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Design Exploration for a Martian Habitat through a Digital Tool for Parametric Interior Architecture

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Abstract

Space exploration has always granted the achievement of great accomplishments in research and has provided innovative techniques that have improved technological advancements. For this reason, this paper focuses on the field of space architecture, a discipline that concerns the planning of structures in space. Research in this field makes it possible to update the methods usually followed by traditional architecture, thus finding novel and more technological approaches.

Designing a resilient and sustainable infrastructure for manned missions on Mars is a new challenge that requires new conceptual design approaches, this concerns both the materials selection and the tools used to develop the project. Architecture in Space, as the synthesis of scientific domains that organize the life of humans, relies on some fundamental pillars that are intrinsically interconnected: space sciences, engineering, robotics, industrial design, ergonomics, medicine, psychology, and art. The extreme environmental conditions are a major technological challenge, but also an opportunity of exploring new construction methods using alternative materials, enabling architecture to progress and update traditional methods.

In this paper, a habitat on Mars, E.L.L.E., an Extreme Livable Lightweight Environment, for 6 astronauts and a mission of 600 days has been designed within a cross-disciplinary environment at different scales, from architecture to interior design, and built on the knowledge and technologies developed for space applications. Challenging both space and terrestrial architectures to consider the relationships between human activities and the resources which support them.

Previous research concerning human factors was crucial to make choices for the interior design process. Several psychological and physical factors must be considered because long stays in Mars' environment in isolation condition can have negative effects on astronauts, therefore architecture must respond to these needs, by developing smart solutions to reduce the undesirable effects. In this paper the relationships between individual-environment and individual-individual have been analyzed and taken into consideration to develop a circular interior architecture strategy, using a parametric software, and creating a script in Grasshopper, which is an algorithmic modeling program. This is an adaptive design tool, that defines the organization of the interiors of the habitat and can change according to several habitability requirements and astronauts' needs.

A computational design approach has been applied to perform multi-objective optimization and form-finding analysis to support the decision making process for E.L.L.E. and future Martian habitats.

Keywords: Space Architecture; Computational design; Optimization; Inflatable; Analogs.

Acronyms/Abbreviations

E.L.L.E. = Extreme Livable Lightweight Environment
SOM = Skidmore, Owings & Merrill
MIT = Massachusetts Institute of Technology
NASA = National Aeronautics and Space Administration
BIG = Bjarke Ingels Group
SeARCH+ = Space Exploration Architecture
TransHab = Transit Habitat
ISS = International Space Station
HI-SEAS = Hawaii Space Exploration Analog and Simulation
EURO-M.A.R.S. = European Mars Analogue Research Station
CAD = Computer Aided Design
EVAs = Extravehicular Activities
LSS = Life Support System

1. Introduction to Space Architecture and Computational Design in the Aerospace field

Designing habitats for space exploration purposes sets several technical challenges.

For projects on orbit, on the Moon and Mars, aspects such as the level of radiations, external temperature and pressure must be taken into consideration. These are extreme environments and humans cannot normally survive under these circumstances. Therefore, the habitat design should provide the required protection against external hazards.

The high complexity of the projects for space habitats entails the use of tools that can control multiple variables.

A computational design software, such as Grasshopper, can provide the kind of adaptability, precision and control that a space project needs. Using algorithm-based systems to develop a project means that the design can be optimized, and its parameters can be easily controlled and manipulated.

This paper proposes the use of these programs to design and optimize the interiors for E.L.L.E., a habitat for planet Mars. The purpose of the research stands in the development of a digital tool inside Grasshopper that can be used both for designing the interiors of E.L.L.E. and provide a method that can be applied for other space and analog projects.

1.1 The field of Space Architecture

The discipline of space architecture was officially born during the Space Congress held in October 2002 in Houston. In this occasion the main points of this matter were determined and a definition of “space architecture” was elaborated. It can be described as the "theory and practice of designing and building inhabited environments in outer space" [1].

Even though this discipline was technically born in the early 2000s, architects and designers began working in this environment much earlier, helping with the design of space structures. In 1968 an architect named Dalton Maynard and a designer named Raymond Loewy worked on the Saturn-Apollo projects and on the architectural plans for the Skylab space station. Another architect involved in this field was Galina Balashova, who designed the Russian space stations Salyut and Mir, she can be considered the first female space architect [2] (see Fig. 1).

