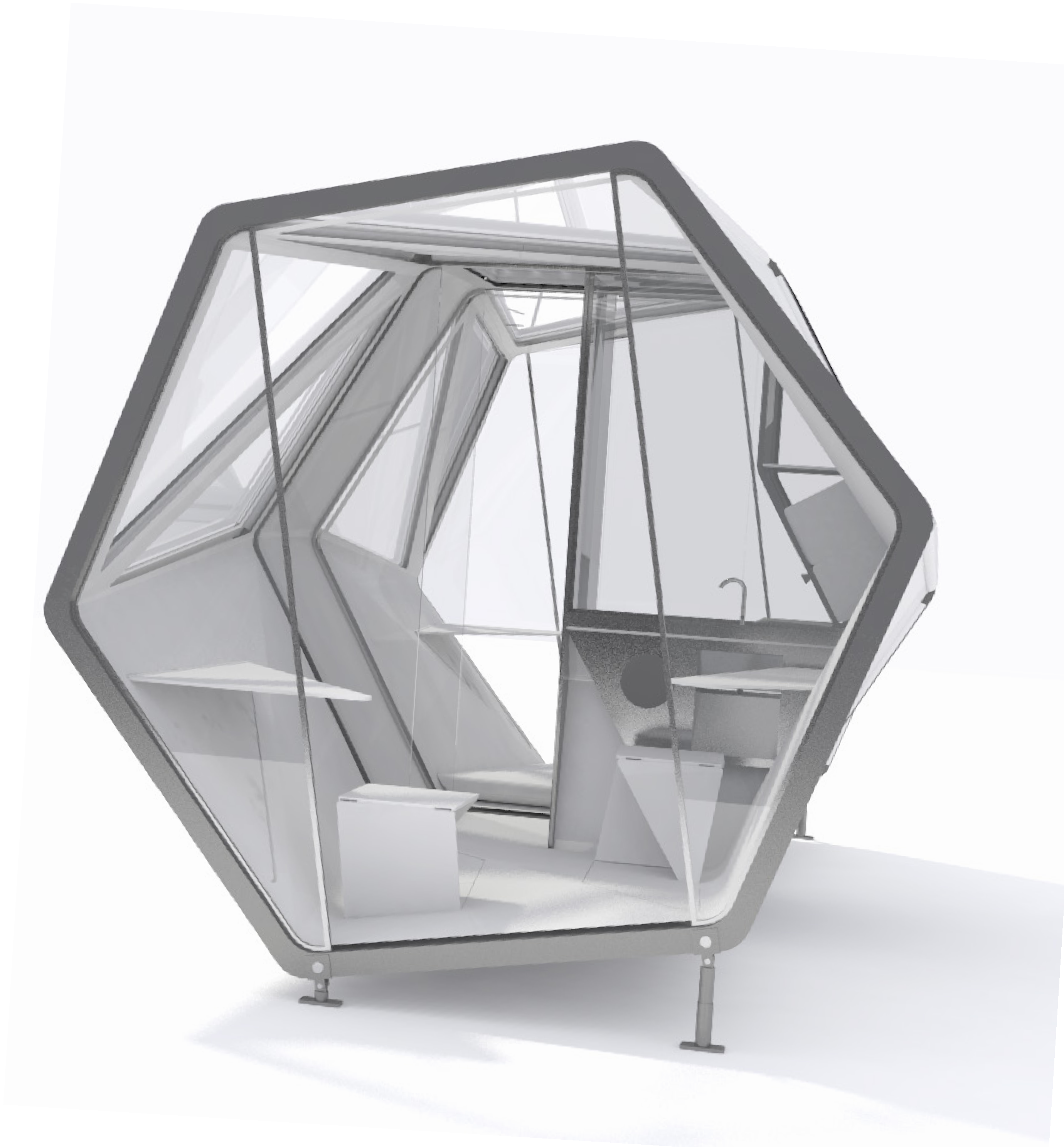


Legend

01	Alu-frame with polycarbonate panel
02	Pipe hinge carbon fibre composite 50mm
03	Folding table
04	Structural insulated aluminium panel
05	Folding chair
06	Adjustable pedestals
07	Cooking top

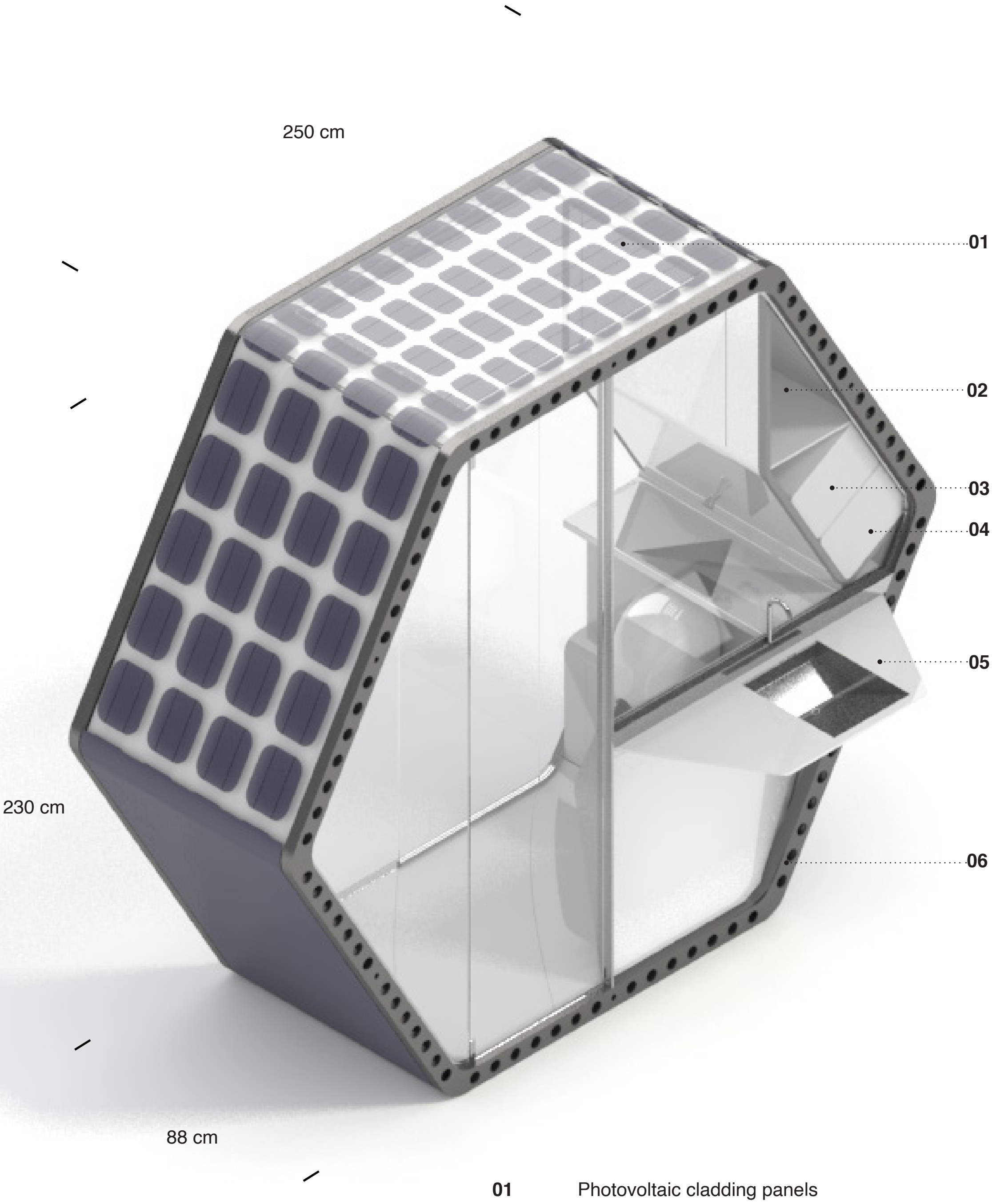
50 100 cm

Fig. 5.2.25: Visualization - configuration of folding & saniary units



Compact sanitary unit and cooking top

Fig. 5.2.26: Sanitary unit with folding cooking / sink top



01	Photovoltaic cladding panels
02	Storage
03	Fresh water tank
04	Solar-powered warm water mini boiler/ Solar power storage battery
05	Folding cooking top
06	Structural aluminium/carbon fibre frames
07	Sink
08	Grey water tank
09	Waste water tank
10	Toilet - swinging upwards (lota - design concept)
11	Slanted floor with drainage

