AIAA Propulsion and Energy Forum
19-22 August 2019, Indianapolis, IN
AIAA Propulsion and Energy 2019 Forum

10.2514/6.2019-4059

Mars Garden: an Engineered Greenhouse for a Sustainable Residence on Mars

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As global interest in deep space exploration rises, new mission architectures and new dwelling solutions must be sought for to accomplish longer and safer permanence in space. Less dependency from Earth supplies, better psychological and physical conditions for the astronauts, higher safety and lower energy and resources consumption are the main requirements for such missions, and must be matched and experimented from the very beginning of human deep space exploration. To address this same need for higher feasibility and sustainability, the paper proposes a novel design for a greenhouse module that can supply 100% of the food required for a crew of four astronauts on an extended mission to Mars, while also providing physical and mental health benefits for the crew members. The module accomplishes this by maximizing space and minimizing mass with a novel spiral system within an inflatable, cylindrical shell designed to protect astronauts from harmful radiation. Crops, which supply the food for the crew, grow in modular hydroponic trays that descend from the top floor of the module along six spiral tracks. The lighting, temperature, nutrient supply, track length, and vertical separation of each spiral is matched to plants growth patterns and needs, thereby maximizing volume for growth, optimizing growing conditions, and providing isolation in case of disease.

I. Introduction

In recent years, a renewed interest in Mars colonization, channeled into a variety of programs developed and supported by worldwide private and public space agencies, is boosting the effort for the exploration of the Red Planet through both unmanned and manned missions [1]. NASA's Mars Exploration program [2] and Journey to Mars vision [3], ESA's Aurora program [4], the Starship / Superheavy System by SpaceX [5] stand out as the largest and most ambitious of ongoing plans, including and forecasting multiple steps of technological and scientific development. The lack of sustainability in proposed extra-planetary dwellings is one of the key aspects preventing the feasibility of space exploration: reliance on Earth supply for sustenance and maintenance needs implies too high risks and too low sustainability for the purpose of deep space exploration missions. When focusing on the human exploration of Mars, In Situ Resource Utilization (ISRU) can grant the needed self-sustainability and self-sufficiency of a mission system, with astronauts relying on the use of local resources such as water, air, nutrients and light as the basis for on-site energy and food production. The colonization of Mars opens up a broad spectrum of opportunities for the development of novel technological solutions to support human life in unconventional environments: solutions that might also be adopted for a more sustainable and safe life on Earth.

This paper proposes an innovative space habitat concept that combines a residential module and an original greenhouse module which are integrated in a near closed-loop ecosystem to support human life on Mars. Figure 1 show the integration of the two habitats. The residential module is the Mars Ice Home designed by NASA [7]. The greenhouse module is a novel concept proposed in this work and specifically developed to address the critical dependence from Earth supplies characterizing current space exploration, together with the poor physical and psychological conditions of astronauts. To achieve these goals, our greenhouse module combines three key elements: (a) a crop cultivation system through hydroponic technologies, (b) the optimal use of internal space through a unique helical internal layout that optimizes space usage, and (c) the integration of technology solutions chosen and adopted by NASA in the Mars Ice Home program, to guarantee full compatibility and efficient coupling with the design solutions developed for the residential module, such as the implementation of an ice layer for radiation shielding. The design of the greenhouse module addresses the choice and cultivation of crops, the internal and external layout of the module and its systems equipment and integration. It therefore requires the coordination of multiple expertise from a variety of domains including nutrition, psychology, ecology, materials science, systems engineering, waste and energy management.

This work presents and discusses our original design proposal through three main aspects that synthesize the different constitutive elements: Ecology, Architecture and Systems Engineering. Ecology addresses the sustenance requirements of the crew and the growing methods of plants in the greenhouse. Architecture describes the external and internal layout of the module, including its structure, materials selection, and deployment systems. Systems Engineering details solutions for artificial ecosystem creation, thermal and radiation shielding, environmental control, In Situ Resource Utilization (ISRU), and maintenance of the designed greenhouse module.

The work presented is an international effort of two research teams based in Europe (Politecnico di Torino and Politecnico di Milano) and the United States (Massachusetts Institute of Technology). The collaboration led to the multidisciplinary project "Space Architecture for Extra-planetary Exploration" (SAEXE), funded by Alta Scuola