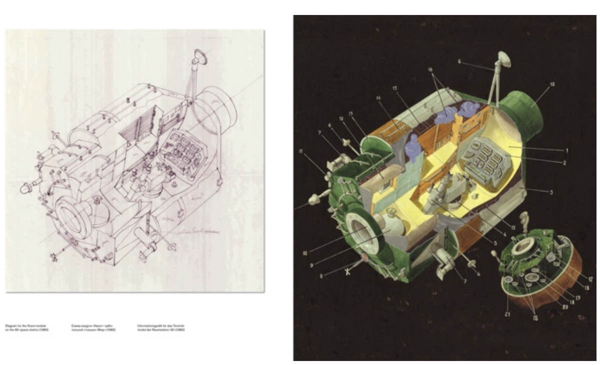

Fig. 1. Design of the technical module of the MIR space station by Galina Balashova [3]

Space architecture can be classified into three categories: orbital architecture, planet surface architecture and Earth-based space architecture [4]. The first one regards the projects for habitats on Low Earth Orbit (LEO) or cis-lunar orbit, examples of this type of space architecture are represented by the International Space Station (ISS), the space station currently orbiting around the Earth, and the Lunar Gateway, a cis-lunar space station that is programmed to be launched and assembled in 2024 [4].

Planet surface architecture concerns the projects for human outposts on other planets, like Mars or the Moon. The only realized example of this kind of habitat is the Apollo lunar module, which was used on the Moon during the Apollo missions in the 1970s as a human outpost for short periods. Since the 1970s no other structure of this kind has been realized, however there are many projects both for Mars and for the Moon, an example of which is represented by the Moon Village, a design developed by Skidmore, Owings & Merrill (SOM) in partnership with the Massachusetts Institute of Technology (MIT) [4-5] (see Fig. 2).

Fig. 2. View of the Moon Village [5]

Earth-based space architecture consists of those structures that serve as support for space missions and for the development of space architecture projects. Among these there are analogs, which are used to simulate and test future missions, an essential step, as it helps correcting eventual errors and perfectioning structures before missions [4].

1.2 Lightweight materials in Architecture and in the Aerospace field

The use of lightweight materials in the aerospace field is crucial because the lightness of the structures can reduce the mass of the payloads and the costs of fuel. Therefore, the introduction of lightweight structures in the aerospace field is essential, since having more efficient structures means that it could be possible to push the boundaries set by traditional methods.

An example of this kind of structures is the inflatable technology, which allows to reduce the mass and the volume of the transported payload.

There are architectural concepts, inspired by space applications, which have been explored over time. In 1966, Archigram proposed the Living Pod project, a free-roving exploratory house inspired by the Lunar Modules that NASA was preparing for a Moon landing. A few decades later, the architect Dante Bini developed two design proposals, Lunhab and Lunit, in collaboration with Harrison Schmitt, the twelfth astronaut to set foot on the Moon in 1971 during the Apollo mission. Today, other inflatable solutions for Moon habitats have been explored by prominent architectural firms such as Foster & Partners, SOM, Andrea Vogler, BIG, SEArch+, ICON, Hassell, SAGA, and others. The proposals are similar in that they both include a deployable structure but differ in how they respond to loading due to micrometeoroid impact and radiation protection [6]. The projects by Foster & Partners and SOM [5] include a shield over the tensile pneumatic structure made from regolith, or Lunar soil. Vogler's design, Moon Capital, is composed of domes, over inflatable modules, that form an intelligent skin realized by a 3-meter-thick layer of small-regolith sandbags, filled, and mounted by swarm smart robots. Recently, several inflatable structures have been deployed and tested in space applications.

TransHab [7] (see Fig. 3) was a concept pursued by NASA in the 1990s to develop the technology for expandable habitats inflated by air in space.

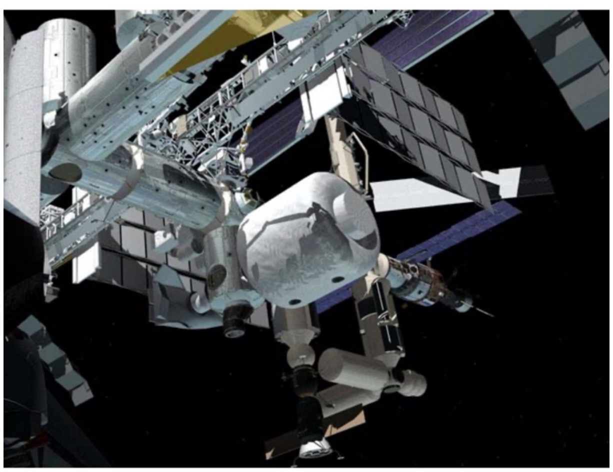

Fig. 3. View of the TransHab habitat [7]

When deflated, inflatable modules provide a compact folded form. When fully inflated, TransHab would expand to 8.2 meters in diameter (compared to the 4.4-meter diameter of the Columbus ISS Module). TransHab's inflatable shell consisted of multiple layers of blanket insulation, protection from orbital and meteoroid debris, an optimized restraint layer and a redundant bladder with a protective layer [6].

1.3 Space analog structures

Space analogs are used to test structures before they are launched into space and to simulate the physical and psychological effects on people during spaceflights. These missions are performed in places that try to reproduce the characteristics of the extreme environment they are supposed to be in the future or the effects that space harsh conditions have on individuals.