Fig. 5.2.27: Sanitary unit - shower / toilet

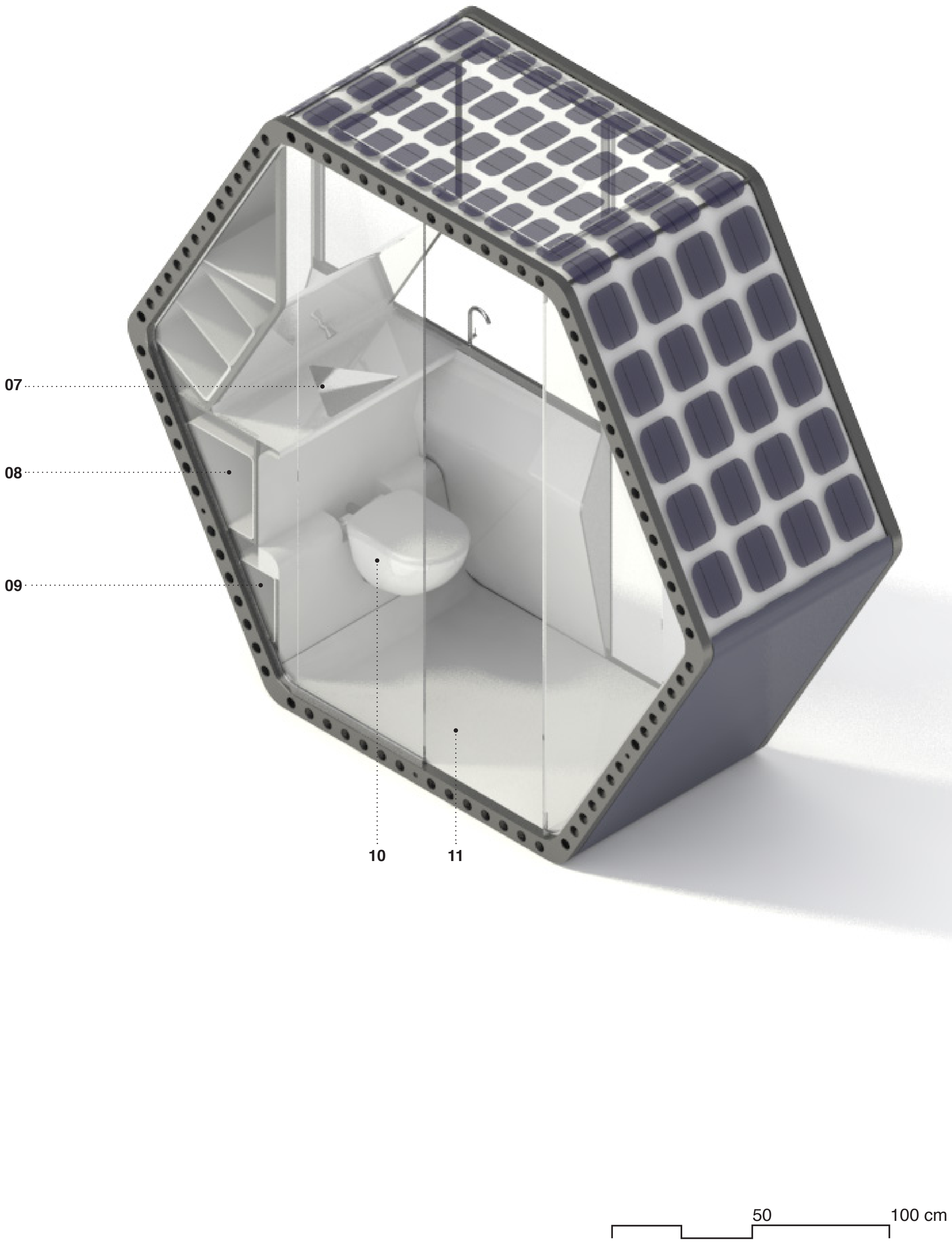


Fig. 5.2.28: Sanitary unit - with openable roof window

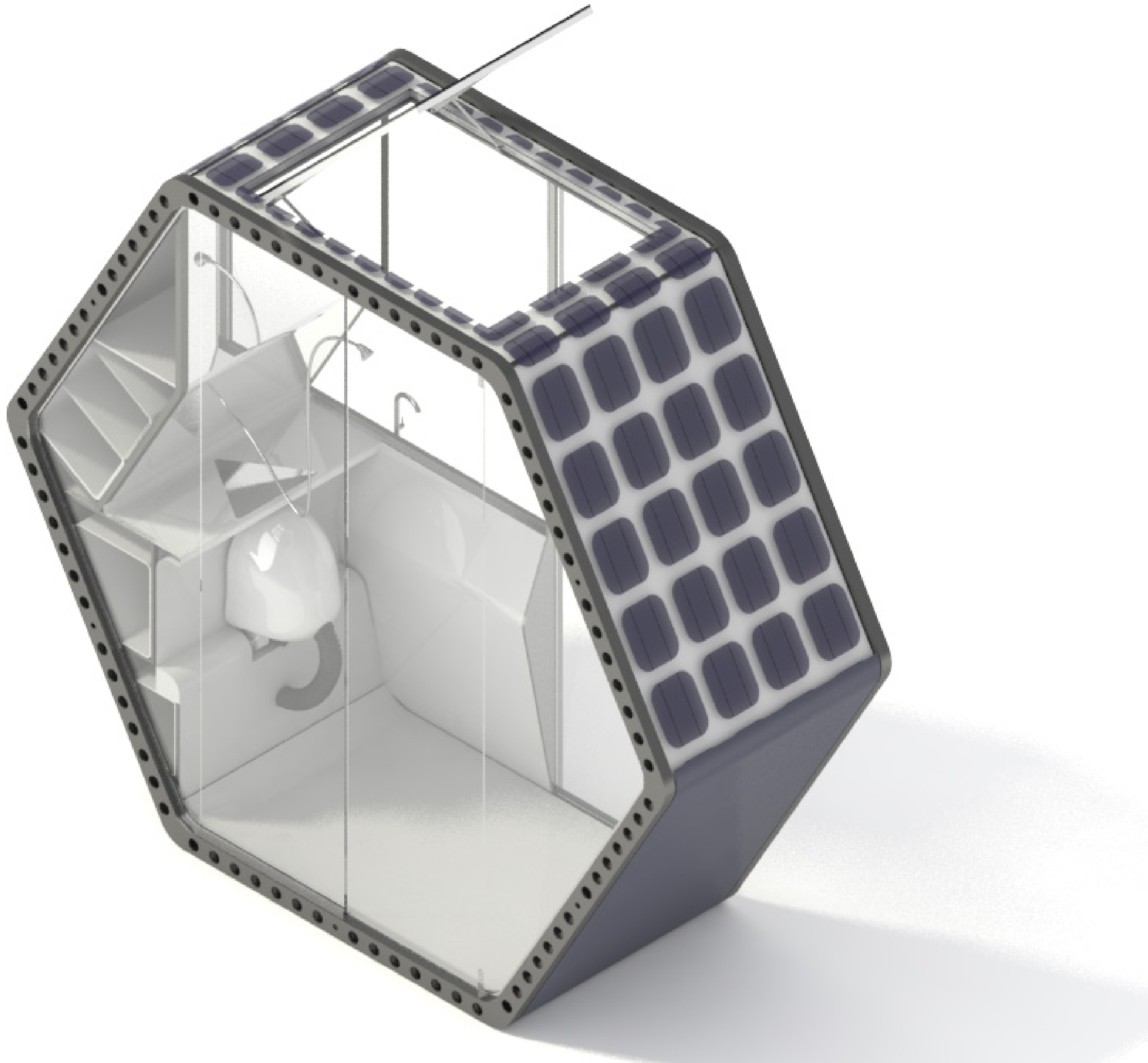
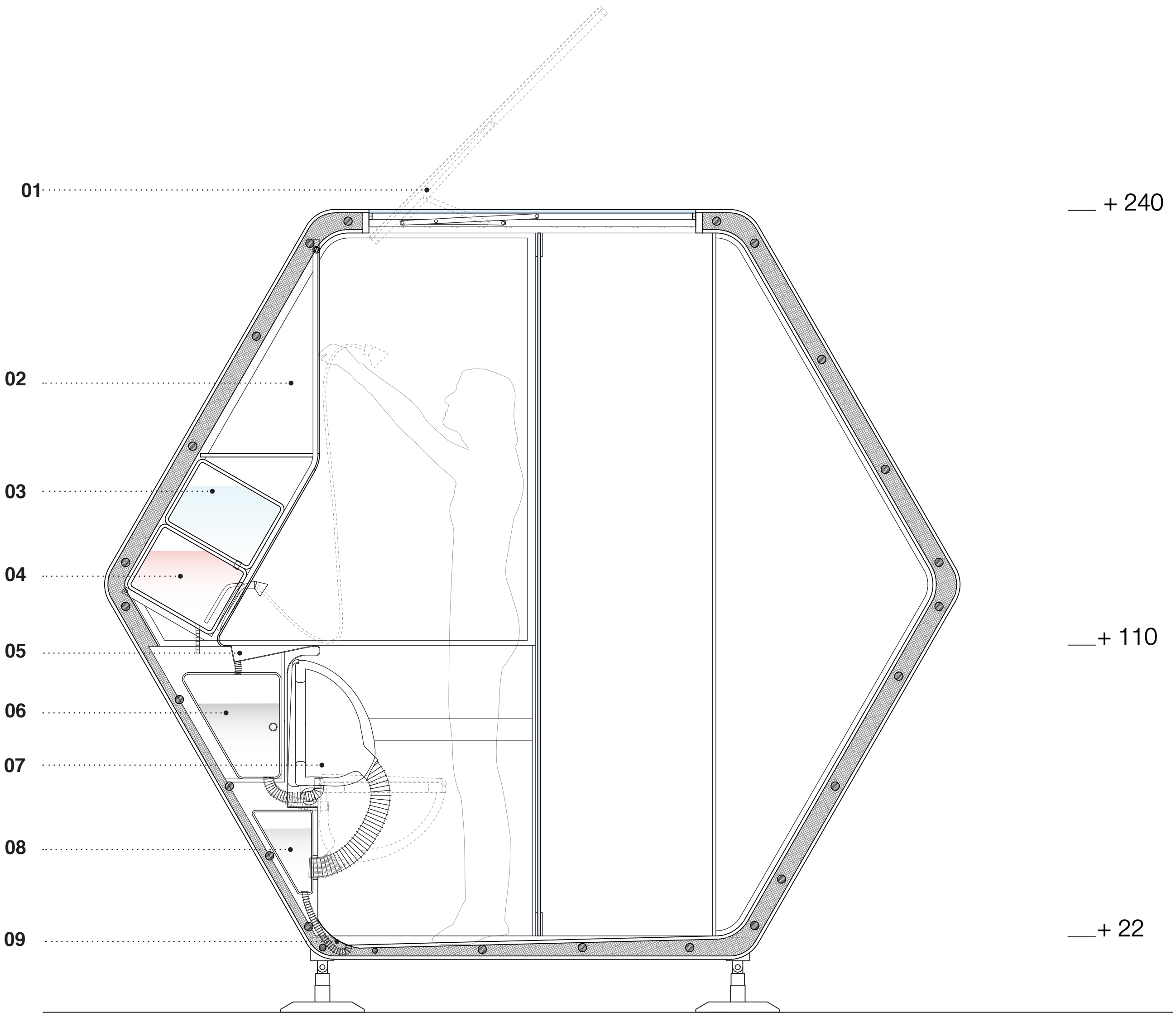


Fig. 5.2.29: Cross section - sanitary unit



Legend

01 Openable roof window with photovoltaic cells
02 Storage
03 Fresh water tank 60 litre
04 Solar-powered warm water mini boiler/ Solar power storage battery
05 Integrated Sink
06 Grey water tank 60 litre
07 Toilet - swinging upwards (Iota - design concept)
08 Waste water tank 40 litre
09 Drainage with mini-pump

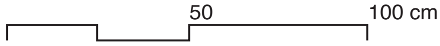
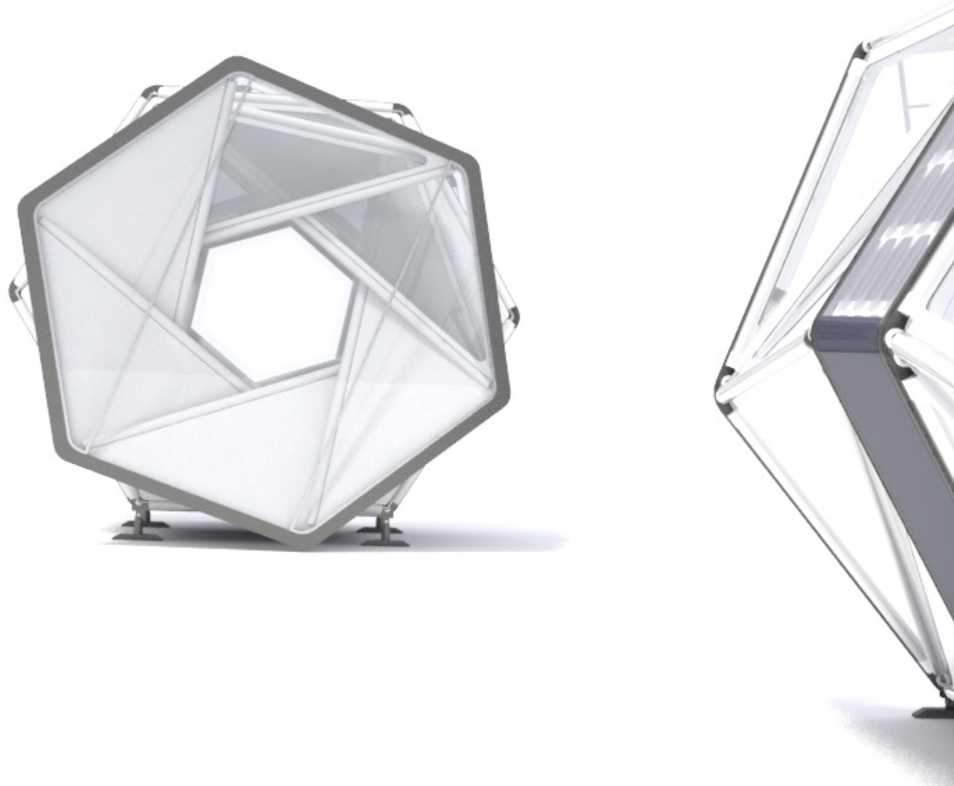


Fig. 5.2.30: Pod units in deployed and folded state



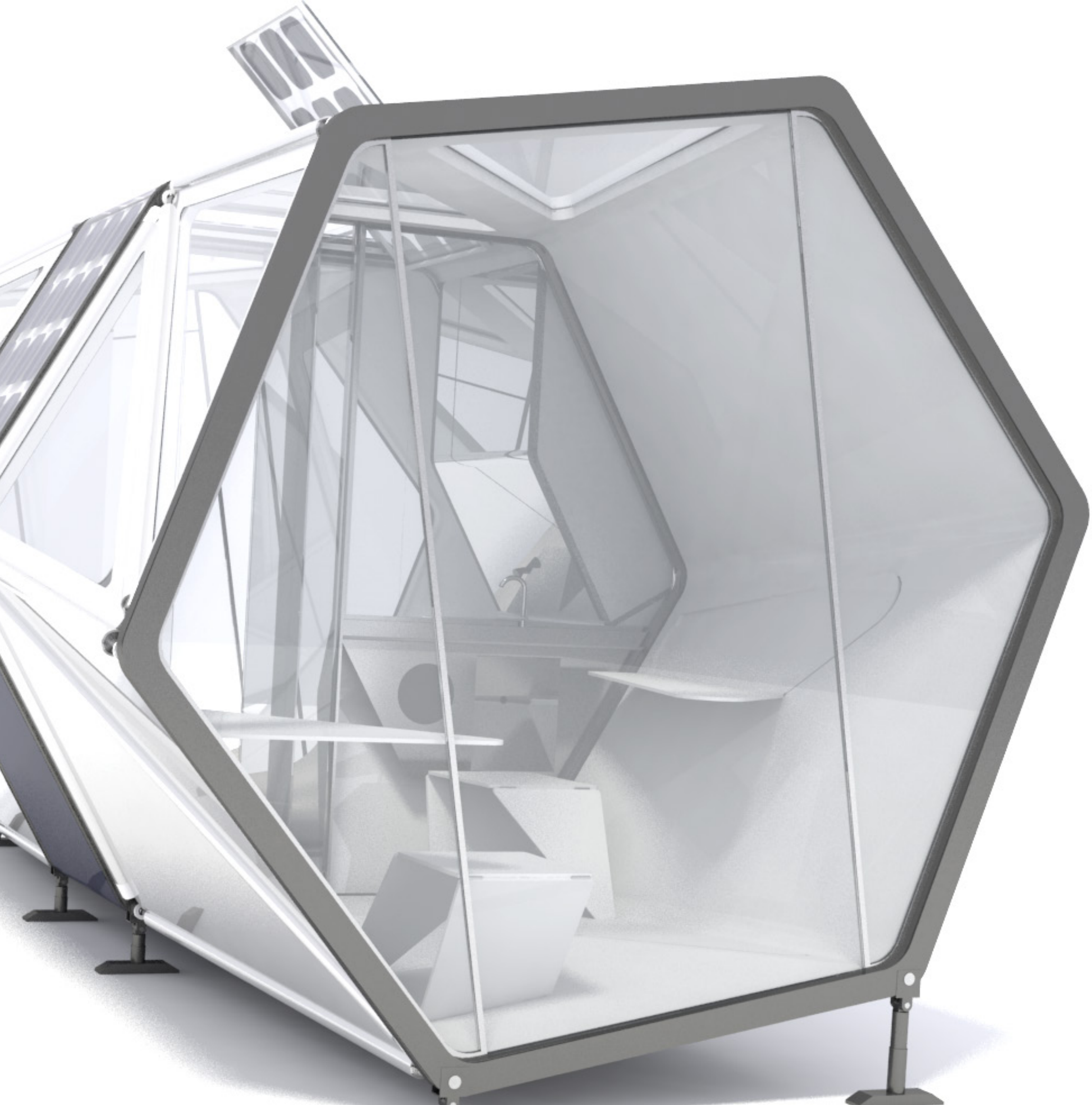


Fig. 5.2.31: a) Floor plan - folding units attached to sanitary unit - deployed state

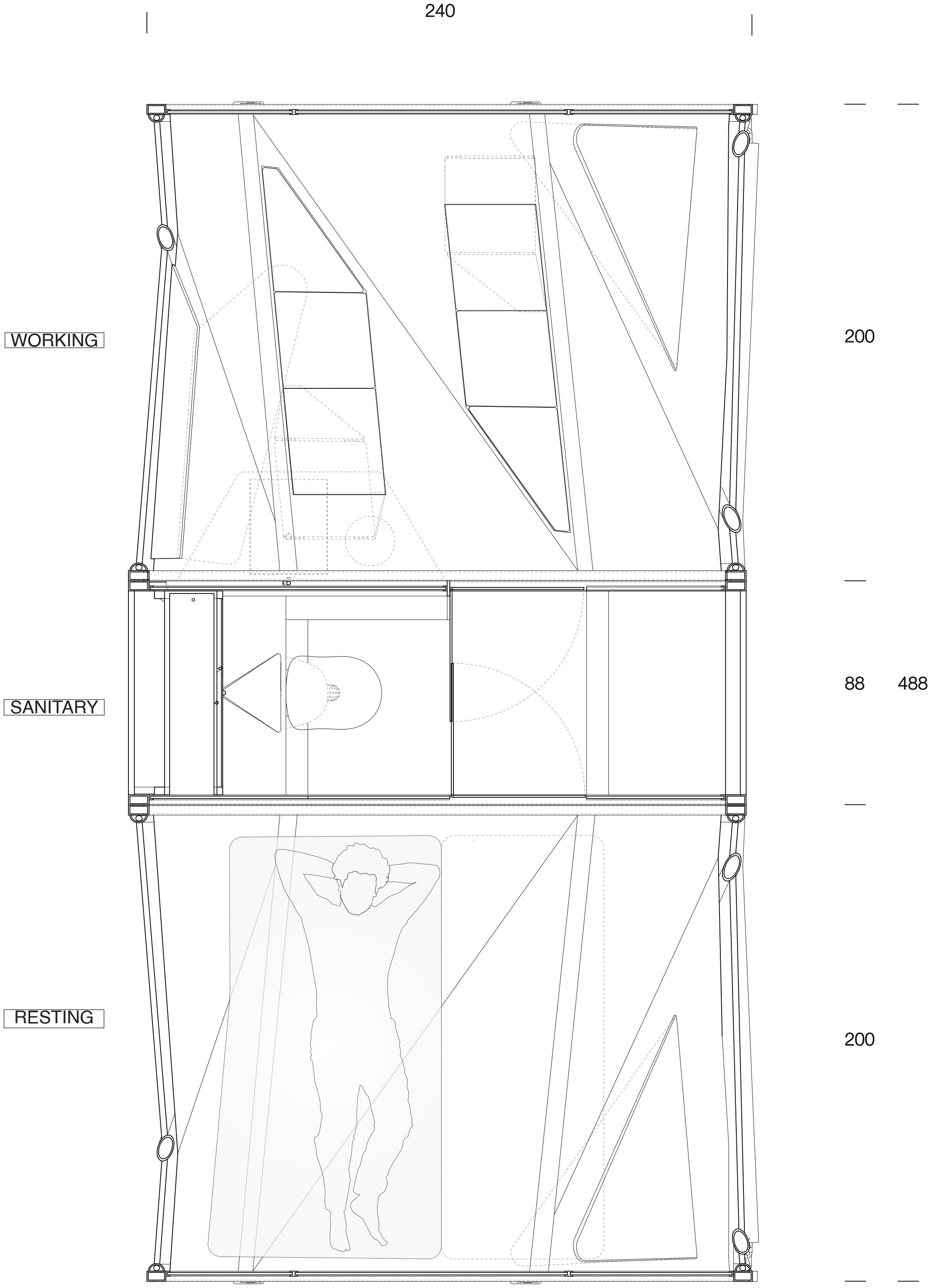


Fig. 5.2.31: b) Floor plan - folding units attached to sanitary unit - collapsed state