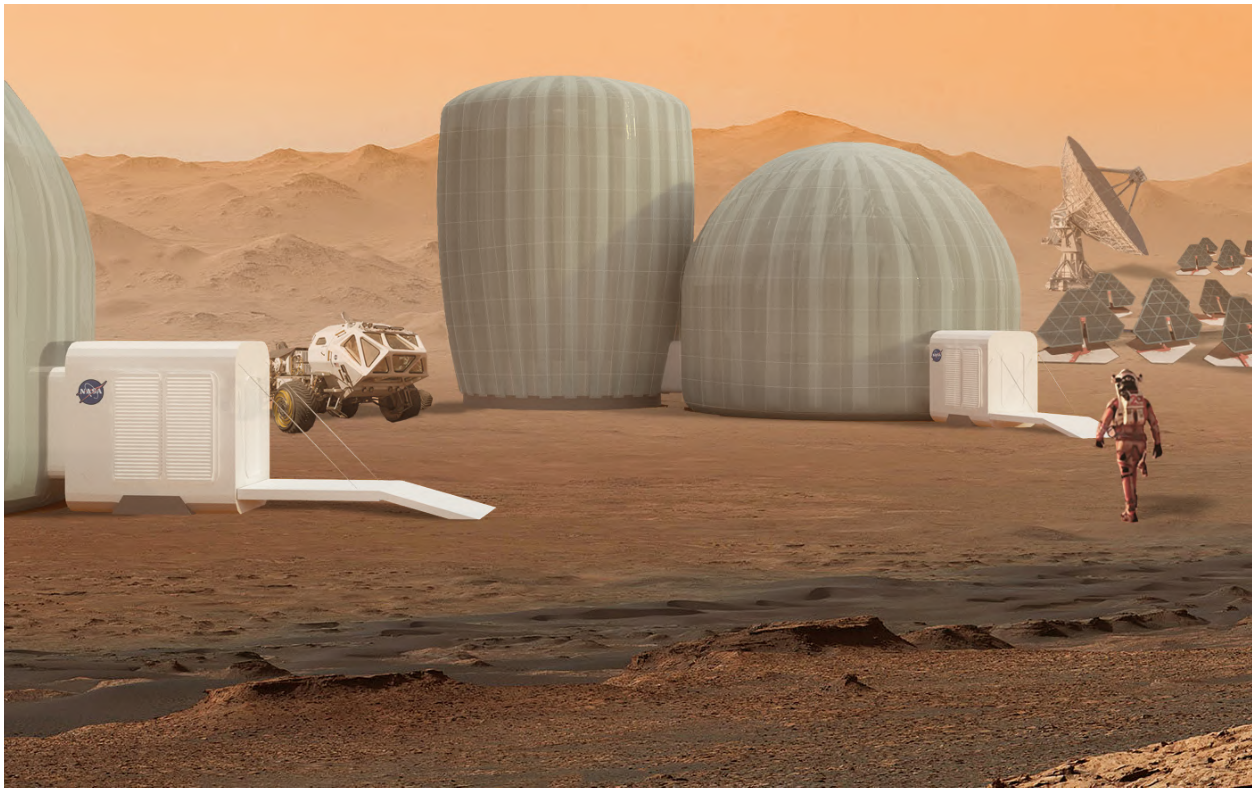

Fig. 1 Render of the proposed greenhouse module integrated with the NASA Ice Home

Politecnica (a leadership excellence program of the two Italian universities) and the preparation of the "Biosphere Engineered Architecture for Viable Extraterrestrial Residence" (BEAVER) proposal submitted and awarded by NASA in the Big Idea Challenge in 2019. For the cross-mission effort and for all the requirements taken into account, the proposed design is aligned with an internationally shared road-map towards Mars colonization.

Section II of this paper recalls and discusses design objectives, requirements and constraints. Section III introduces the concept of operations for the mission, Section IV describes the greenhouse module concept, and Section V illustrates models, trade-space and results that motivated the design choices. Finally, Section VI makes concluding remarks and provides an outlook on the concept's future developments.

II. Objectives, Requirements and Constraints

Requirements and constraints defined for the presented concept are associated with the need to grant a higher level of self-sufficiency to human missions to Mars through on-site food production, to increase mission feasibility and safety, as well as to safeguard the psychological and physical well-being of the astronauts during a long-term stay in space. Structures and systems are designed to survive each phase of deep space travel, from launch to landing and deployment, while also providing maximum functionality for mission operations. Mass, loads, energy and resources consumption are minimized to reduce reliance from Earth and fully support a long term mission. The design is developed through the application of principles of Ecology, Architecture and Systems Engineering.

Ecology Sustaining human life on Mars means providing reliable and complete nutrition to the crew of astronauts. Therefore, the plants to be harvested in the greenhouse have to fulfill nutritional requirements, provide steady yield rates, and stay healthy. To fulfill nutritional requirements, the crops must provide a balanced diet with an average of 2,700 calories per person per day [8]. Plant health is also of vital importance and, while it cannot be guaranteed, must be maximized with respect to both Mars micro-gravity [9–11] and the spread of disease. Moreover, the growing system itself needs to assure crops grow efficiently and reliably and must be space efficient, in order to maximize productivity and minimize material delivery from Earth. Finally, a balance between human labor and automation to complete tasks must be sought; a more automated system reduces the labor requirements of the astronauts but increases system complexity.

Architecture The key drivers of the design of space architecture are structural needs, functional needs and human needs. In a low-pressure environment, vertical loads become minor constraints compared to internal pressure loads, especially when an inflatable structure is used. Therefore, the shape of space modules needs to be optimized to best carry perpendicular loads. Additionally, the internal layout of the greenhouse must be arranged to host as many crops as possible, while also allowing room for a recreational area to provide mental health benefits for the crew. The entire structure must also be designed for compression and expansion in order to match a limited rocket fairing space. Finally, the selection of materials for the interior must take into account each material's versatility, durability, strength to weight ratio, cost, and precedent in space use.