There are two different kinds of space analogs, the physiological analogs, and the isolation analogs.

The first ones reproduce the effects that spaceflight has on people from a health and physical perspective, this means that these analogs replicate the consequences that different factors in space have on people, such as the absence of weight, that causes health issues like bone fracture and muscle deconditioning [8].

The isolation analogs test the psychological consequences of confinement in a small habitat for a long time. This type of analogs is placed in extreme environments here on Earth, like the Polar regions or the desert, to simulate the harsh conditions that can be found on another planet. These structures can also be located in controlled environments, that are specifically built to replicate the conditions of space and the various steps of a mission [8].

Testing with analogs is crucial for space exploration as it can mitigate risks during missions and can provide useful information to improve technical and practical aspects of the habitats.

There are several examples of analogs that try to reproduce other planets' environments, among these there are: HI-SEAS and EURO-M.A.R.S. [9].

HI-SEAS is an acronym for Hawaii Space Exploration Analog and Simulation, it is a dome-like structure, developed over two levels and it intends to simulate missions on Mars. For this reason, it is located in an environment with similar conditions to the ones on Mars. The location site is Mauna Loa volcano on the Big Island of Hawaii. It is used to perform isolation mission that reproduce what one day will happen on a Mars mission [10] (see Fig. 4).

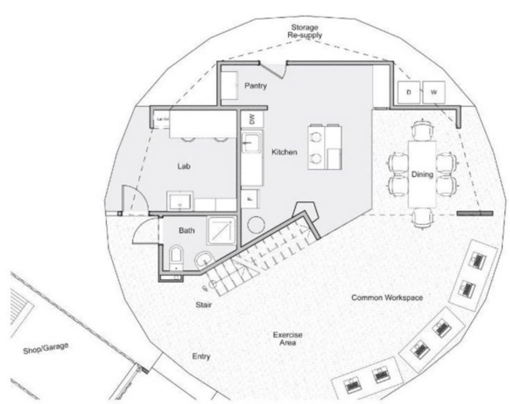

Fig. 4. HI-SEAS ground floor [11]

EURO-M.A.R.S., acronym for European Mars Analogue Research Station, is a cylindrical analog habitat with three levels. It is a living and working habitat that works as a simulator for missions on Mars. EURO-M.A.R.S. can host 6 people and its proposed location is the Krafla region in Iceland, due to its similarities to Martian geology. Unfortunately, because of lack of funding this project was not built, however it can be considered a good example of isolation analog [9] (see Fig. 5).

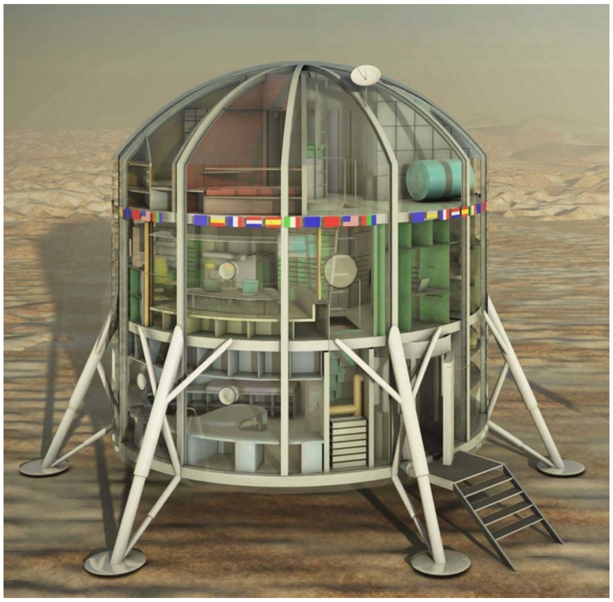

Fig. 5. EURO-M.A.R.S. interiors [9]

1.4 Computational design in the Aerospace field

Computational design is a tool that uses algorithms and parameters to elaborate models, therefore starting from a set of instructions some design solutions are automatically generated [12]. It differs from Computer Aided Design (CAD) because CAD is used as a digital support for technical drawings, while computational design can calculate design solutions itself.

CAD can be described as a digital blackboard, which helps speeding up the actual drawing representation part of the design, nonetheless it does not process solutions as a computational software does [13]. CAD was first born in the late 1950s with the Sketchpad system invented by Ivan Sutherland; in the 1980s CAD programs started being accessible on the market. The introduction of these tools was a turning point in the architectural field. A step even further was made in the 1970s when for the first time the use of computation for building performance simulations was taken into consideration [12].

Computational design is an even more powerful tool than Computer Aided Design and it is especially useful for complex projects, since it allows to make alterations to a model in a simple way, and it automatically computes the results. On the other hand, CAD is a more time-consuming design aid: making changes to a model using CAD programs can take more time and can deliver imprecise results, while a computational design software conveys a higher level of precision [14].