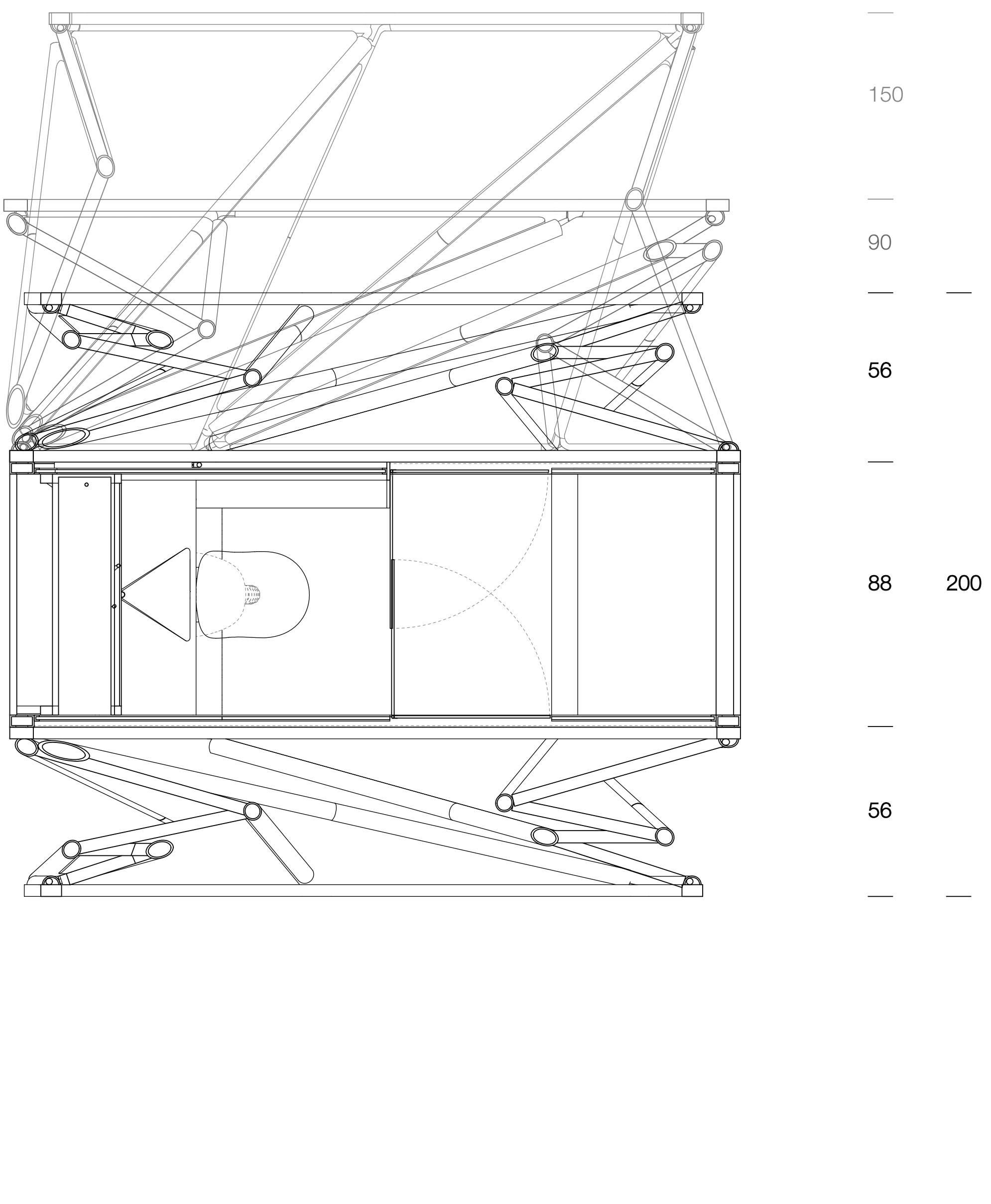


Fig. 5.2.32: a) Side elevation - deployed units

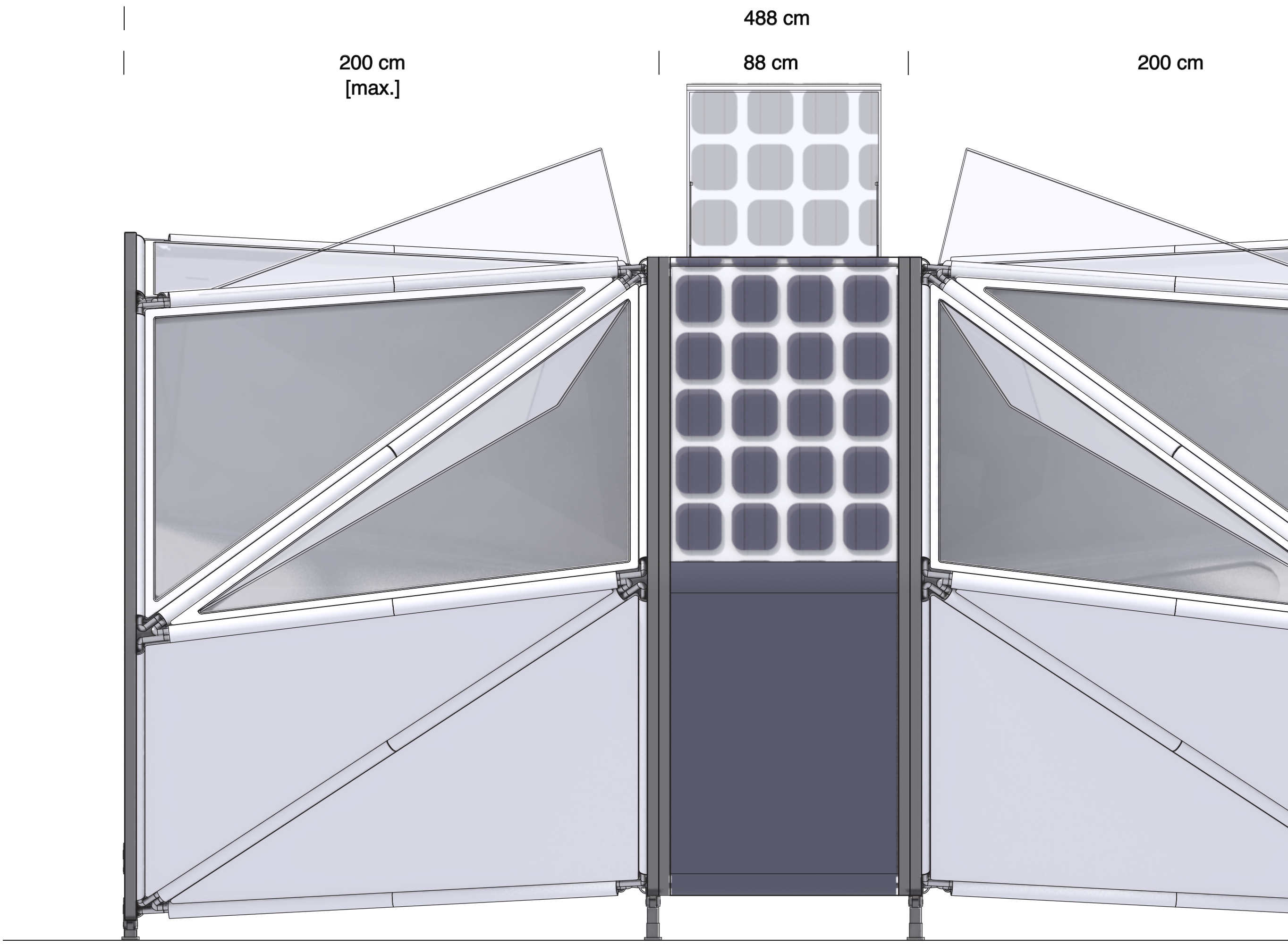
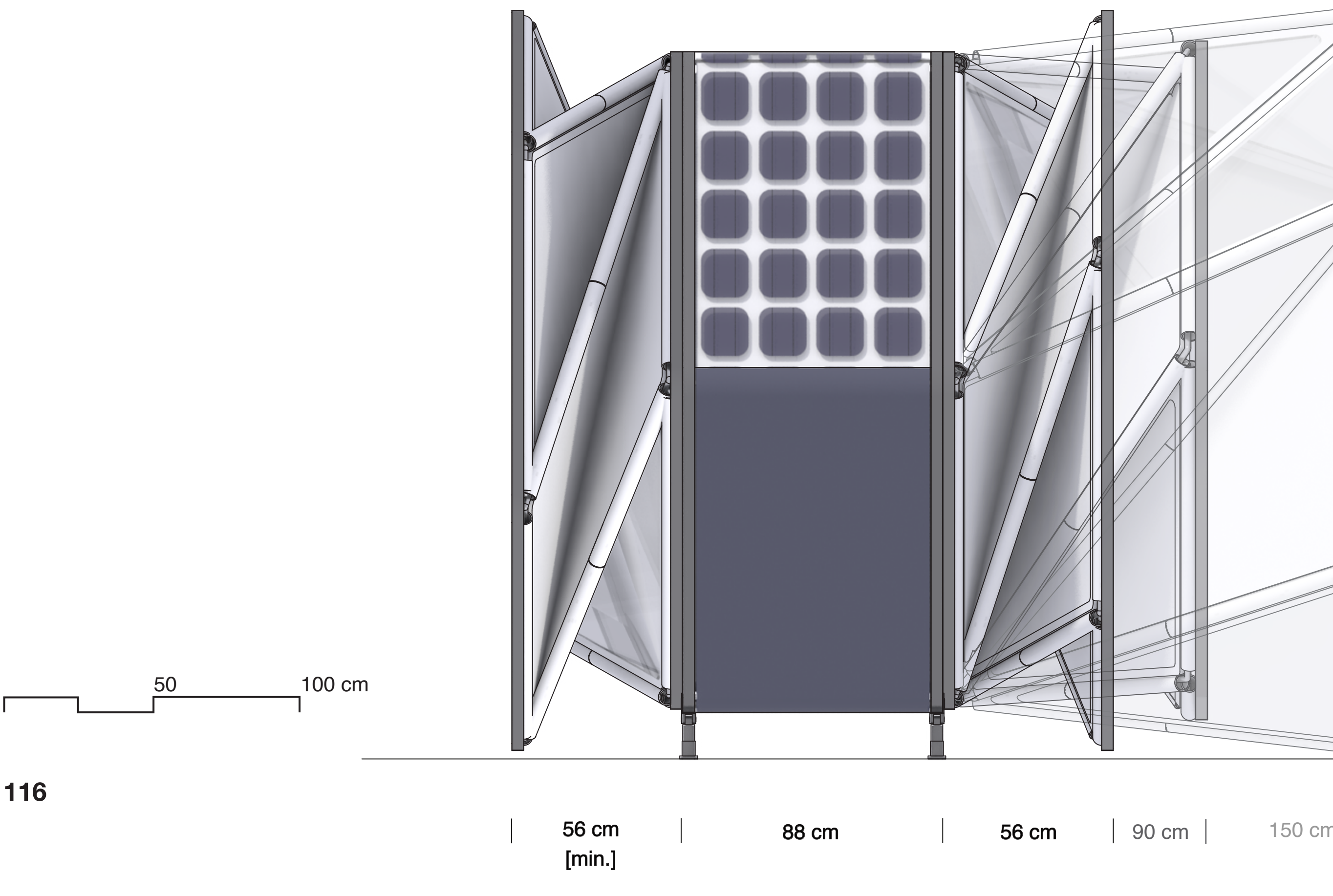
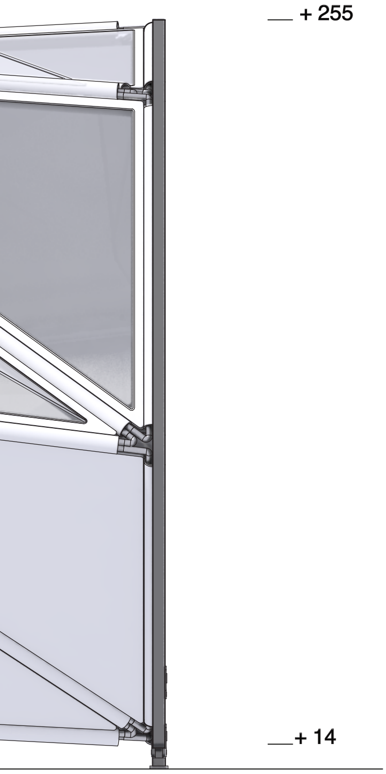


Fig. 5.2.32: b) Side elevation - folding units





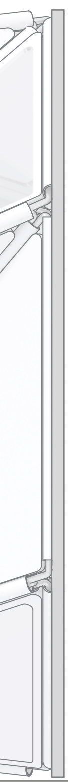


Fig. 5.2.32: c) Side elevation - collapsed state

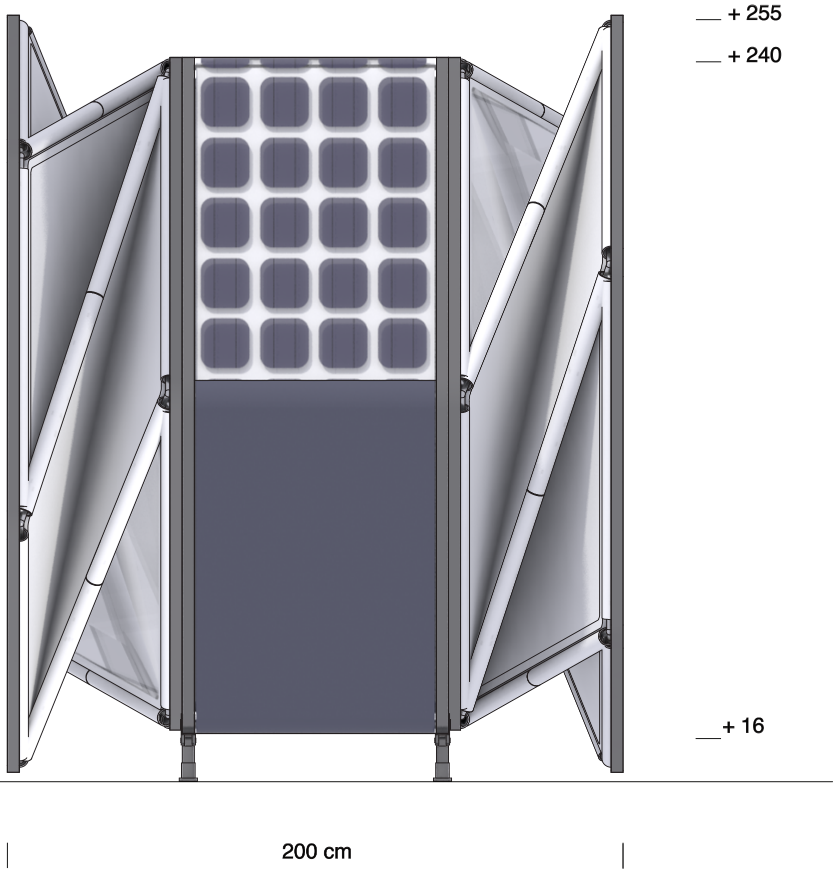
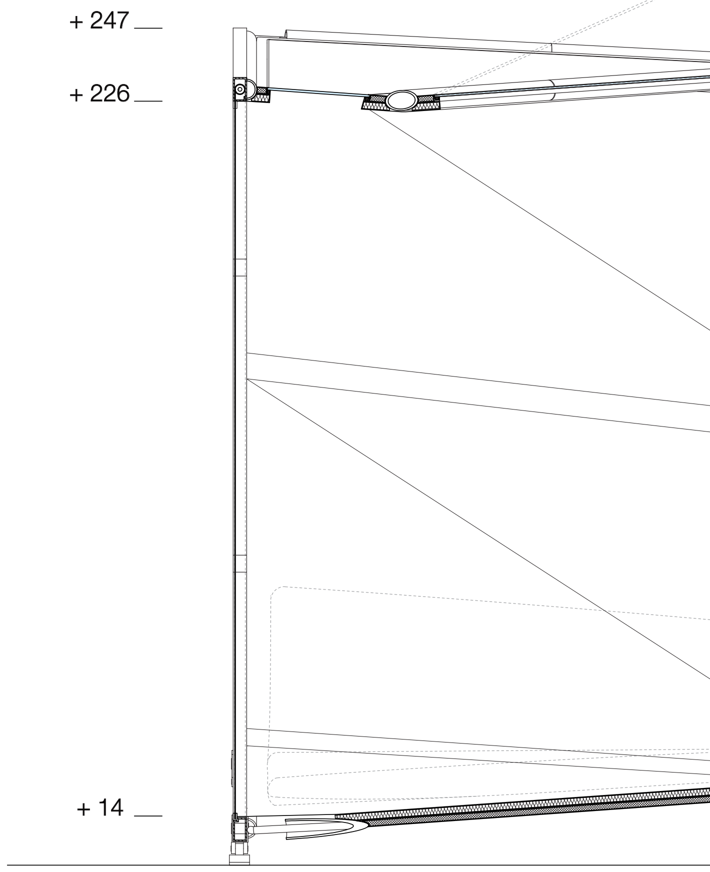
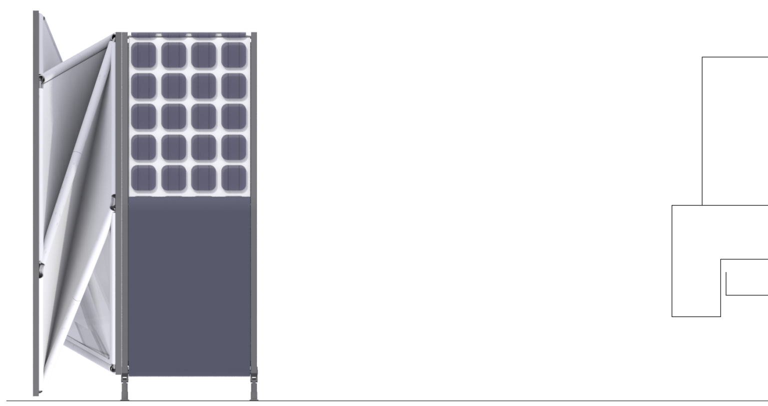