Systems Engineering Three primary drivers lead the proposed design of systems: environmental control system, efficient resource utilization and risk mitigation. The environmental control and life support system, the tailored and original architecture designed for human well-being, and the adoption of automation technologies to enhance cultivation productivity make the greenhouse a physical and psychological healthy environment, realize a functional and ergonomic workplace, ease the intervention of the crewmembers, and foster human-machine integration. Sizing, supply, power demand, recycling and multipurpose systems are optimized to ensure an efficient use of the available resources. To mitigate the risk associated with malfunctioning and disruption, systems are designed to be multi-functional and integrated to achieve redundancy for all the critical functions.

III. Concept of operations

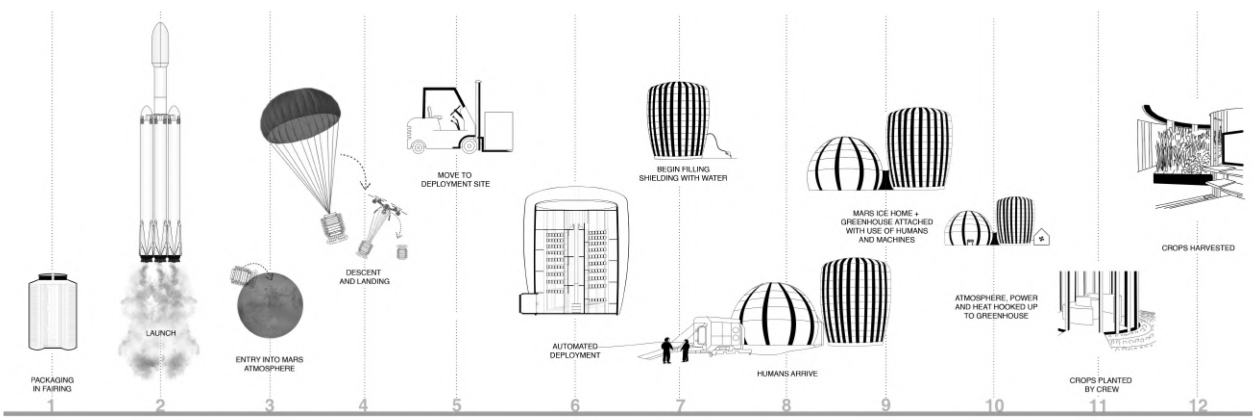

Fig. 2 Concept of Operations

Figure 2 illustrates a high-level ConOps for the greenhouse, which demonstrates the major steps of the launch, landing, and setup phases of the greenhouse. The system is initially put into its compressed state and packed in a 6.7 m diameter x 9.3 m height rocket fairing. This is consistent with the fairing size expected by future heavy launch vehicles [7]. It is planned to launch from the Earth and undergo a planned 6-month journey to Mars. The seeds are planned to be packaged and sealed to ensure their survival during the trip. Once the system reaches Mars, it is expected to undergo a heavy lander entry, descent, and landing (EDL) sequence. This is dependent on future EDL technology development, but will likely include a retro-propulsive landing. After landing, the packaged greenhouse is designed to be picked up by a robotic transport and moved to the Mars Ice Home site. The site area may be prepared in advance to provide necessary level surface for its placement. The transporter will have been pre-deployed on a previous mission in order to move the initial Mars Ice Home habitat into place. Once in place, the automated deployment sequence is set to begin and the greenhouse is planned to expand to its full size. Assuming the Mars Ice Home has already had its shielding filled with water from a nearby ISRU plant, the water feed line will be plugged into the greenhouse shielding to begin filling it with water.

A predetermined amount of time later (likely 26 months, to match optimal Earth-Mars launch windows), crew is expected to land on the surface of Mars. One of their first tasks, once they are able to move effectively about the surface, will be to attach the pressurized interface between the Mars Ice Home and the greenhouse so that they can move between the two modules without donning spacesuits. They are also required to set up the controls and power systems within the greenhouse to create a breathable environment, and assemble furniture, lighting, and piping to finalize the structural elements of the greenhouse. Once assembled, the place is designed to be configured as multipurpose area suitable for work, storage, food production, recreation and relaxation. Next, the crew is expected to begin planting seeds in the trays according to a predetermined schedule. The latter involves planting only a few trays per day in order to produce a continuous supply of food and minimize crop storage requirements. The crew is planned to perform maintenance tasks on the plants throughout their growth cycle, including pollination and pruning. Finally, when the first crops have reached maturity, the crew will begin harvesting and will transition from eating Earth-supplied food to Martian-grown food.

Day-to-day operations and maintenance of the greenhouse are planned to be kept to a minimum once the greenhouse is operational. The Module Operational Management System produces a Daily Task List for the astronauts based on the following input parameters: (a) the information about each tray's location, crop, and stage of growth, (b) input from the sensor network informing the state of each tray, and (c) how much time the astronauts are able to dedicate to crop management on this specific day. The manual tasks are those that cannot initially be completed by robots, or are planned as psychologically beneficial tasks for the astronauts; while some harvest tasks can be completed robotically, they are considered emotionally fulfilling and are therefore suggested to be completed by humans. The greenhouse tasks are planned on a day-to-day basis, but flexibility is included to allow tasks to be completed within a +/-3 day tolerance without impact. Maintenance is expected to be another labor requirement of astronauts. General maintenance on the pumps and electronics cabinets is planned to be conducted as necessary in accordance with a preventative maintenance schedule. When maintenance is conducted, the secondary system will be placed online first to ensure continued operation.