Using computational design programs in the aerospace field is a clever strategy to tackle highly complex projects, that require automation and optimization to reduce the time of the design process and to obtain solid and precise structures. Optimization can be easily achieved using a computational design software, such as Octopus [15], and it helps computing optimized design solutions that deliver a perfected project, which respects some given inputs.

Besides optimization another advantage of computational design is the possibility to continuously analyze the model, rather than keeping the design and analysis processes separate. Therefore, the model can be built, and data can be input and extracted at the same time. This can be done because these programs discretize in real-time geometries into meshes, whose purpose is to describe the model with a set of equations which can be solved in a computational way [14].

2. Material and methods

The research goal set for this paper is to develop a computational design tool that can be applied in the aerospace field to improve and optimize the interiors of a space architecture project.

To achieve this goal some steps have been followed:

1. Analysis of the existing literature about space architecture, lightweight materials, and computational design; this is needed to comprehend what this field has offered since now and which are the main points that a space architecture project must cover.
2. Collecting examples of space analogs to later compare them to the proposed project and take them as examples of future applications of the novel digital tool.
3. Defining requirements for the mission, to establish a set of parameters for the project.
4. Developing a Grasshopper model, using Kangaroo as a form-finding tool and Octopus for a multi-objective optimization.
5. Defining the optimized interiors with a specific computational strategy.
6. Demonstrating how the digital tool developed in this research can benefit the design of other projects in the future, with a special highlight on space analogs, as the ones described in paragraph 1.3.

3. E.L.L.E. an Extreme Livable Lightweight Environment

Designing in an extreme environment introduces many challenges, therefore it is necessary to build a set of requirements.

E.L.L.E. is an acronym for Extreme Livable Lightweight Environment and it is an inflatable habitat designed for Mars.

The primary objective during the design process is to create a safe and comfortable environment, that considers the physical and psychological needs of the crew that will inhabit the settlement.

The first step consists in the definition of some key words that identify the main themes of the project:

- inflatable;
- lightness;
- compactness;
- safety;
- redundancy.

Is it also necessary to specify the requirements that the project must respect: the habitat will need private spaces for each crew member, rooms dedicated to leisure and physical training, workstations, hygiene areas, an infirmary, dressing rooms for Extravehicular activities (EVAs), a galley, a kitchen and storage spaces. The system should also have a good level of self-sufficiency, since the habitat will be far away from Earth, and it will not be possible to send supplies on a regular basis.

Due to the hostile characteristics of the environment the habitat will need a Life Support System (LSS) and airlocks to go outside. Aspects like compactness and minimization of the mass are important, because of the payload capabilities of the launch vehicle and consumption of fuel. Therefore, minimizing the weight of the entire system is crucial to get a habitat with a higher volume and a minimal mass, and thus also lowering the economic costs.

For this reason, the inflatable technology seems to be the best option for this kind of project, since it is a lightweight structure and during transportation it occupies a small volume, that increases after its deployment once arrived on site, thus providing a habitat with a larger livable space.

3.1 E.L.L.E.'s inflatable shell

As previously stated in the last paragraph, E.L.L.E. is an inflatable habitat and it is intended for a mission of 600 days for a crew composed by 6 people.

A significant aspect of the project is represented by the selection of the materials that will constitute the entire system. Due to payload capabilities of the launch vehicle and to the need to limit the economic expenses, it is necessary to conceive a technological system which can withstand these problems.

For this reason, E.L.L.E.'s inflatable shell is made of lightweight materials. It is a multilayer structure, with an inner layer, a bladder, a restraint layer, a protection layer against micrometeoroids and debris, and finally a layer that guarantees thermal and radiation shielding. Respectively, the layers are made of Nomex, nylon laminate combined with ethylene vinyl alcohol, Madflex, Vectran joined with Duocel and Kapton combined with Cermex (see Fig. 6). These materials provide protection against radiation, low temperatures, different pressure and micrometeoroids and debris [16].