Fig. 5.2.33: Section - deployed units

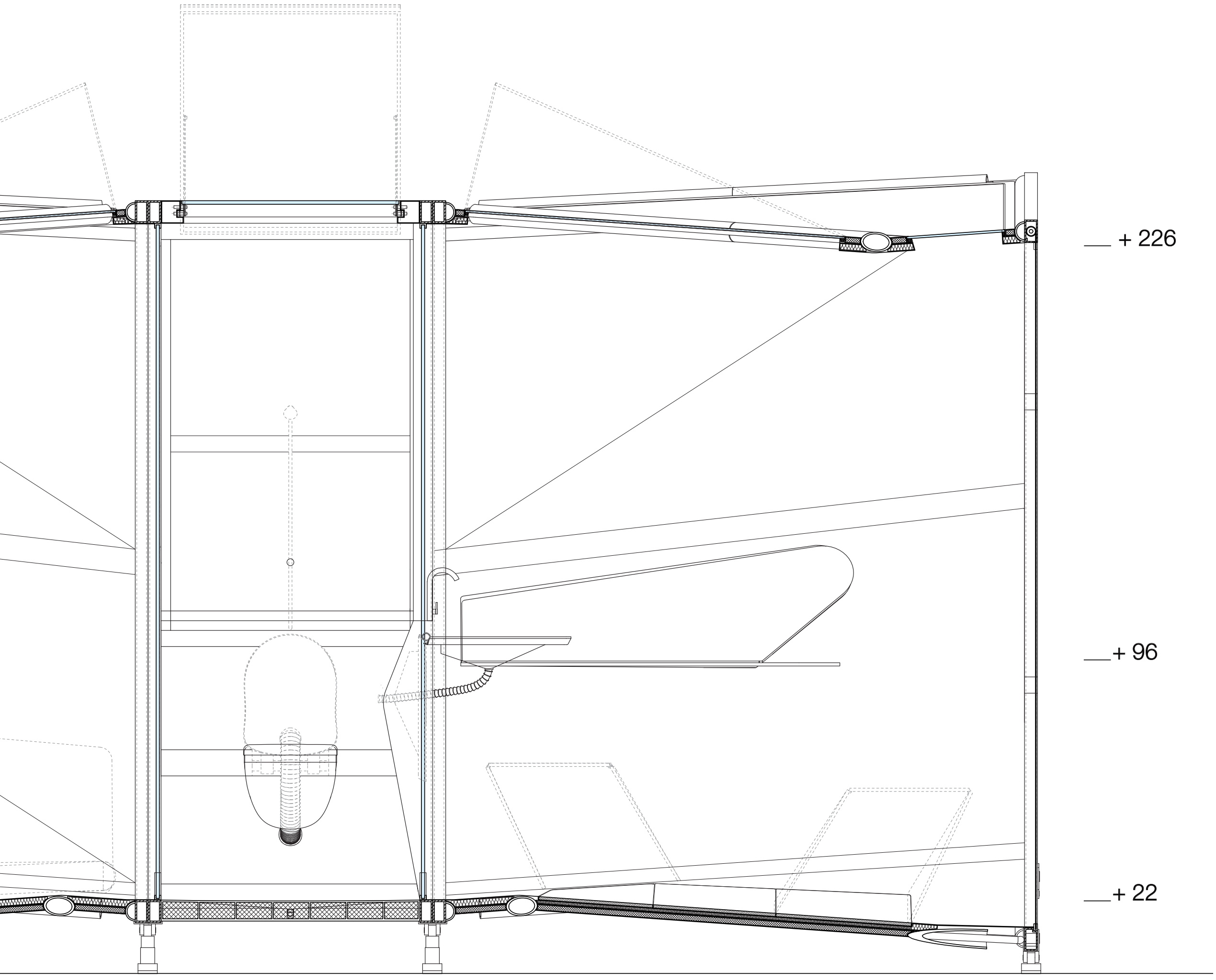


50 100 cm

Fig. 5.2.34:Transportation



50 100 cm


+ 226
+ 96
+ 22

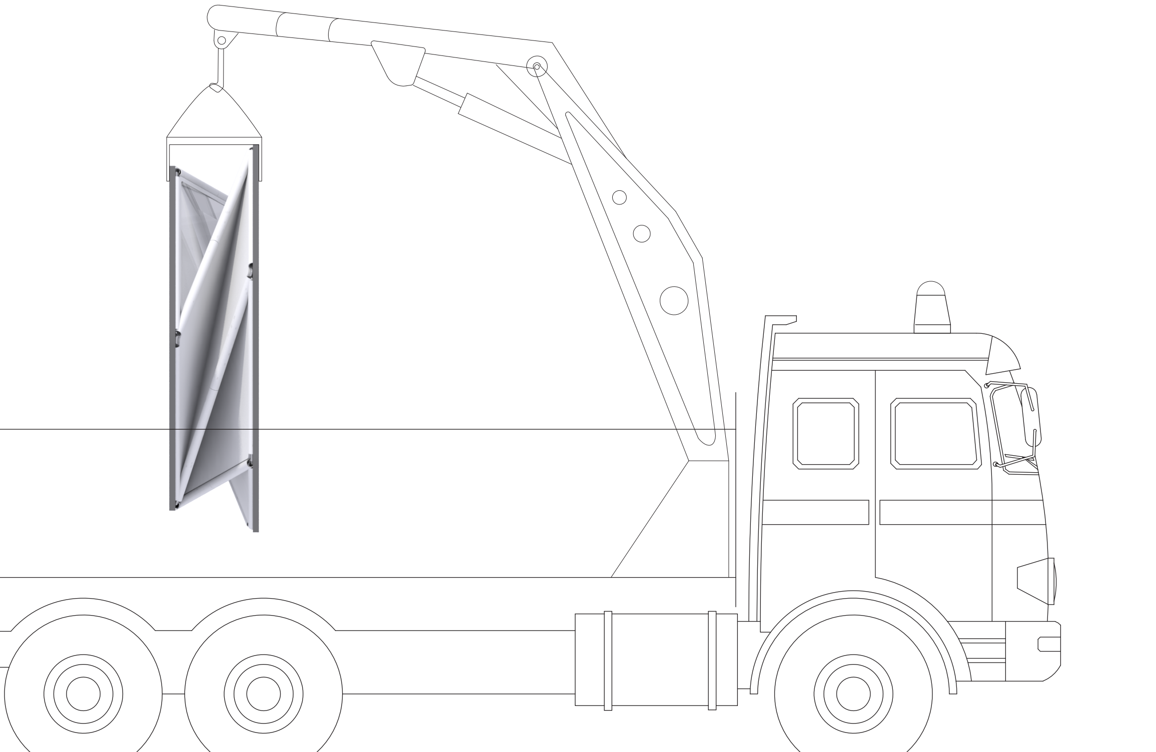
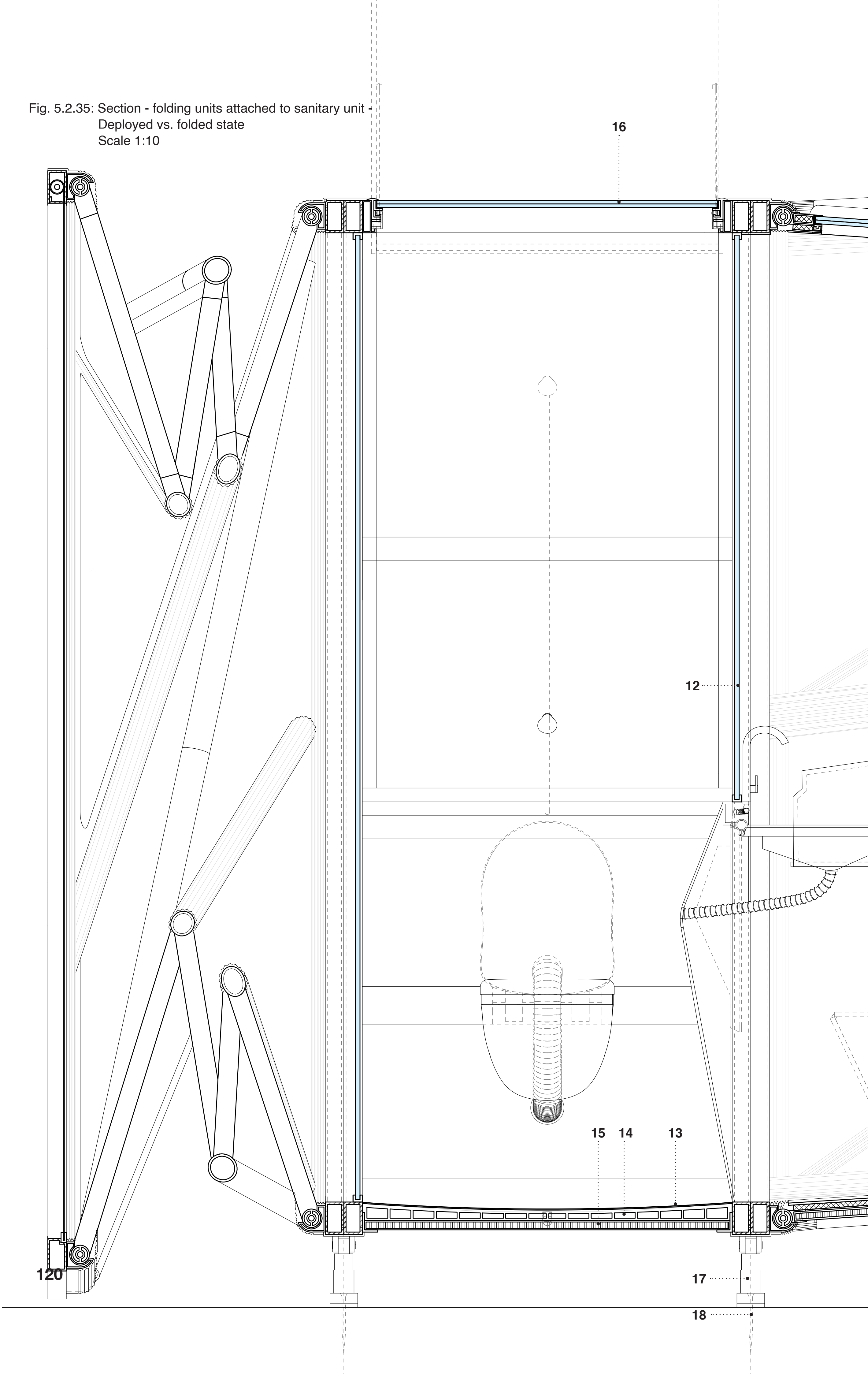
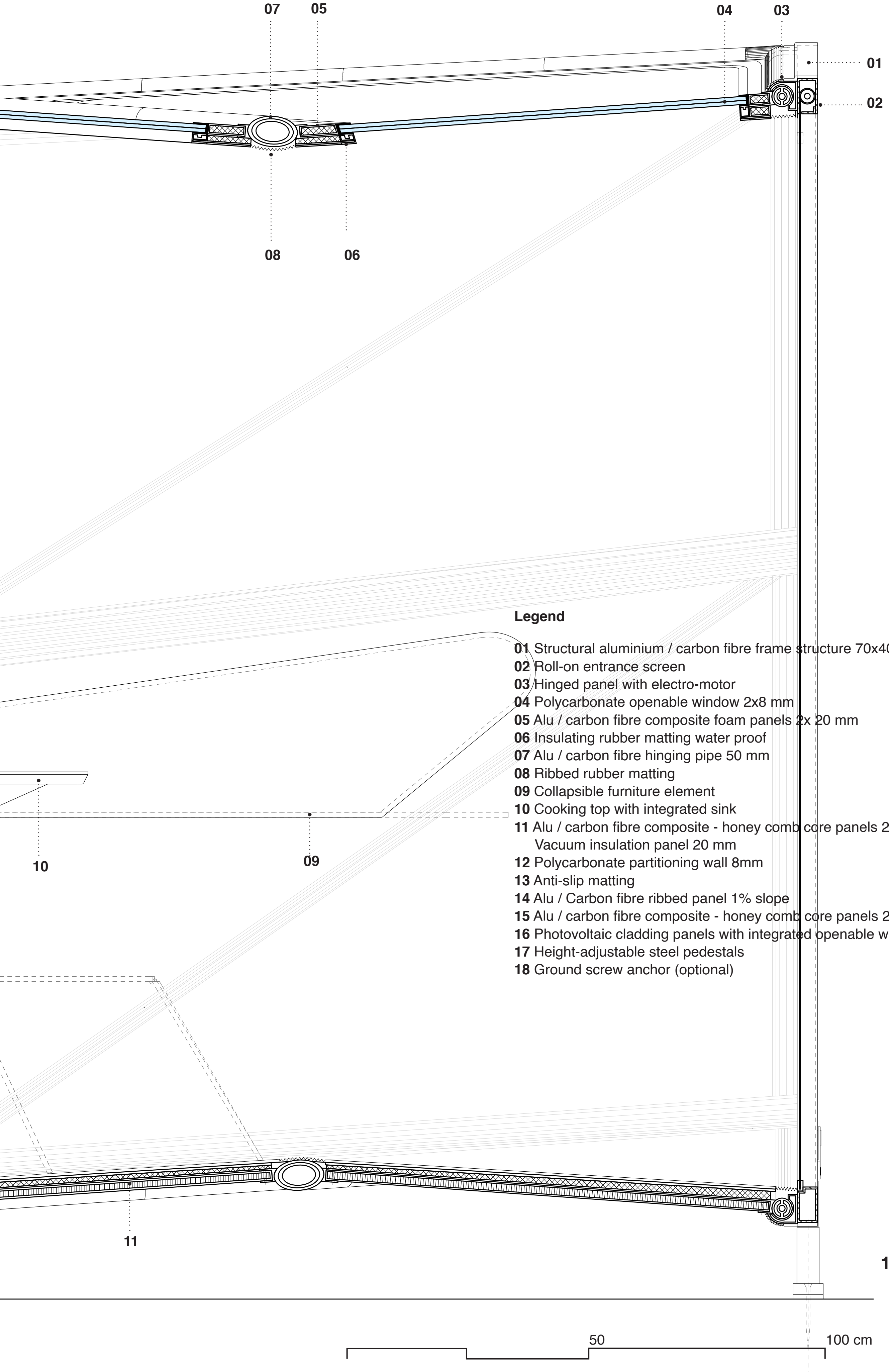