IV. Design Concept

The greenhouse is designed to integrate the NASA Ice Home prototype with a complementary food production module. The habitat implements a novel closed-loop hydroponic system to provide food support for a long-term extraplanetary mission. Its architecture is centered around an elegant and purposeful spiral that takes seedlings as inputs at its top and produces plants ready to harvest at its bottom. The heights between levels of the spiral increase as one moves down the spiral in order to match the growth of plants and thus maximize vertical space. The greenhouse is stowable in a standard rocket fairing and can autonomously deploy to a larger configuration able to produce enough food to meet 100% of the astronauts' nutritional needs. The module is designed to minimize the risks of structural and energetic failure, as well as plants disease spreading with redundant systems and simplicity. The greenhouse is also conceived to minimize labor, and maximize production.

A. Ecology

The selection of crops to be harvested in the greenhouse covers all nutritional needs of the crew and includes several archetypes of crops. Eight example crops are selected to be representative of 'families' of crops with similar growing needs: wheat, oats, rice, rapeseed, potatoes, peanuts, tomatoes and lettuce. Once on Mars, earth supply and later on-site production provide nutrients for the plants. Our concept incorporates a plant growth system based on a closed loop hydroponic network that relies on Martian water. The pilot study [12] of the ongoing Subsurface Water Ice Mapping (SWIM) project [13] has identified nearby parts of Arcadia Planitia region as being consistent with the presence of excess subsurface water ice, thought to be abundant throughout this entire region. Water for the greenhouse's shielding and hydroponic systems is planned to be harvested from Hydrated Minerals on Mars in the same way that it is harvested for the Mars Ice Home, at low rates over long periods of time. A water production rate of 0.125 m^3 per day, half of the Mars Ice Home production rate, is assumed to support the greenhouse system. Initially, this limited water is expected to be used to begin filling the ice shield starting from the top and to support plants growth in one track of the spiral. The plants receive nutrition through their roots via a thin film of nutrient solution [14–16]. Seeding is completed in a separate chamber of the greenhouse, and artificial wind or human intervention carry out pollination. A full-range, color-tunable LED system provides lighting for the crops, implementing an optimized blend of blue and red wavelengths capable of enhancing crops yields by greater than 10% [17–19] while still appearing as natural light to the human eye.

Disease prevention and mitigation are crucial to avoid the potentially catastrophic consequences of the loss of food production for the mission. Therefore, the hydroponic system is integrated with indirect safeguard methods such

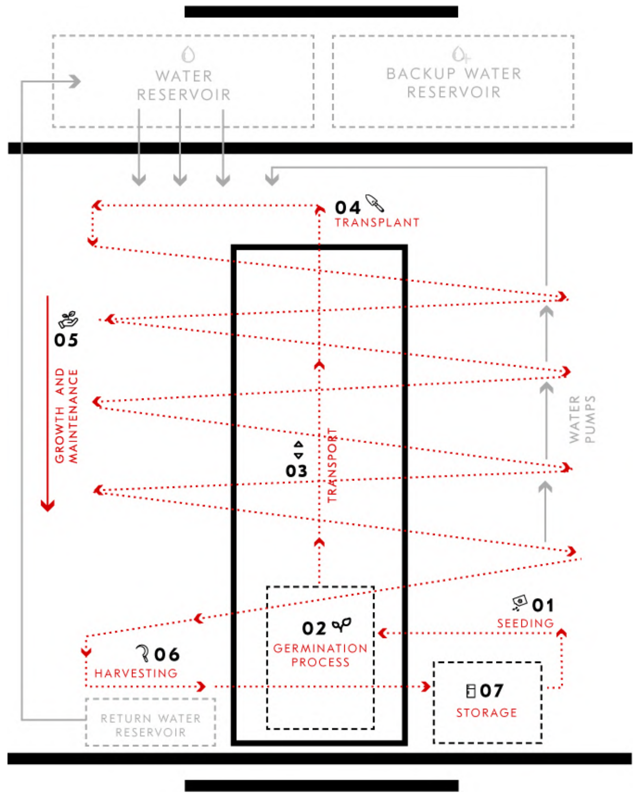

Fig. 3 Diagram of the closed-loop hydroponic network

as health monitoring (to be carried out through cameras for visual inspection and image processing algorithms for automated condition assessment), direct use of leaf protectant chemicals, and integration of growth medium additives to hinder the growth of parasites and fungi [20]. A pre-mission breeding program is planned to start a decade before the launch to Mars; similarly to what already experimented by NASA for the International Space Station (ISS), the breeding program allows for a principled selection and development of disease-resistant and highly performative lines of crops. Once genetics have been fixed, the lines will undergo several generations of isolated breeding (but without preventative fungicides) to identify and select out any genetically carried parasites and diseases.

Figure 3 illustrates a diagram of the designed hydroponic system. The use of a closed-loop system implies recirculation of the water medium and reuse of human and plant waste as a source of nutrition for breeding crops. Passive filtration systems, such as fine meshes and sand, sterilization through the use of UV-based technology [21] and reverse osmosis, guarantee a safe and efficient reuse of the nutrient solution. Urea, processed from human urine, is utilized as a nutritional supplement for older plants [22–25]. Biomass generated from the growing system is initially stored in an Isolated Composting Bin (ICB) located outside of the habitat structures, and can later be used as a source of chemically extracted nutrients.