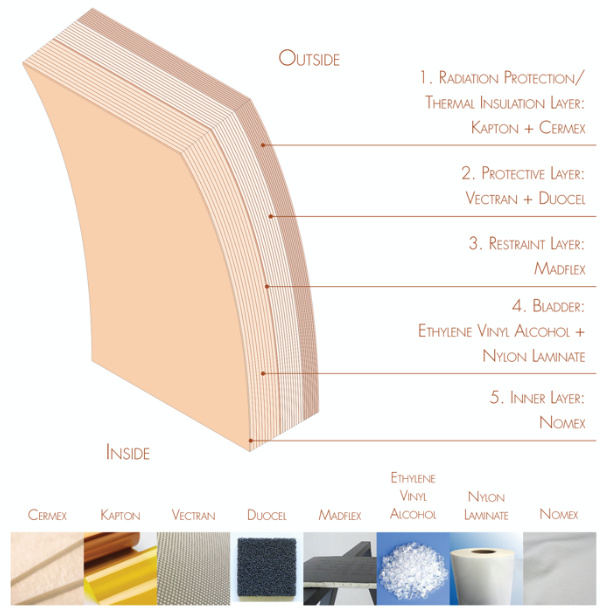

Fig. 6. E.L.L.E.'s inflatable shell

A crucial aspect to keep into consideration while defining the composition of the shell is redundancy. This means that the same object is duplicated for safety reasons, so in case one of them fails there still are those critical and vital components that guarantee a sufficient level of performance of the system. Indeed, to achieve full cosmic radiation and solar flares protection for a long-term mission on Mars, a further Martian regolith shell of about 1.5 meters of thickness will have to be built on top of the inflatable structure.

3.2 Computational design strategy

The 3D model was built using some plugins that work inside the Rhinoceros environment: Grasshopper and Kangaroo 2, which is a Live Physics engine for simulations, form-finding and constraint solving.

The model was realized by first starting with a simple flat geometry, a circle, whose inputs are defined by the optimization process, which decides the size of the habitat.

The external shape of the shell is a result of a form-finding process in Kangaroo. Inside Kangaroo's solver some important data is entered: the tensile strength of the inner layer of the shell (Nomex), which corresponds to 340 mPa, the anchor points of the structure and the internal pressure that is set to 0.6 Atm. Kangaroo simulates the inflation of the structure and it elaborates a mesh, which is then smoothed with Weaverbird, a plugin that provides useful tools to manipulate meshes.

After the smoothing process, the mesh can be closed and a thickness value can be associated to the mesh, thus simulating the layer composition of the shell (see Fig. 7).

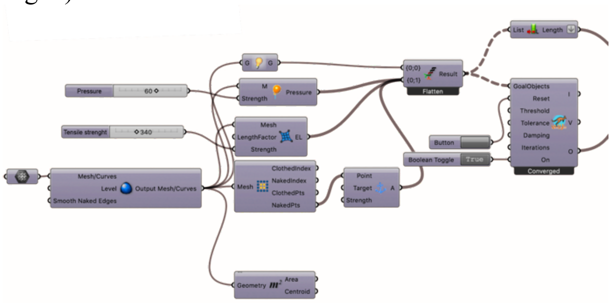

Fig. 7. Kangaroo script

After the form-finding process, the internal layout is generated. Some offsets are made to create the corridors and the central room dedicated to the greenhouse. The circle that was created as a base to start the model is divided into slices to generate the subdivisions between rooms. At this point there are lines intersecting one another, not all of these are needed to draw the plan, so some of them are trimmed. Another offset creates the thickness of the interior walls. Going from 2D to 3D is achieved by creating a surface from the lines of the walls and then extruding them for the entire height of the level.

Openings for doors are made with Boolean operations: intersections between solids produce openings for doors by using a subtraction operation, an addition operation creates the elements that will fill the holes created during the previous operation, thus obtaining doors.

The furniture is entirely designed in Grasshopper, so that its parameters can be changed, and it can potentially be adapted to different needs (see Fig. 8).

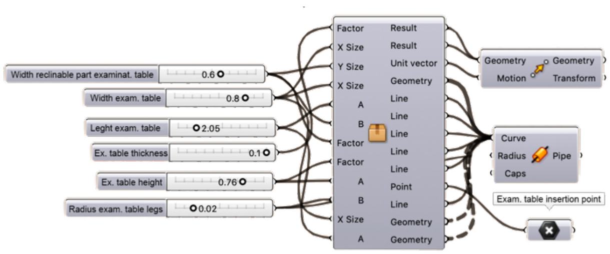

Fig. 8. Script of the furniture

Every piece of furniture is placed in the correct room thanks to an anchor point that fixes the placement of the object to a certain point of the room.

Everything in the model is built using Grasshopper algorithms, the purpose of this is the creation of an easily manipulable geometry, with specific relationships between every element. Therefore, a circular strategy was created: the model and its connections between parts are established, the optimization process in Octopus changes the shape and the organization of the internal layout, and consequently the walls and the furniture automatically rearrange themselves and create an optimized and complete new version of the project.

3.3 Multi-objective optimization

The peculiarity of this research stands in its optimization phase that helps developing the digital tool for parametric interior architecture.

The habitat was modeled using an algorithmic modeling software called Grasshopper and optimized with Octopus, a multi-objective evolutionary optimization program.

Optimizing the model allows to calculate different options starting from a set of objectives, and therefore the trade-off solution between requirements can be easily identified so that the project achieves its best version, and it is a more suitable option with respect to the objectives.