Fig. 5.2.35: Section - folding units attached to sanitary unit -
Deployed vs. folded state
Scale 1:10

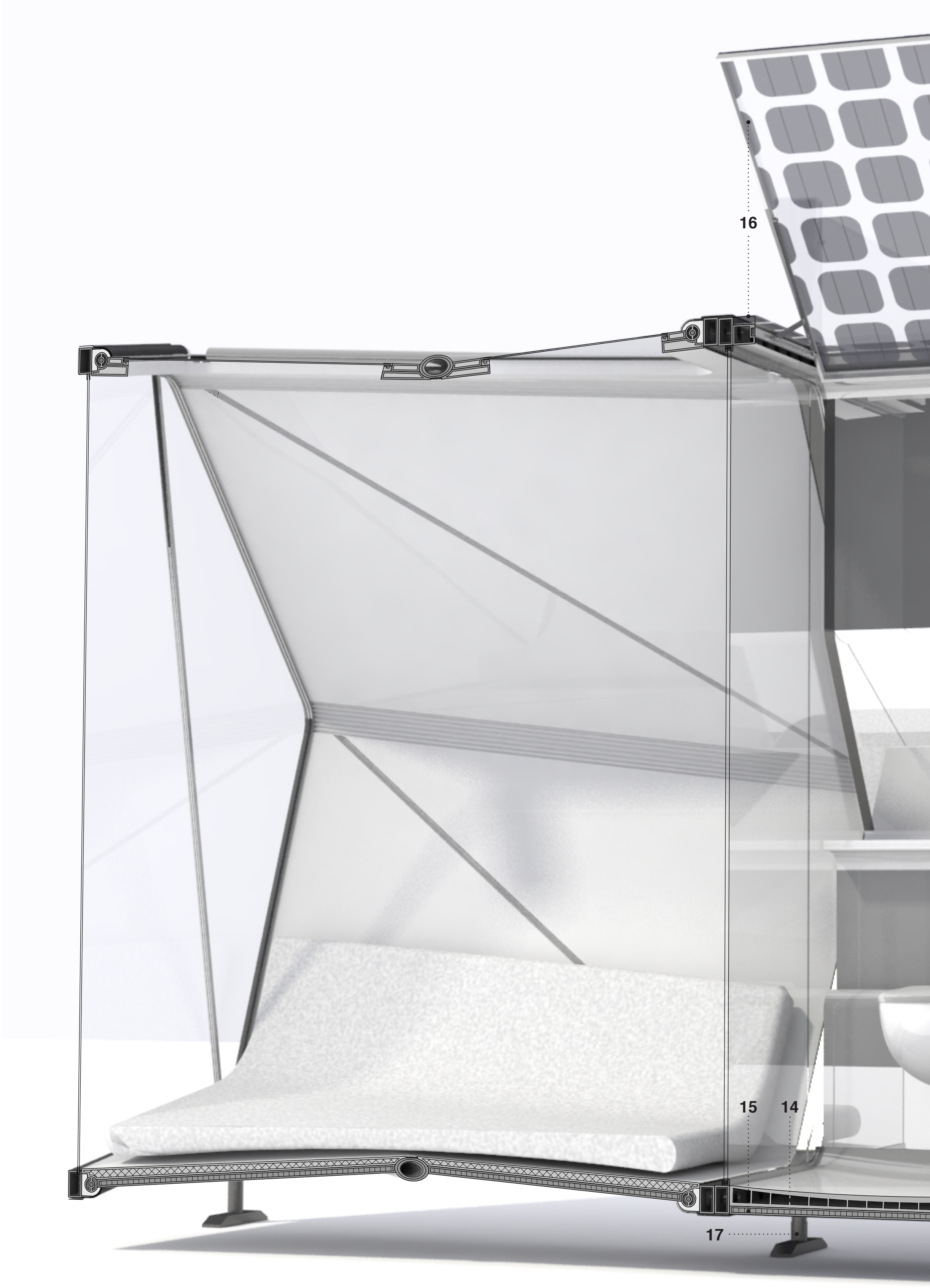




Legend

01 Structural aluminium / carbon fibre frame structure 70x40 mm
02 Roll-on entrance screen
03 Hinged panel with electro-motor
04 Polycarbonate openable window 2x8 mm
05 Alu / carbon fibre composite foam panels 2x 20 mm
06 Insulating rubber matting water proof
07 Alu / carbon fibre hinging pipe 50 mm
08 Ribbed rubber matting
09 Collapsible furniture element
10 Cooking top with integrated sink
11 Alu / carbon fibre composite - honey comb core panels 20 mm
Vacuum insulation panel 20 mm
12 Polycarbonate partitioning wall 8mm
13 Anti-slip matting
14 Alu / Carbon fibre ribbed panel 1% slope
15 Alu / carbon fibre composite - honey comb core panels 20 mm
16 Photovoltaic cladding panels with integrated openable window
17 Height-adjustable steel pedestals
18 Ground screw anchor (optional)

Fig. 5.2.36: a) 3D section - folding units attached to sanitary unit - deployed state



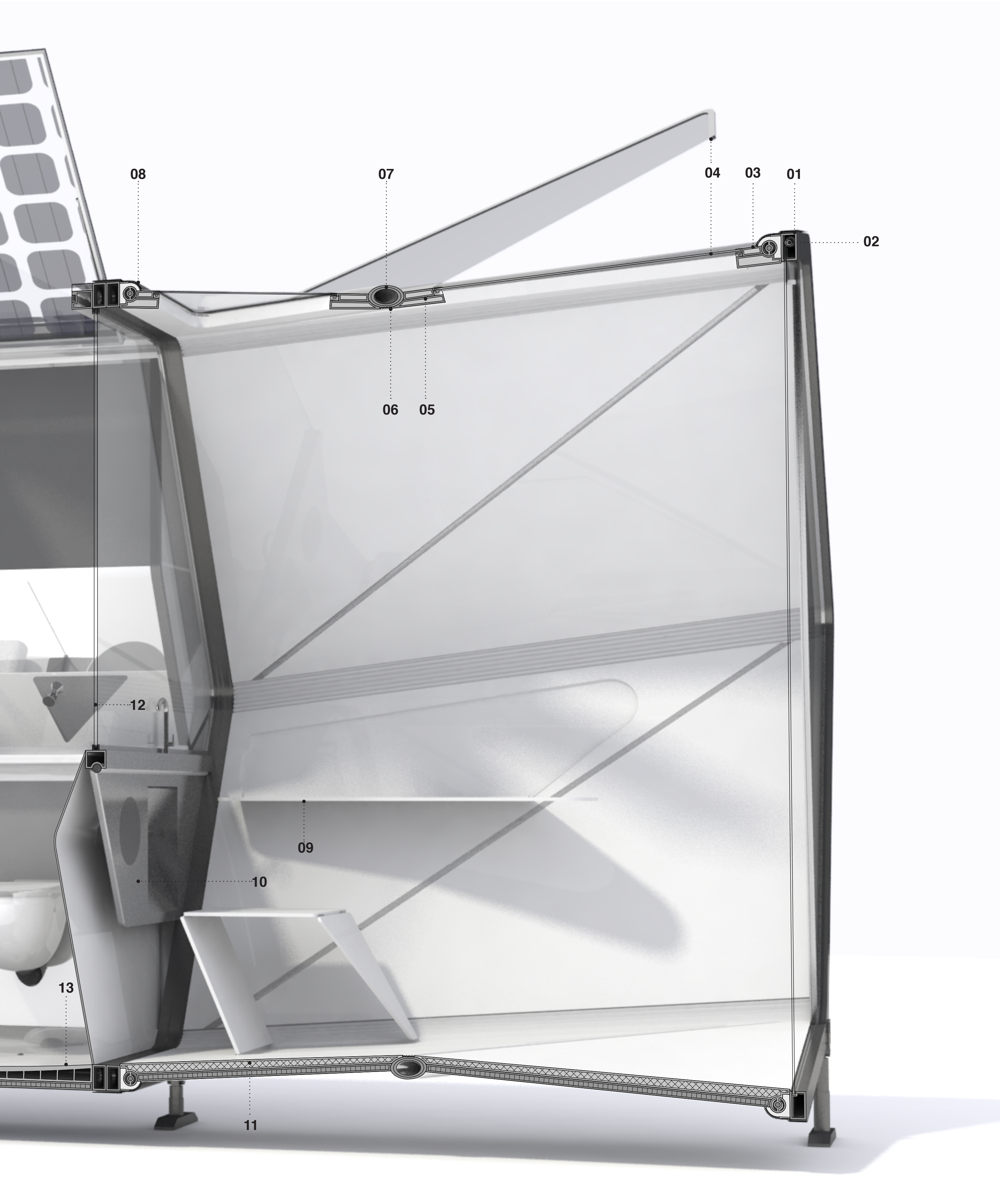

08
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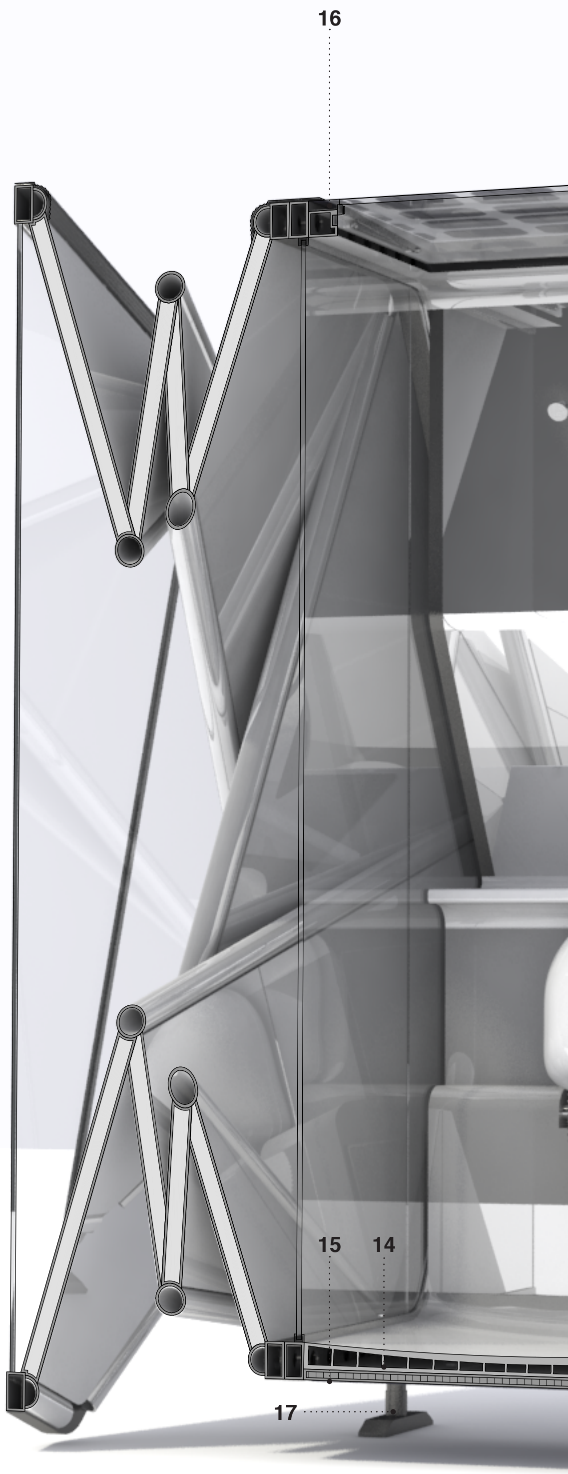
Fig. 5.2.36 : b) 3D section - folding units attached to sanitary unit - folded state



Legend

01 Structural aluminium / carbon fibre frame structure 70x40 mm
02 Roll-on entrance screen
03 Hinged panel with electro-motor
04 Polycarbonate openable window 2x8 mm
05 Alu / carbon fibre composite foam panels 2x 20 mm
06 Insulating rubber matting water proof
07 Alu / carbon fibre hinging pipe 50 mm
08 Ribbed rubber matting
09 Collapsible furniture element
10 Cooking top with integrated sink
11 Alu / carbon fibre composite - honey comb core panels 20 mm
Vacuum insulation panel 20 mm
12 Polycarbonate partitioning wall 8mm
13 Anti-slip matting
14 Alu / Carbon fibre ribbed panel 1% slope
15 Alu / carbon fibre composite - honey comb core panels 20 mm
16 Photovoltaic cladding panels with integrated openable window
17 Height-adjustable steel pedestals

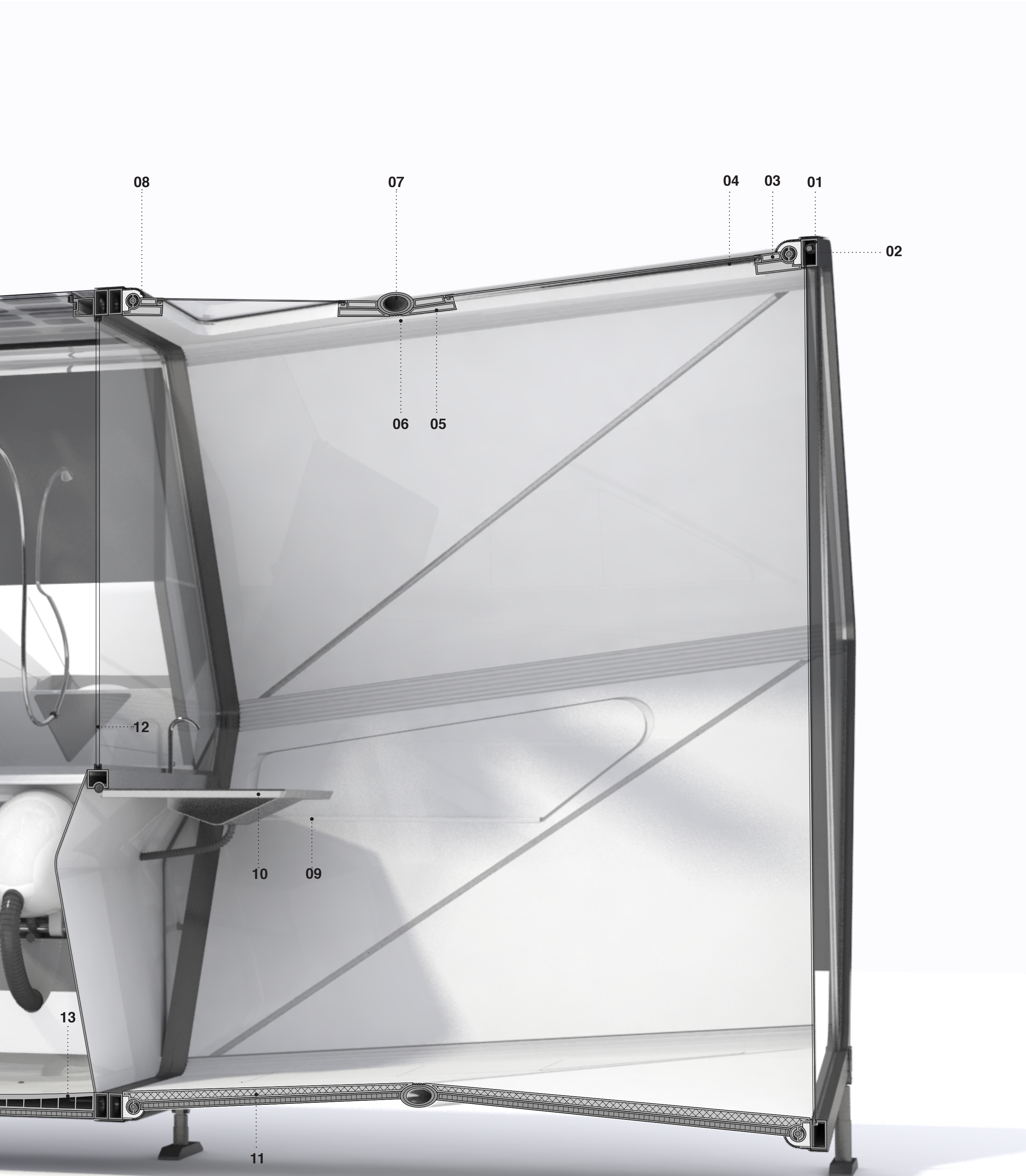

08
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Fig. 5.2.37 : a) Ground screw anchor

To ensure the stability of the units while in use a truss frame structure can be used instead of the individual pedestals. While it provides better stability of the structure as a whole especially for the case of lateral forces like strong wind it is only suitable for flat plot where the pod is placed. In the case of an uneven plot with height differences the pedestal elements attached to the lower corners of the pod frames are the best option. They can be additional grounded to an installed foundation system like ground screw anchor.