Human intervention is integrated throughout the plant life-cycle, from seeding to pollination to harvesting, and includes manual tasks that cannot be completed by robots or are considered to provide psychological benefits to the crew. In total, the module requires less than one labour hour per each of the four crew members per day to maintain the crops.

B. Architecture

The greenhouse module has a cylindrical shape, with a reduction of the diameter at its base to decrease horizontal loads at ground support. As illustrated in figure 4 the structure is primarily based on a cylindrical core and two circular series of aluminum columns. The inflatable layers are attached to a top and a bottom aluminum plate. Two helical elements revolve around the module: a first inner track for growing plants; and a second outer ramp for crewmembers to move vertically within the two main floors of the module. Figures 5 and 6 show plan and section drawings of the greenhouse module. The ground floor is dedicated to the harvest and germination of plants and includes a work space

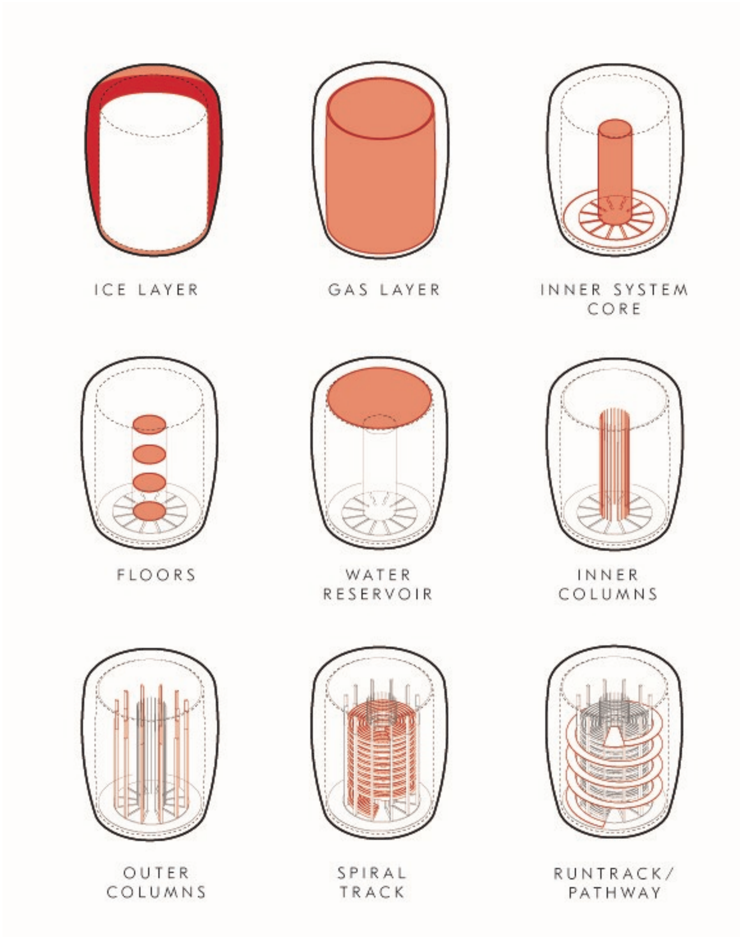

Fig. 4 Conceptual diagrams of the module

and areas for control and storage. The top floor is reserved for a relaxation area, combining additional space for plant growth with psychologically beneficial features such as a water fountain and lounge furniture.

The inner helical track optimizes productivity by working as a conveyor belt: crewmembers use trays to plant crops at the top of the module, and the trays slowly move down the track to the bottom via gravity and rollers, reaching the ground floor when plants are ready for harvesting. In order to optimize this solution, the distance between successive rounds of the spiral tracks decreases with height: at the top of the greenhouse when the plants are young and short, the spirals are close together vertically, while at the bottom when the plants are mature and tall, the spirals are farther apart. The outer helical ramp can be used for maintenance of the growing system and as a running track for the crewmembers. The ramp is inflated out of the module's shielding layers and attached to the outer row of columns. A short bridge connects the ramp with the human factors area at the top of the greenhouse next to the start of the helical growing track.

The core is the heart of the structural and functional system of the greenhouse. At ground floor, the core hosts a germination darkroom for seedlings, with two additional rooms for growing vine-like plants placed at mezzanine levels between the top and the bottom of the module. The remaining space contains ventilation, electrical and water systems, two platforms, LED lights, hydroponics for the crops and a small lift for transporting trays from the germination room to the top end of the helical track. A spiral staircase revolves around the core in order to provide an additional connection between the ground and top floors, grant access to the growing rooms, and allow for an easy and practical maintenance of the innermost portion of the helical track.