The first step of the optimization process consists in establishing the requirements. For this project, obtaining a compact and low-mass habitat is important. The interiors should provide enough livable space, while maintaining a certain level of compactness. These goals can be achieved by setting some objectives, that combined can deliver the optimal solution, which is compact and livable at the same time.

Octopus allows to input objectives of maximization or minimization, so the selected goals for the optimization process are:

- maximizing the compactness,
- maximizing the floor surface,
- maximizing the number of rooms,
- maximizing the distance between the walls of the rooms.

Having a higher compactness means that less materials will be used to build the habitat, and the entire system will be smaller. However, this objective alone cannot give the best solution as an output because the higher level of compactness does not necessarily coincide with an appropriate interior livable space, that contemplates the psychological repercussions of living in small spaces for a long time. Therefore, adding the second objective is necessary, since it balances the effects of the first one: increasing the compactness tends to shrink the structure, while maximizing the floor surface expands the module.

The same logic is applied to the interiors: the purpose is to get more rooms, while expanding the distance between them, thus giving as a result as many rooms as possible with a decent livable space.

Compactness is calculated by subdividing the surface of the habitat and the volume, the floor surface corresponds to the walkable area, the number of rooms is established by the number of slices subdividing the floor area and the distance between the walls is calculated by measuring the distance between the slices.

This data is put into Octopus, together with the mesh that the program must interact with. By launching the simulation some calculations are elaborated and solutions are developed.

The results of the computation inside Octopus are represented by Pareto front diagrams, which contain the set of the solutions considered optimal by the program.

The objectives are improved as much as possible, and the solutions displayed in the Pareto front represent all possible design configurations.

So, each solution is a trade-off between the conflicting objectives and respects in different ways the objectives as the solution changes.

By using Pareto front diagrams, it is possible to extract a trade-off solution amongst the different goals, this way the selected option will be the one that gives the same relevance to each objective (see Fig. 9-10).

The result of the optimization process is a certain design solution with specific parameters, and it will be used to develop the next stages of the project.

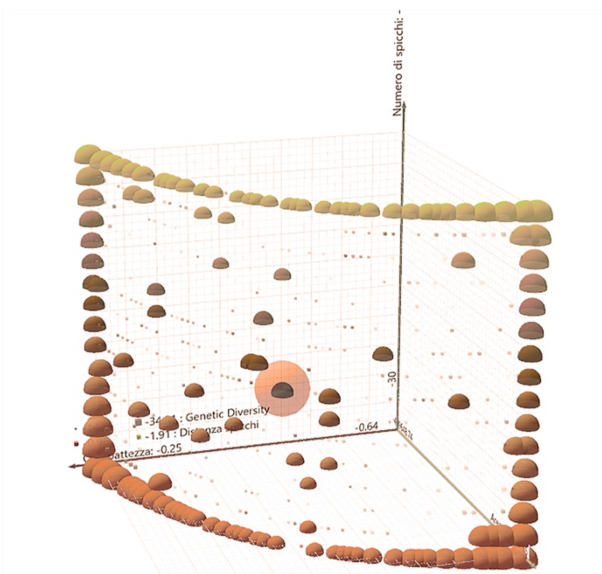

Fig. 9. Pareto front diagram with trade-off solution selected

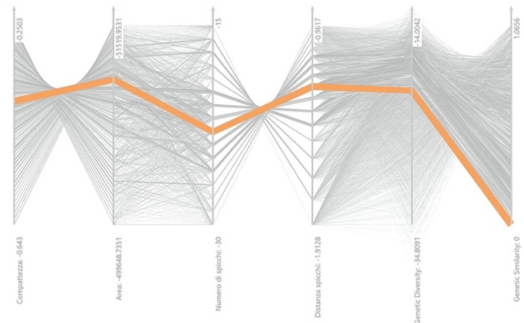

Fig. 10. Pareto front diagram with trade-off solution selected

3.4 Interior design of E.L.L.E

The psychological component plays a significant role during the design process of a habitat for an extreme environment. The astronauts that will be part of the crew will have to face a long journey to Mars and a stay in a place extremely distant from Earth, rather hostile, in isolation and with a small group of people.

It is necessary to know the possible problems that a long isolation can bring out and what stratagems can be adopted to reduce them, by designing spaces that help the crew remain in a comfortable situation.

The different factors that describe the meaning of habitability change drastically according to the circumstances: being in a state of poor comfort for a limited period almost does not cause negative effects on people's psychology, however, when the time interval increases, health can be affected.

One of the main aspects for this matter is the relationship between the environment and the individual, these must be conceived as a single organism, whose parts work well together. It is essential to know in advance what problems could arise between the individual and the environment and make intelligent architectural choices which may help avoiding them.

After the quarantine periods experienced by the whole world during 2020 and 2021, due to the COVID-19 pandemic, everyone has now an idea of what it means to remain in isolation and what are the elements which contribute to worsen the psychological balance of people.

The space available inside the habitat is certainly very important, as is the separation of functions.