Fig. 5.2.37 : b) “Spinnanker”

Fig. 5.2.37: c) Pod on truss structure

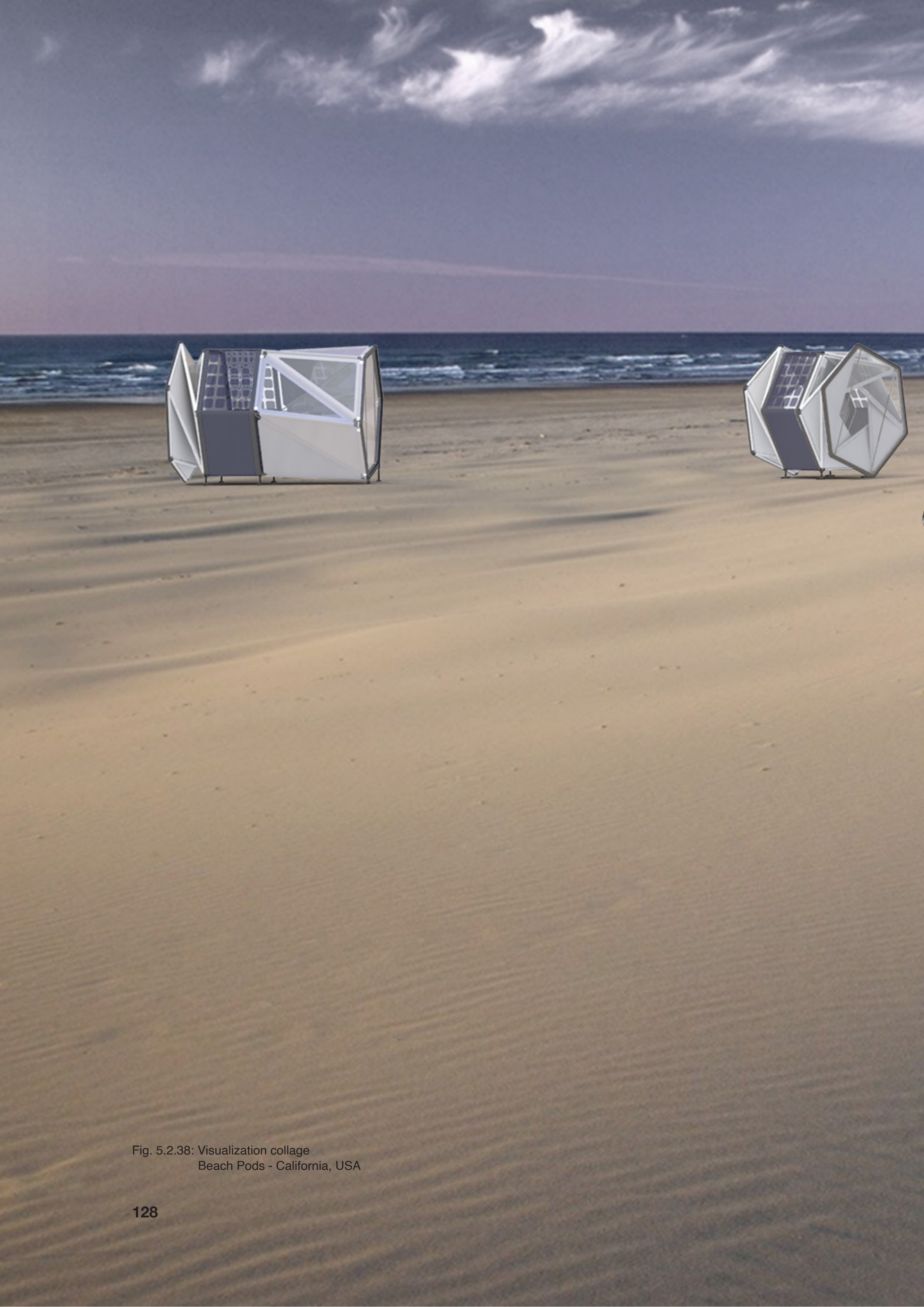


Fig. 5.2.38: Visualization collage
Beach Pods - California, USA

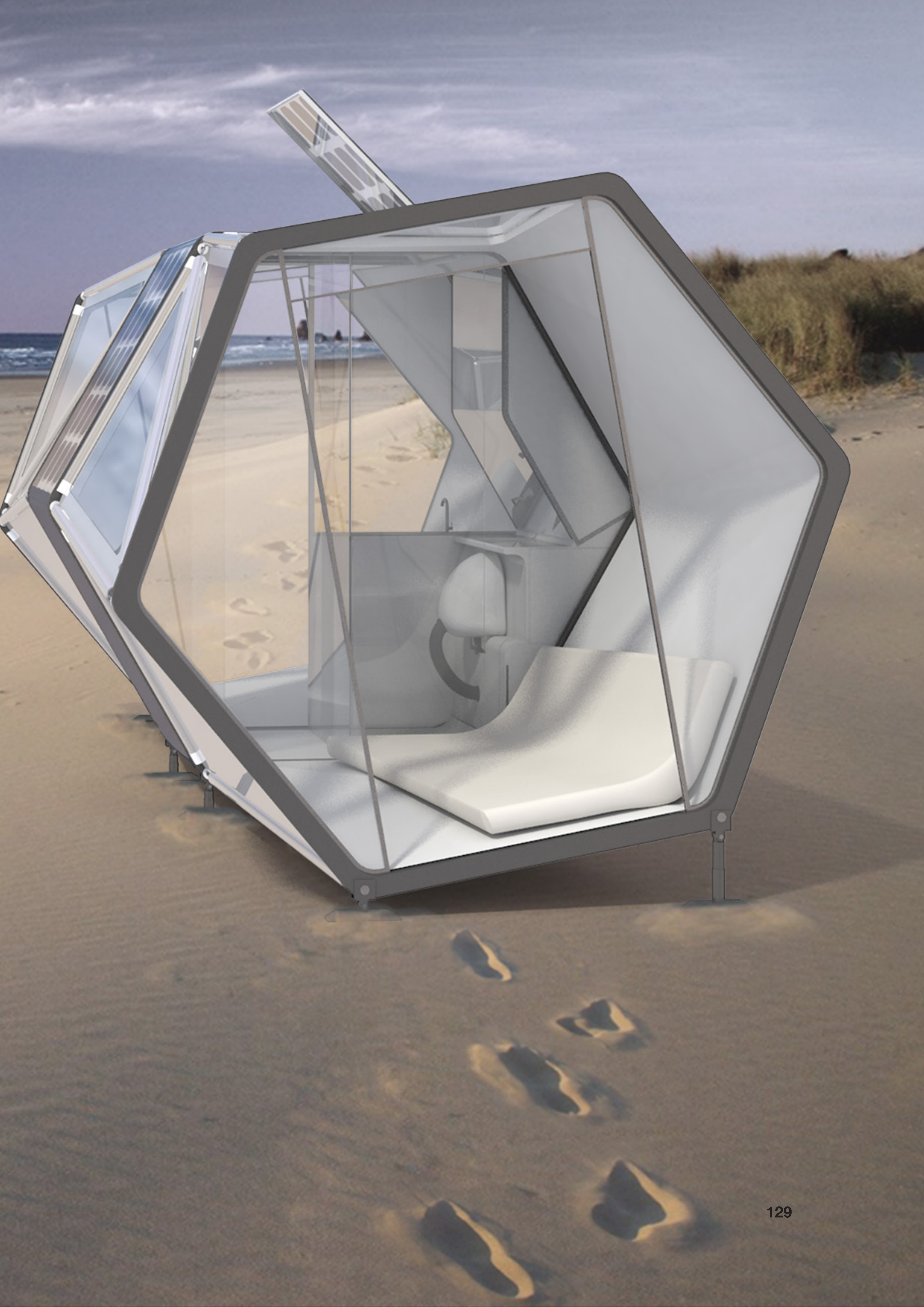


Fig. 5.2.39: Visualization collage
Ski Pod Accommodation - Bergdorf, Salzburg - Austria

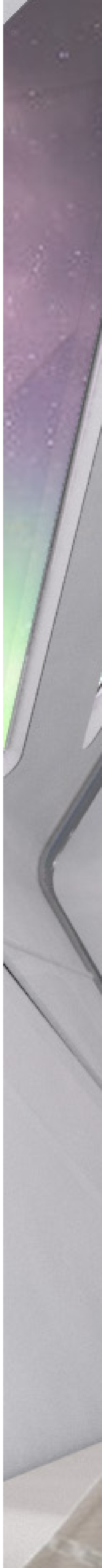
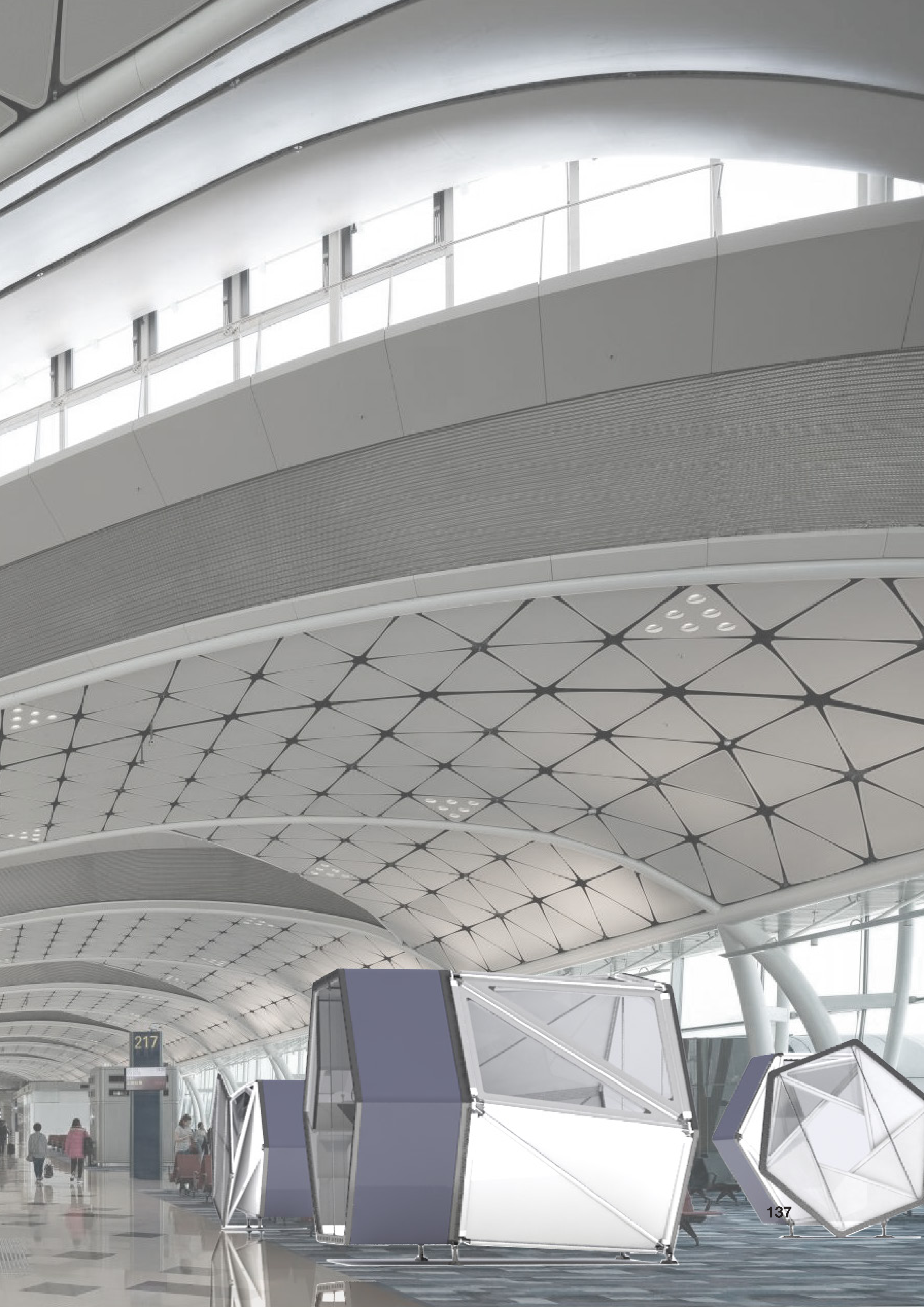


Fig. 5.2.40: Visualization collage
Pod Accommodation - Aurora spotting in Saariselkä, Finland

Fig. 5.2.41: Visualization collage
Urban Pod - Rooftop hostel Paris, France

Fig. 5.2.42: Visualization collage
Sleeping pods - Hong Kong International Airport


217

Connectivity - Joining folding modules with rigid units

The folding units can be extended along the central axes with as many units as needed. However the folding pattern does not function with intersecting units. Therefore for bifurcating configuration a rigid unit is needed to which the folding units can be attached. Up to 4 sides can be connected in this way generating aggregation of rigid units and folding elements in the horizontal plane. Also a similar configuration could function in the vertical direction with an appropriate load bearing structure. The rigid connecting elements could house the vertical circulation infrastructure.