The design reserves space for working and leisure on both the top and bottom floors of the greenhouse. The space beneath the bottom revolution of the spiral contains two desks and two closets, with movable and expandable furniture and screens displaying information about the specific health condition and operation of the module. This space can, therefore, be adapted to fulfill the needs of the crew members, such as management of the crops, maintenance of

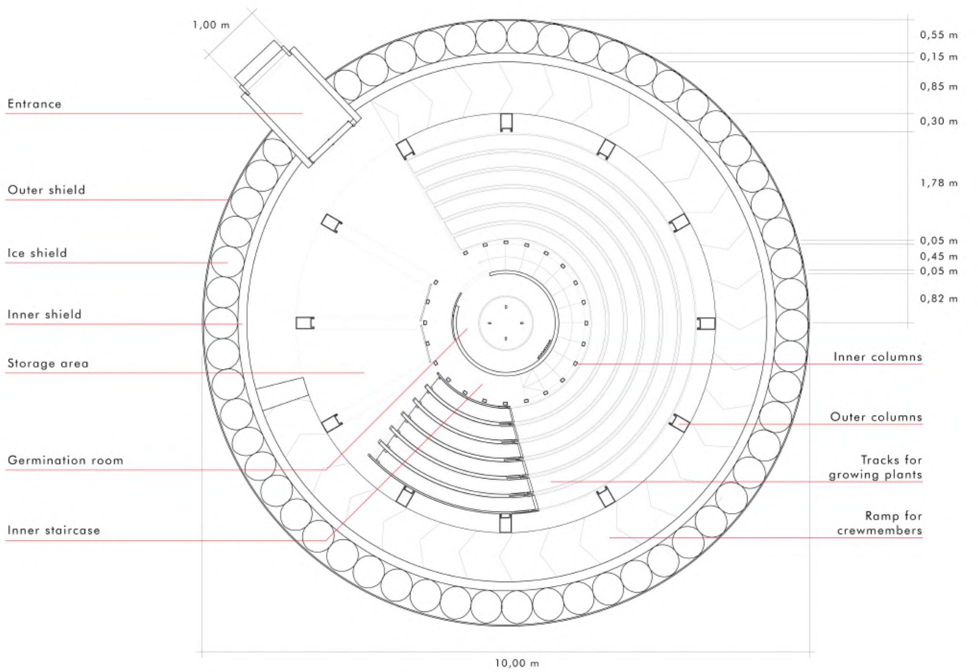

Fig. 5 Bottom floor plan of the module

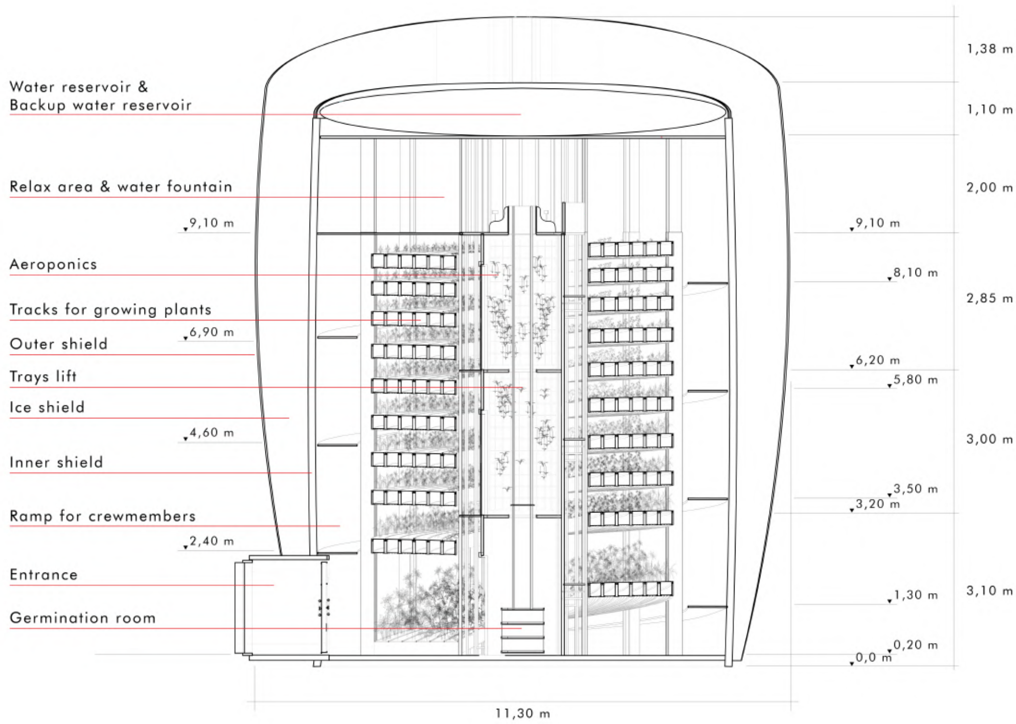

Fig. 6 Section of the module

the module, plant harvesting and seeding, providing also important psychological benefits. The top of the module is conceived as a quiet space for relaxation and intimacy of crewmembers. Above the inner core, an inflatable sofa, with embedded digital screens, is arranged around the core shape, allowing room for resting. Water pours from the water reservoir on top of the greenhouse into a fountain, which introduces a natural sound inside the otherwise artificial environment of the module. Then water flows towards the helical tracks to irrigate the hydroponic system below. Figures 7 and 8 show renders of the bottom and top floors of the greenhouse.