During lockdowns, billions of people were forced to work or take school lessons from their homes. Bedrooms were transformed into offices, school or university classrooms, meeting rooms and gyms, thus generating some confusion between different activities. Mixing functions in the same place can lead to a state of oppression and a sense of sadness and dissatisfaction, hence it is crucial to ensure these divisions between the activities, giving each function its own space [17].

Another element noted during the experience of confinement at home is the great importance of the relationship with the external environment. During quarantines many spent a lot of time on balconies and/or in the gardens of their homes, demonstrating that the connection with the outside environment is essential to live in a healthy and peaceful way.

The interactions between crew members should also be considered because forced cohabitation can lead to conflicts if there is not a right balance between privacy and sharing. The choices made throughout the designing process must be led by the need to create this equilibrium, realizing both spaces dedicated to social activities and spaces for private matters.

The ability to decorate and customize the environment in which people live affects the mood of individuals, for this reason even a habitable module on Mars must guarantee the possibility for each crew member to add personal items to their quarters, thus being able to feel comfortable in a place that will be their home for a long time.

E.L.L.E. is organized over two floors, both levels have a central circular room dedicated to a greenhouse and a staircase that connects the two levels. The greenhouse is a fundamental function in this type of project: due to the long duration of the mission it is essential that the system has a certain autonomy, the greenhouse satisfies this requirement allowing to grow products directly on the planet.

The circulation system of the ground floor (see Fig. 11) is simple: there are two corridors which allow distribution into the rooms, the first surrounds the central room, while the second runs along the boundary of the inflatable shell. Furthermore, the ground floor is directly connected to the external environment thanks to the two lateral airlocks, both preceded by two dressing rooms, used to prepare for the Extravehicular Activities (EVA).

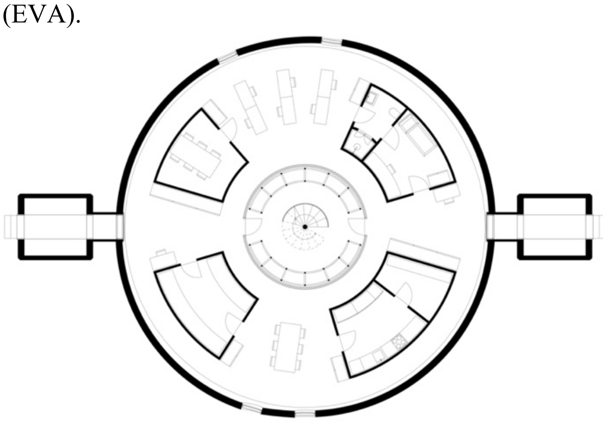

Fig. 11. E.L.L.E.'s ground floor

In the upper half of the plan there is an area dedicated to work, a bathroom and an infirmary. The work area consists of an open space where there are six workstations, one for each crew member; in this area there is also a meeting room, separated from the rest of the environment, to assure a higher level of privacy for certain work activities. The open space is directly connected to the bathroom, located here to facilitate the access from the work area. Near the bathroom there is an infirmary, accessible from the bathroom and from the dressing room.

In the lower half of the plan there is a deposit, which also contains the life support systems needed to guarantee the survival and the well-being of the crew. Next to this room there is the galley area, equipped with a table that can be occupied by all the crew members at the same time, this interfaces with a separate room that contains the kitchen, which is connected to a deposit for food supplies.

On this floor there are four openings that allow the view of the external environment, all strategically positioned.

The presence of the portholes is vital, as it allows the crew to establish a visual connection with the outside world, thus improving their experience inside the module.

The absence of openings could cause a sense of oppression, claustrophobia and disorientation. To avoid these effects, the portholes (see Fig. 12) are located in the dining area and in the open space of the work, so that the astronauts can look at the external environment while performing their daily tasks.

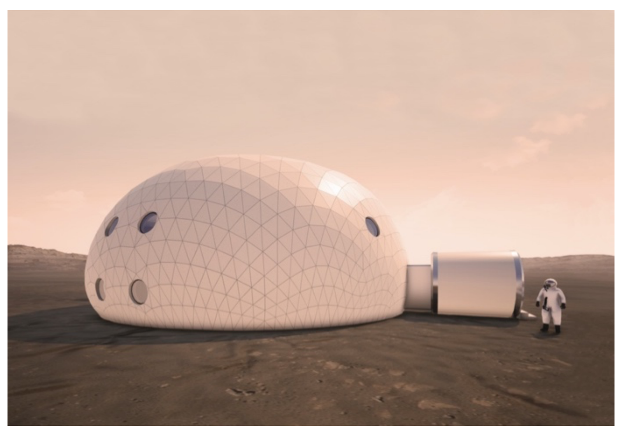

Fig. 12. Rendering of E.L.L.E.'s exteriors

The greenhouse is made of transparent walls, which allows one to see the plants that grow inside the room, creating a relationship between the other living spaces and the greenhouse.