Fig. 5.2.43: a) Linear connection b) + folding modules c) + folded state

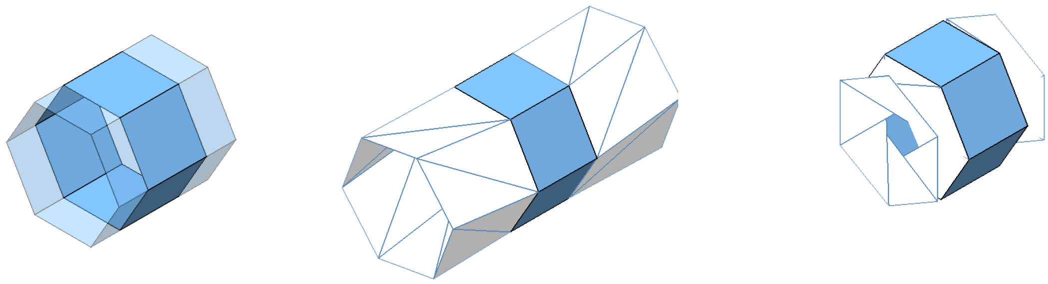


Fig. 5.2.44: a) T-shaped connection b) + folding modules c) + folded state

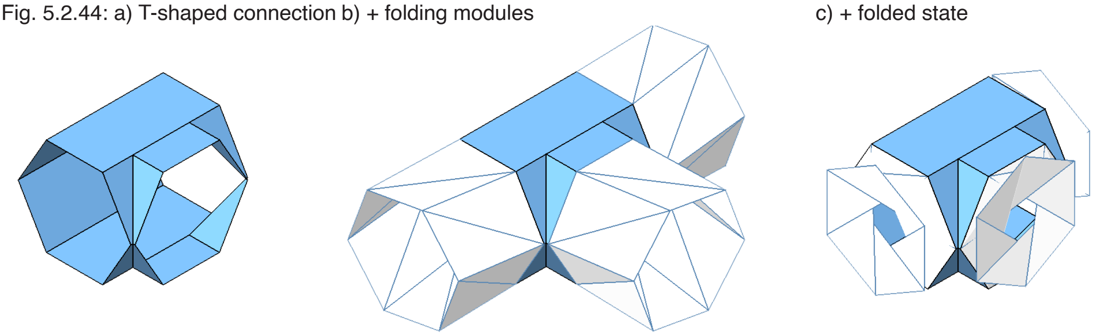


Fig. 5.2.45: a) Cross-shaped connection b) + folding modules c) + folded state

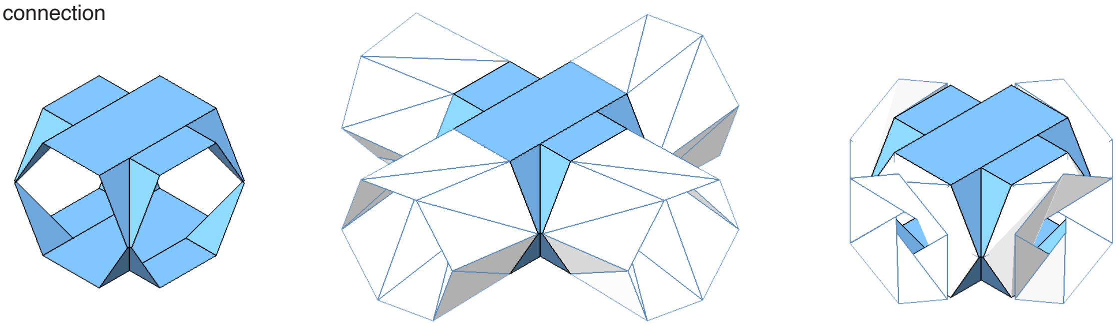
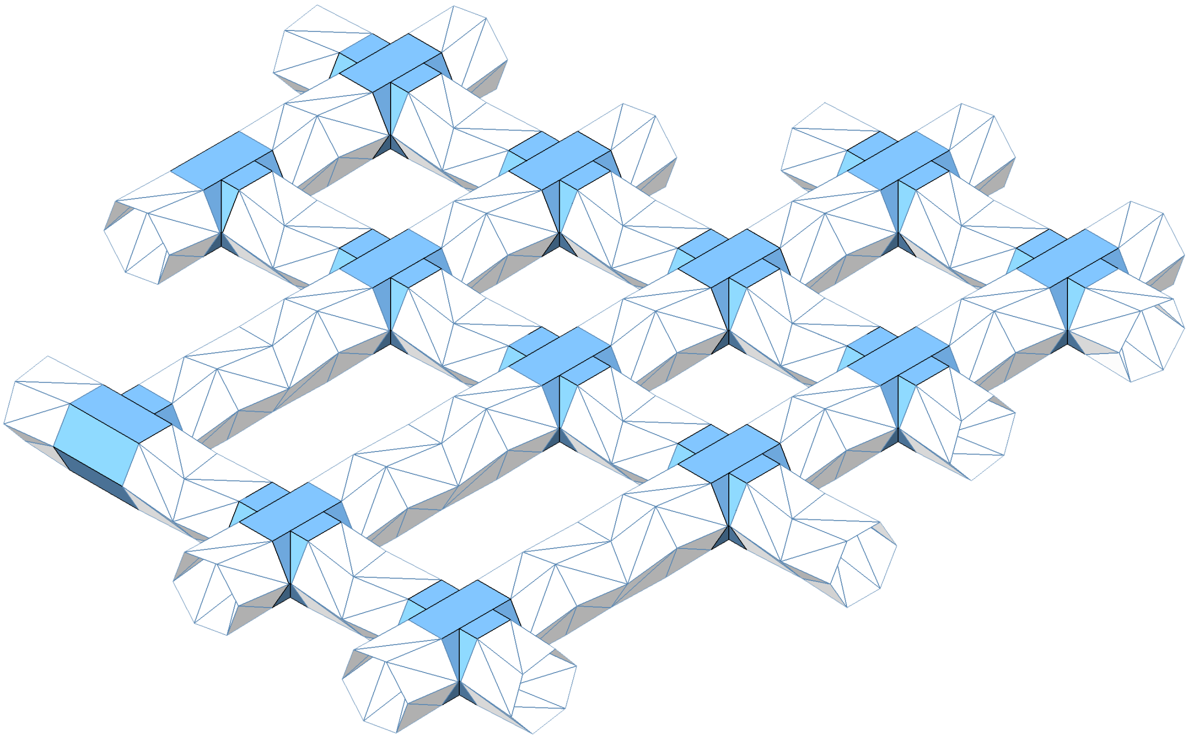
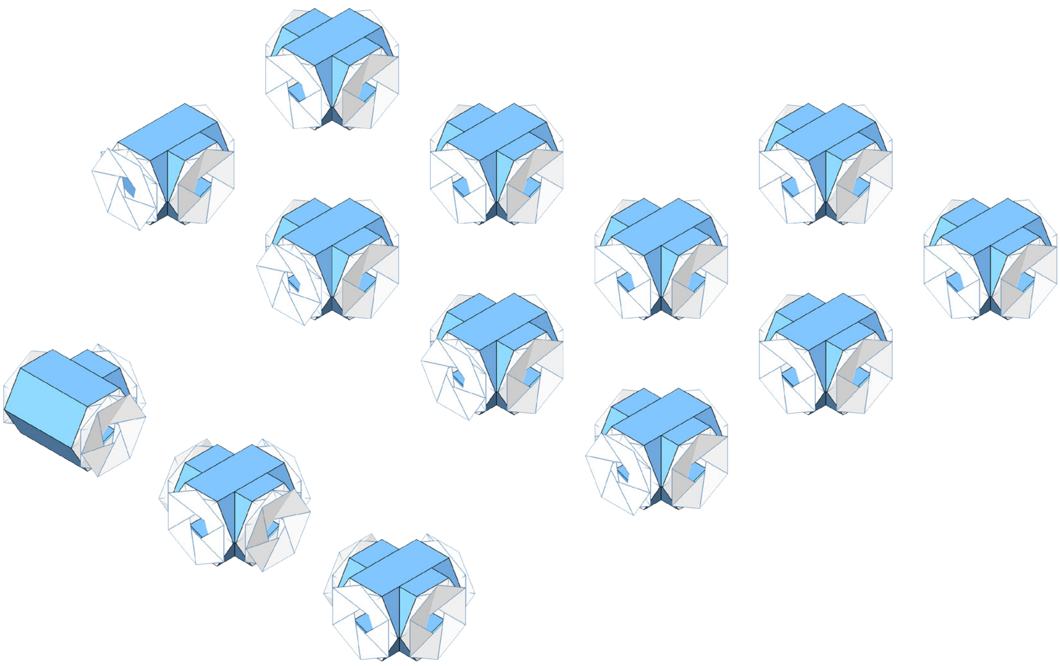


Fig. 5.2.46: a) Aggregation - deployed state



b) Aggregation - collapsed state



5.3. Mock-up Photos

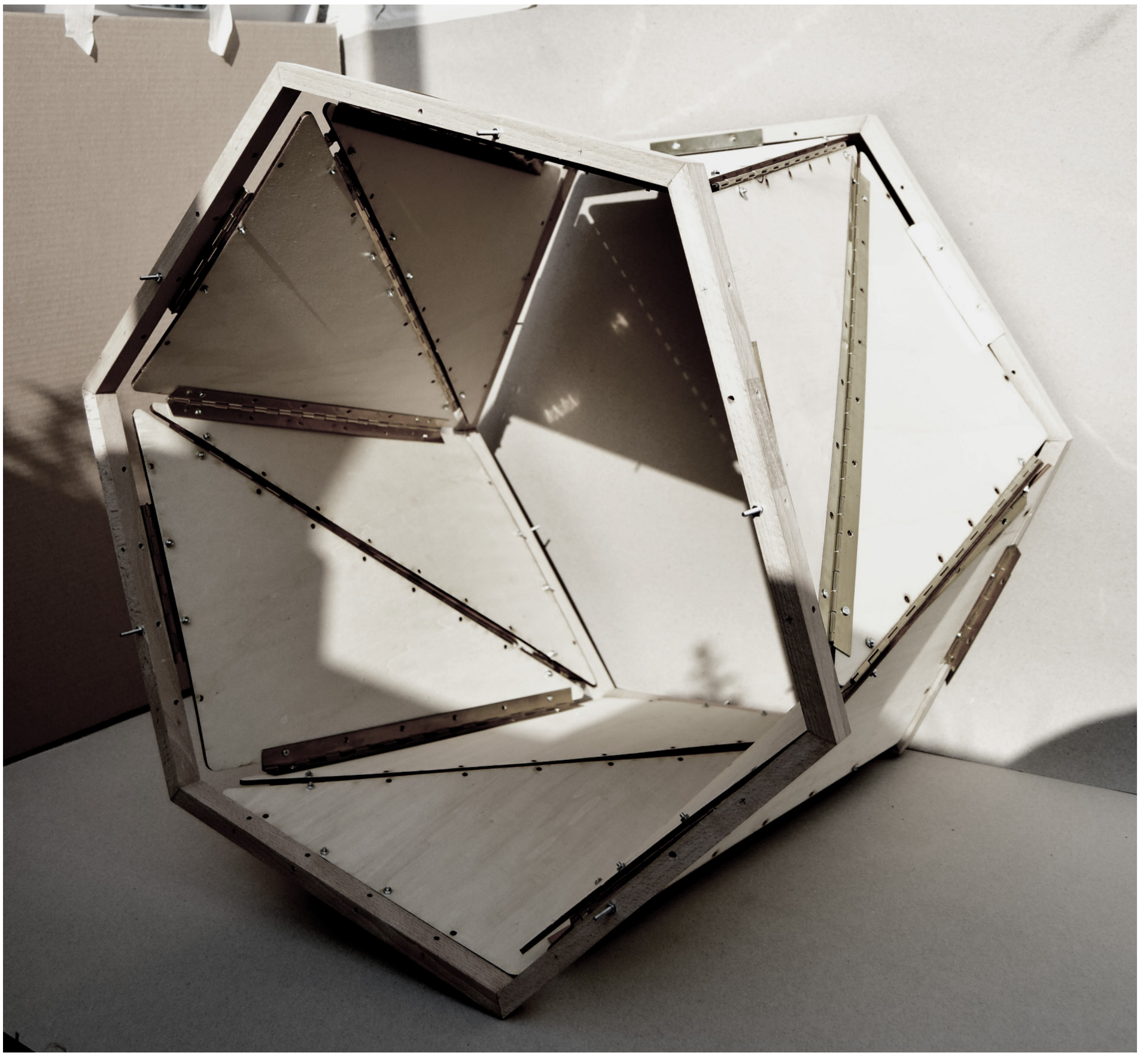


Fig. 5.3.01: Scale model 1:4 - deployed state

The built scale model represents 1:4 of the actual size the structure was designed at. In the built mock-up as is usually the case with architectural models an abstraction process was necessary in order to be able to create the model with the available tools and use materials that could be cut in shape with the available model building machinery (laser cutter, CNC-mill). Different timber elements were chosen for frames and plates elements. To ensure deployment of the model hinging elements where used. The supporting structure consists of timber beams, which were cut at a 60° angle and then glued together to form the hexagonal frame. The plate elements were laser-cut from 3mm ply-wood panels. All the rigid parts are connected with hinging elements by bolt and nuts, which make the structure fold and unfold. While it was an easy and fast way of getting an idea of how the structure would behave at 1:1 scale, the materials would not exactly emulate the performance of the designed structure. While timber was chosen due to its ease to use as a model building material and test out the overall deployment mechanism, it would not offer the best choice for larger sized mock-ups especially in combination with the metal hinges and bolt and nut connections, as they increase the dead load of the model substantially, while the timber elements are lightweight. Also the folding mechanism and the torsion force taking action in the process are not favourable for the timber properties. While timber is ideal for transferring compression and bending forces along the grain in the case of torsion the thin plywood plates can easily

Fig. 5.3.02: Folded state

shear at the connection with the bolt and nuts. However the bolt and nut connections can be disassembled and the plate and frame elements replaced with other parts from different materials. Other alternatives would be polystyrene or propylene sheets. Metal sheet material could also be used however the available numerically controlled machineries accessible for students at TU Vienna were not able to cut metal parts.
To sum it up although the built mock-up offered insights into the physical behaviour of the structure more details and costly material and fabrication tools have to be considered in order to produce a fully working prototype. Needless to mention a prototype would also help optimize the design as a lot of aspects cannot be easily understood only from the digital model and a prototype would change the consequential order of CAD-drawing to physical model to the latter making changes necessary to the digital model. Also the knowledge of specialists form the field of mechanics, fabrication, material safety would have to be consulted and based on their expertise the design would have to be optimized in order for the structure to function and be safely operated by users.