Fig. 7 Rendered image of the bottom floor of the module

The compression and expansion of the module are illustrated in figure 9. The deployment is completed through radial and vertical movements, exploiting the cylindrical layout of its structure. The module is packed in a 6.7 m diameter x 9.0 m height cylindrical volume to fit the rocket fairing space. The top portions of the inner core and of the columns are compressed, and the outer row of columns is slid towards the center of the module, leaving space for the folding of the shield layers. The outer spiral is deflated and folded together with the shield. The inner helix is compressed vertically and horizontally. After landing on Mars, the top portions of the inner core and of the columns are activated and expanded via a standard telescoping mechanism. The outer shielding layers and helical ramp are then inflated with air. The outermost circle of columns is pulled outwards to its original position, while also decompressing the inner helix. The ice shield is robotically attached to the water tank to begin filling. Once the structure is in place, the helical track is lifted into position with a controlled and remote activation of gas springs.

C. Systems Engineering

The system engineering design was strongly driven by the implementation of two different functions for systems, subsystems and components of the module. For instance, plants are used to produce food, but they also enhance the mental well-being of the crew and they recycle air; the relaxation area at the top of the module is also used for placing crops on the helical tracks; the led lighting system produces heat that is reused for maintaining environmental conditions of the module. Human and plants waste is reused for feeding crops, aiming at minimizing energy and organic material losses and generating a closed ecosystem for human survival in space. Pressure, temperature, air and light inside the

Fig. 8 Rendered of the top floor of the module

greenhouse are closely monitored to always assure the best conditions for the growing of crops and for the human presence in the module. An atmosphere control system grants air purity and provide O_2 and CO_2 exchange between the Ice Home and the greenhouse. NASA reports show that astronauts consume roughly 0.84 kg of oxygen and produce 1.00 kg of CO_2 per Earth day [26]. The module can use an averaged value of 32 grams of oxygen released per 150 g of plant tissue grown [27]. The greenhouse produces roughly 7000 kg of plant material each Earth year, which translates into 19 kg of biomass produced per day. This, in turn, means that it will produce 4.1 kg of oxygen per day. Using the stoichiometry of photosynthesis, the plants in the module will consume 5.6 kg of CO_2 per day. These calculations on the estimated production of the two gases by astronauts and crops suggest that the greenhouse is capable of producing 100% of the O_2 needed by the crew, while astronauts could provide up to 70% of the CO_2 for plants, complemented by the extraction of CO_2 from the Martian atmosphere using a scroll pump and compressor [26, 27]. The greenhouse atmosphere is expected to be monitored (H_2, N_2, Ar, O_2, CO_2 and other hydrocarbons level) in the inner volume fan room, which will house a fan for air circulation and an atmosphere monitoring system. The system will utilize mass spectrometry to quantify contaminants by ionizing gas molecules with an electron beam and sorting them in a magnetic field. When levels are known, solenoid-operated valves can increase or decrease levels as desired from gas banks. [28–31].

The walls of the greenhouse are filled with pure water ice from Mars, providing a shield whose thickness ranges between 1 to 2 m, depending on the specific requirements at each level: in particular, higher shielding thickness is designed for the top of the module because this area is the most exposed to radiation. The greenhouse and the Ice Home are connected by a dual pressure door system, granting isolation between the two atmospheres and protection from sudden depressurization. Pipes or cables positioned below the floor of the passageway that connects the two modules, parallel to the pressure doors and isolated with dual-redundant solenoid valves, allow the exchange of data, power, CO_2, O_2, heat, water, biomass and waste between the modules.

Fig. 9 Deployment of the module

V. Models and trade-off space studies

Extensive analysis and simulations were conducted to size systems and subsystems and assess their functioning and performance in an integrated manner. Trade studies were informed by numerical simulations to guide the identification of the architecture for the Mars greenhouse presented in this paper. A computational model is implemented and used to assess food production capabilities and minimize daily crew labor requirements. The model allows to quantify the space required by the crop growth, calculate the hours dedicated to man-labor, estimate the daily pace of the operational life of the crew and compute the yield and work hours. Trade studies are conducted to support decisions about the design solutions for systems and subsystems of the greenhouse module. Critical decisions include the identification of (a) the most appropriate growth system for crops, (b) the best shape and structural properties of the greenhouse module on Mars, and (c) the healthiest internal cabin atmospheric makeup. The power system used to support the greenhouse is also described along with its alternative, and risk mitigation strategies are discussed. At the end of this section, Table 5 summarizes the most significant alternatives considered in the design.

A. Crops selection

A variety of crops are selected in order to meet the nutritional requirements determined for the crew. Table 1 presents a breakdown of the daily nutritional needs estimated for a single crew member. A four-crew, 600 day surface mission is assumed based on an extended version of the Mars Design Reference Architecture from NASA. To identify the most suitable growing configuration and conditions for each plant species, crops were divided into four archetypal typologies: field crops, root-based crops, climbing crops, and leafy greens. A careful crop selection and planning operation, based on the coordination of different harvesting cycles, can grant a balanced diet to the crew while minimizing food storage requirements.