The first floor (see Fig. 13) has a distribution system similar to the one on the ground floor, there is in fact the same central corridor that runs along the perimeter of the greenhouse, however there is no external corridor, as it would not be usable, due to the recess of the walls of the inflatable.

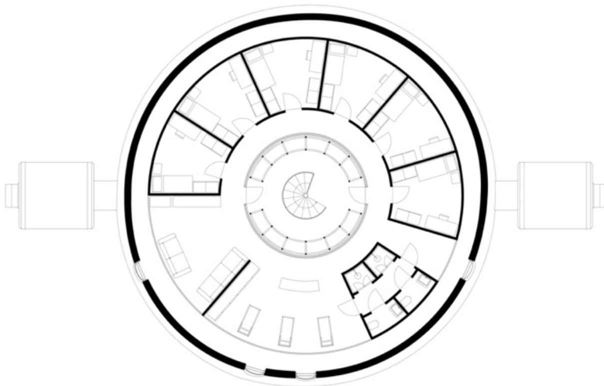

Fig. 13. E.L.L.E.'s first floor

This level is dedicated to leisure activities. There are six personal crew rooms, each equipped with a bed, a desk and two wardrobes for storing personal effects.

Next to the bedrooms there are two bathrooms, with two toilets and two showers. The bathrooms are directly connected to the gym, where there are three treadmills, six lockers and a piece of furniture intended to contain sports equipment.

Lastly there is an area dedicated to leisure, which is in the zone adjacent to the gym. Here are two sofas, a television, and shelves for storing objects for recreation purposes.

On the first floor there are four portholes, placed in strategic points: two are in the gym, thus allowing the establishment of a visual connection with the outside environment during training, one is located in the leisure area and the last one is placed in the interface area between bedrooms and bathrooms.

On both levels, some functions are situated in rooms physically separated from the others by walls and are therefore accessible only through the doors. Other activities are not separated from the rest of the space by the walls but are still spatially defined and independent.

On the ground floor the rooms treated this way are the work area, the galley, and the dressing rooms, while on the first floor only the gym and the leisure area are set up like this. These two spaces overlook directly on the external corridor on the lower floor (see Fig. 14).

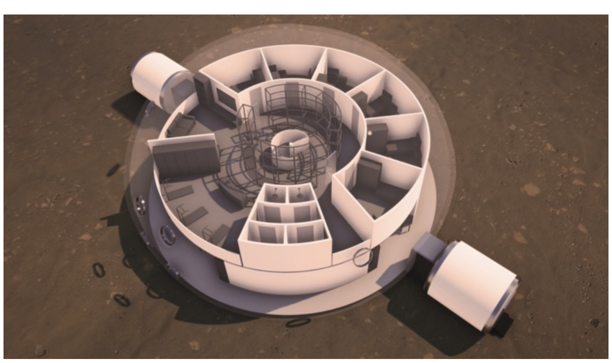

Fig. 14. Rendering of E.L.L.E.'s interiors

The material aspect is also important during the interior design phase because the internal walls must be made of lightweight materials in order to not negatively affect the transport phase due to their excessive weight. Therefore, the technological system developed for this design step consists of carbon fiber facing sandwich panels, assembled on a supporting structure made of aluminum [18].

4. Results and Discussion

The digital tool created during this research involves optimization techniques and is completely controlled by algorithms, so it is circular design strategy whose application could be extended to several other space architecture scenarios.

In fact, the very purpose of the project is to develop a methodology that can be repeated and applied in other projects, to improve the design process and provide an automated circularity of the process.

An interesting field of application of this digital tool could be the one regarding space analogs.

As described in paragraph 1.3, analogs are used to test physical and psychological responses to space missions. Therefore, these structures could also be a test run for the digital tool developed in this paper.

In Fig. 4 we can see the ground floor of the HI-SEAS analog. The interiors of this structure could go through an optimization phase similar to the one described in paragraph 3.3, this could improve the layout distribution and create spaces that host other activities, that could not fit in the original layout.

The purpose is to get the best result from what is initially given, to take the maximum advantage of the available space, in such a manner that there is a minimal waste of resources.

5. Conclusions

In this paper a computational design tool for space architecture interiors has been developed.

The research has shown that computational design in space architecture has many advantages compared to traditional design methods. The multitude of variables involved in a space architecture project requires a high level of adaptability, control, and precision. Indeed, computational design plays a relevant role since it can also be used to create replicable strategies, that will enrich the field and future concepts.

E.L.L.E. is an example of how space architecture projects can be computationally designed and optimized, its aim is to identify a methodology and a circular strategy that this kind of projects can follow.

The application of this digital tool on analogs could also be interesting to test the strategy itself and upgrade it according to the eventual results of an analog mission.

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