Fig. 5.3.03: Frame structure

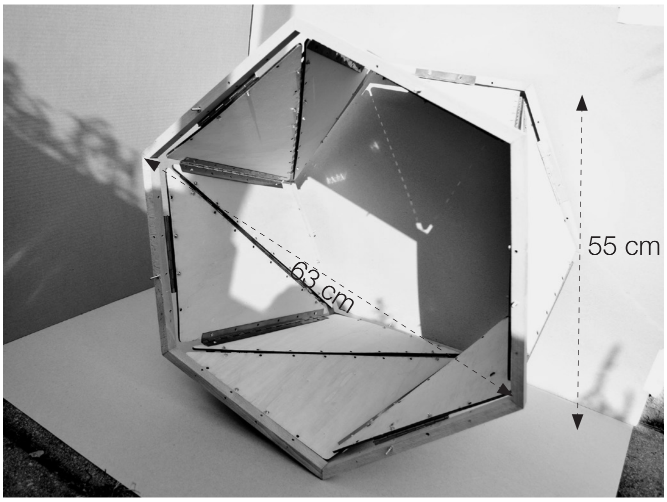


Fig. 5.3.04: Deployed structure


Fig. 5.3.05: Bolt and nut fixing

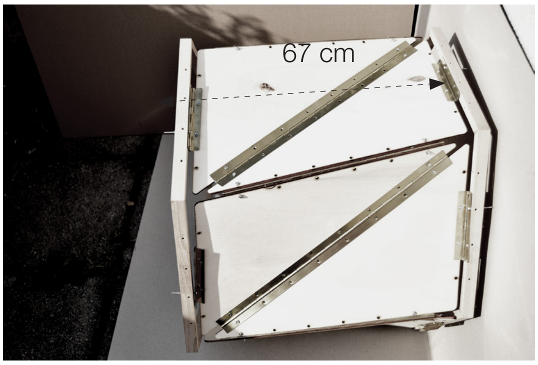


Fig. 5.3.06: Hinges as folding mechanism

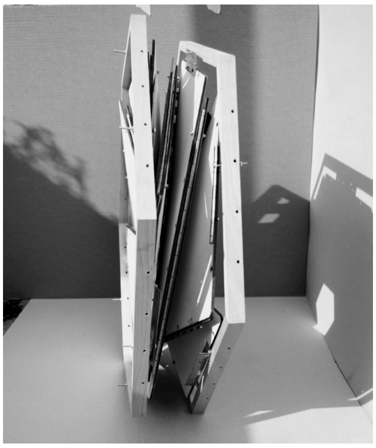


Fig. 5.3.07: Collapsed structure


Fig. 5.3.08: Hinge fixing


Fig. 5.3.09: Hinged plates

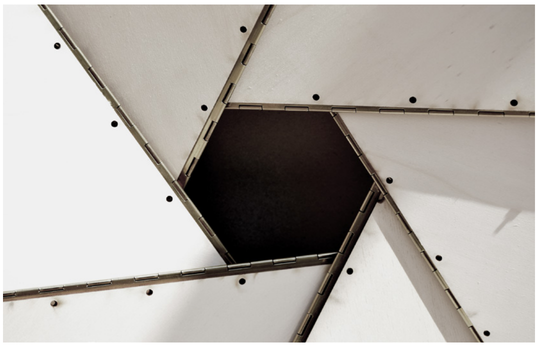


Fig. 5.3.10: Overlapping folded plates

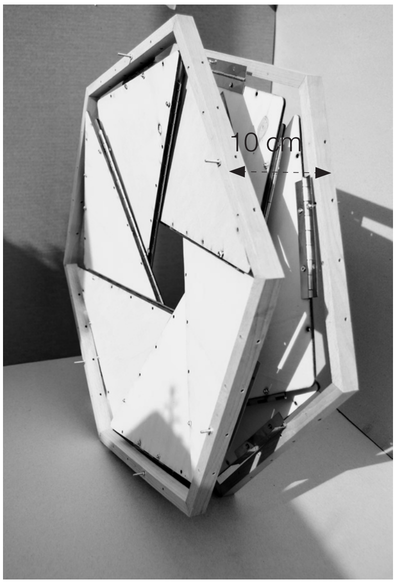


Fig. 5.3.11: Collapsed structure

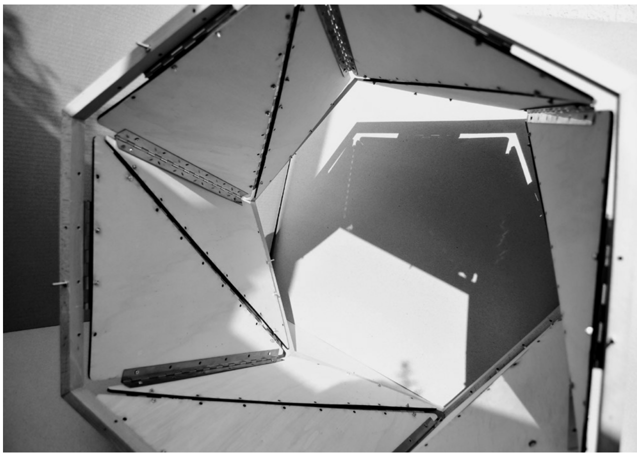


Fig. 5.3.12: Deployed interior space

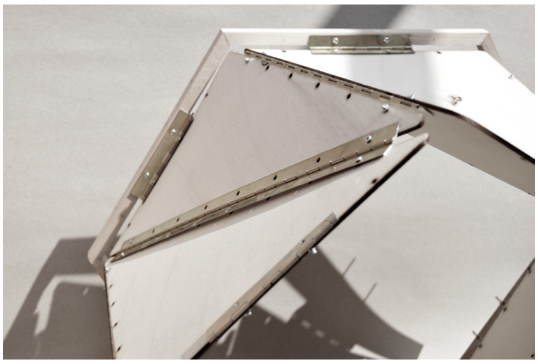


Fig. 5.3.13: Hinged frame and plates

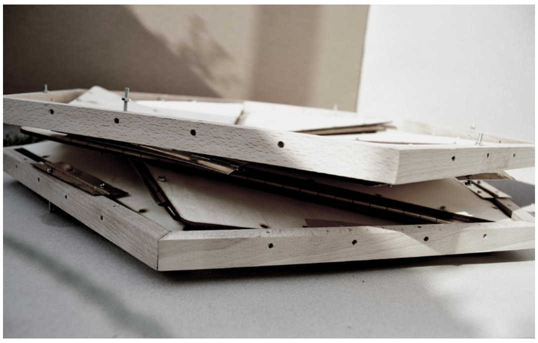


Fig. 5.3.14: Collapsed model

Fig. 5.3.15: Folded plates - close-up

Fig. 5.3.16: Hinged plates close-up

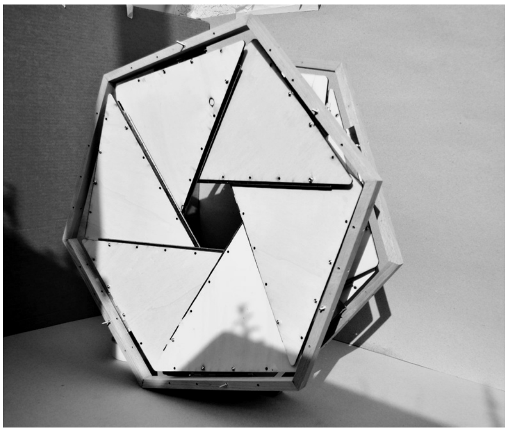


Fig. 5.3.17: Collapsed model - front view

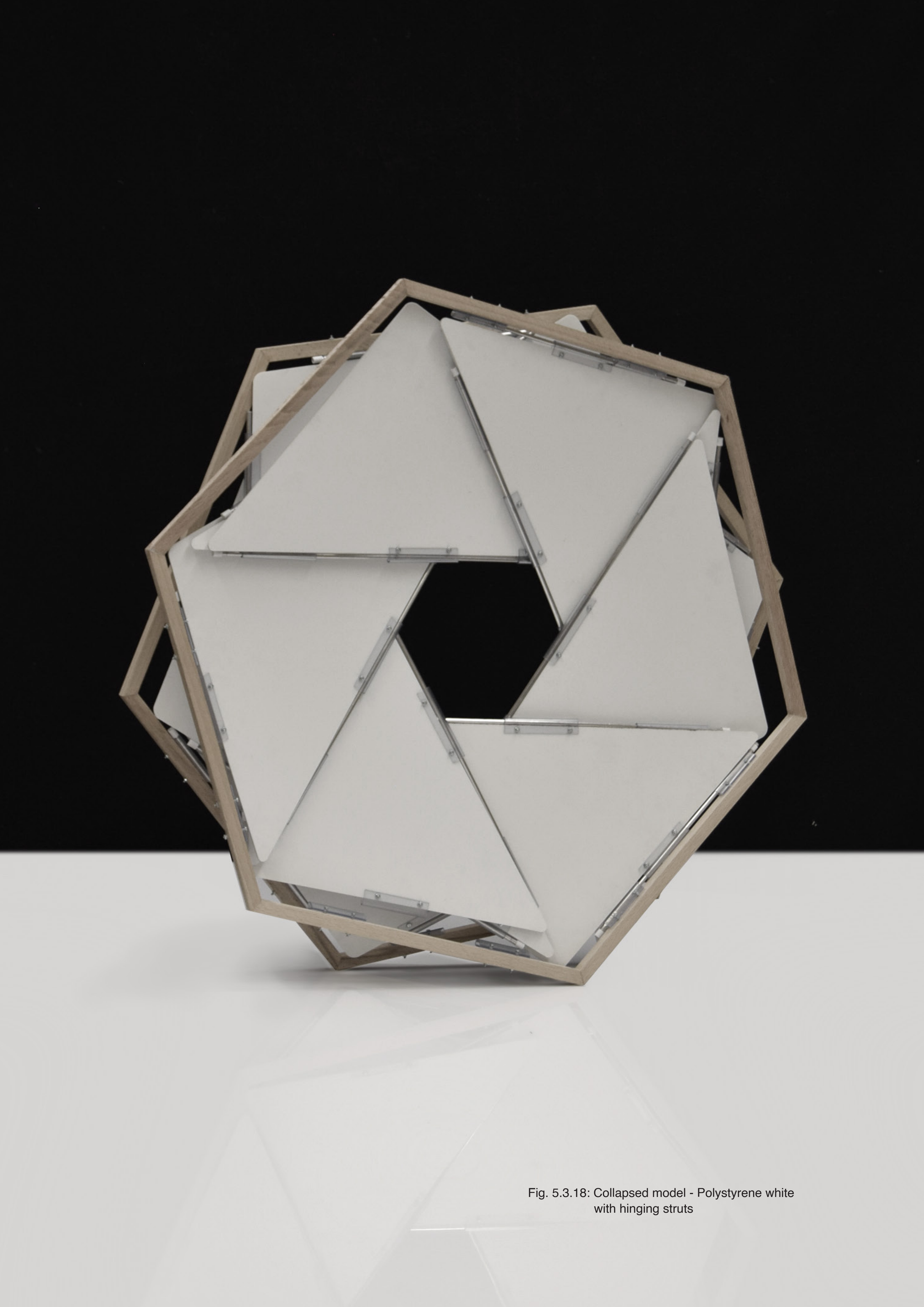


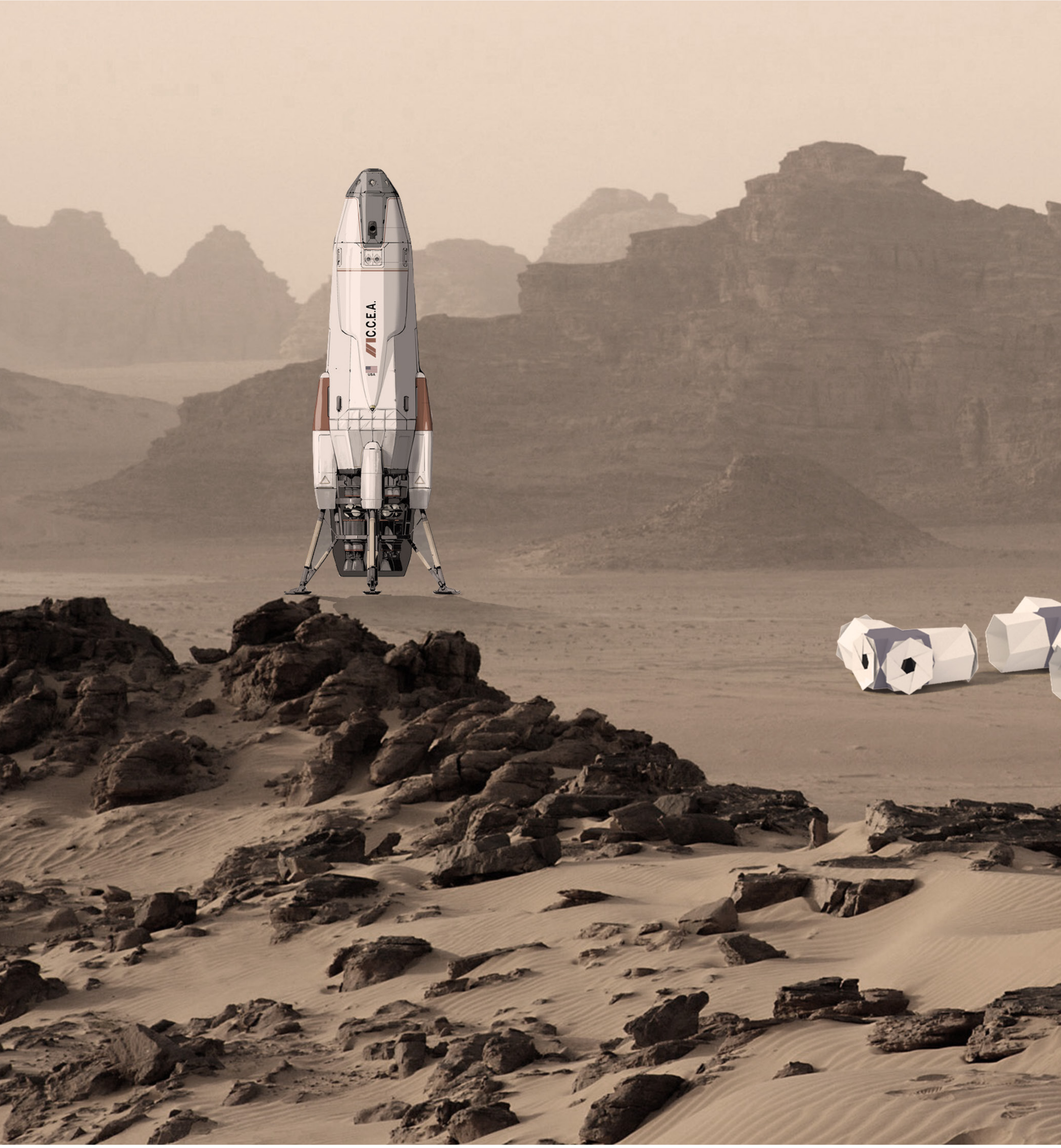
Fig. 5.3.18: Collapsed model - Polystyrene white with hinging struts

6. CONCLUSION

Mobility and adaptability in a broad sense have brought the human being where it is today, namely everywhere on Earth and even further.
A minimal lifestyle and deployable dwellings have been part of mankind long before the profession of architecture even existed. Tents as the most common form of deployable structure are probably the most widespread emergency shelter even in our days.
Even tough dwellings have acquired permanency long ago and there are many other forms of temporary dwelling typologies not related to deployment, combining structural transformability and temporary functionality may offer an attractive alternative and create a new design task, especially given the technological advances, which have given new meaning to our sense of mobility and independence in regard to our built environment.
While this thesis only focused on a small fraction of deployables, precisely hinged plate structures and pivoting elements there is a great inventory of deployable structure with specific properties related to material and geometry.
For the design application two states were considered: of deployment, in which the structure could provide enclosure and compact state, which is ideal to ensure transportation or storage. The first state also had to ensure the stability and load-bearing capability of the system. In a more advanced approach also the deployment process could be considered as a way of reacting and adapting to different circumstance, environmental stimuli and user experience.
Furthermore the circumstances and environments for which deployables are developed are very diverse from medical devices to, large retractable roofs to space missions. The proposed design applications are related to dwelling and how this need can be met temporarily within a space efficient structure . While space efficiency is not always the main design task when considering dwelling on Earth, considering that deployable structure are already well in use for space exploration missions, a collapsible and deployable modular dwelling unit acquires in the context of space missions totally new potential, but would also require far more expertise for developing a feasible structure which would need to provide safety and protection in extreme and unknown environments.

Deployable structures display a tight correlation between form and structural behaviour, meaning that geometry will dictate the structural properties of the mechanism.
When considering form, the materials which constitute the structure have to be carefully considered as their properties have direct influence on the structural performance and deploying mechanism. Movement in a load bearing system is inconsistent with the purpose of providing stability, therefore deployable structures have to ensure stability and movement within the same system which makes them highly complex mechanisms. Regarding complexity also the construction of the structure with materials and technology which provide movement can be costly. However deployable plate structure offer the advantage the elements can be fabricated from flat sheet material.

The proposed design applications were intended to offer structures which are able to deploy and collapse in a space saving mode and be able to be stored away when not in use. But deployable structures can offer solutions in a wide variety of potential scenarios.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