Calories: 2700 /day	Carbohydrates: 500 g/day	Proteins: 80 g/day	Oils/Fats: 140 g/day

Table 1 Estimated daily nutritional needs for a crew member

A computational model has been implemented in Python to assess greenhouse sizing and feasibility. Inputs to the model include sizing, growing duration, and expected yields of each crop. These inputs are based on numbers from standard agriculture on Earth. The model also takes input for labor tasks required to maintain the greenhouse. The team researched and created time requirements for seeding, pollinating, pruning, and harvesting each crop archetype. The model takes these inputs and combines them with the expected harvest times and required pollination cycles in order to output a daily labor requirement for the crew in man-hours. A flexibility factor was given to the various tasks, especially pruning and pollinating, in order to allow them to be delayed or completed early by 1-2 days in each case. This allows the model to 'smooth' the labor curve, so rather than having many tasks fall on one day and create a large spike in labor requirements, the model utilizes the flexibility factors to distribute the labor amongst the surrounding days. This avoids labor spikes. In addition to outputting labor, the model takes the volumetric requirements of the crops along with the required quantity of food to feed the crew and outputs a required growth space area. This determines the sizing of the greenhouse tracks. Figure 10 summarizes the outputs of the model. The results of the model demonstrate that the greenhouse design is both feasible and practical in terms of size and labor requirements. It predicts that an average of roughly three man-hours per day will be needed to maintain all crops in the greenhouse. These three hours can be distributed evenly amongst the crew if desired, resulting in less than one hour per crew member per day. It is important to note that the peak labor requirement on any given day is 3.6 hours, meaning that the crew should not expect any days that demand a significant portion of their time. Additionally, the model shows that the required growth space is 360 m^2, which is feasible in the greenhouse design. Both the growth space and labor requirements begin relatively low, ramp up to a steady state, and then ramp back down. The reason for the first stage of ramp-up is that the crops are assumed to be planted by the crew when they first arrive. The crew will steadily plant a few trays' worth of crops each day and add them to the spiral. This will result in a continuous and sustainable supply of food, as opposed to a scenario in which the crew plants the entire greenhouse upon arrival and then has a large harvest day several months in. That scenario would require large storage areas, which the team determined was a less ideal solution. As a result of this planned ramp-up period, there will be less maintenance and growth space required at the beginning of the mission. It should be noted that at least for the first crewed mission, the astronauts will have supplemental food brought from Earth to get them through this ramp-up period.

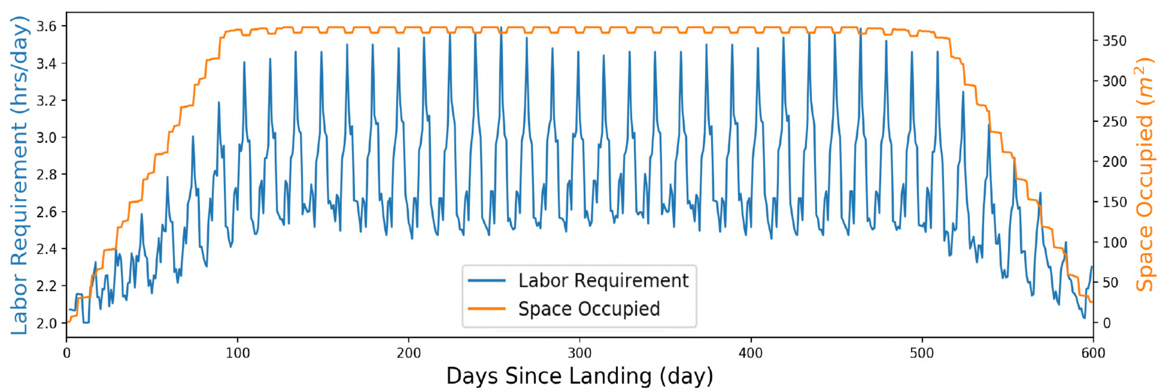

Fig. 10 Simulated labor requirement per day (blue) and estimated growing space required (orange) to provide full nutritional needs for a four-person crew over a 600-day mission

B. Growing system

Four harvesting typologies have been considered for this design: soil, hydroponics, aquaponics, and aeroponics. The idea of having a soil-based system was removed from the trade-space consideration early on due to technical difficulty and scientific uncertainty. The carrying of any growth medium from Earth increases launch loads and volume substantially [33]; alternatively, the use of Martian regolith introduces two significant issues: a high labor requirement for setup and increased risk due to the possible presence of toxic perchlorates in the planet's soil [34]. A hydroponic system overcomes the limitations and issues associated with both of these; in addition, hydroponic technology also grants higher yield rates and provides more rigid control of growth parameters such as nutrient concentration, medium pH, purity, electrical conductivity, and oxygenation [35]. Aquaponics, which integrates crop harvesting and fish breeding, could provide an additional source of protein. However, it was also removed from the trade-space due to poor fish response to microgravity [36] and the unknowns of transporting fish to Mars on long-duration missions. Lastly, aeroponics was also considered, as it has been shown to be conducive to root crops such as potatos [37]. Hydroponics was ultimately chosen over aeroponics because of its aforementioned benefits and the fact that it is a more established technology, resulting in lower mission risk.

C. Module shape

Among several shapes for the structure (including a torus, a sphere, a hemisphere and a modified cylinder), the latter is chosen as it provides a good minimization of surface area to the required greenhouse volume, while considering the structural effects given by the internal pressurization. The structure is inflatable since this option provides different benefits: less volume occupied when packed in the rocket compared to other rigid structures, less weight and the possibility to test it on Earth preventing possible problems that could happen on Mars. To evaluate the structural performance of the outer shell of the greenhouse as well as the internal core and spirals a final Element Analysis is performed. The overall algorithm is parametrically coded in Grasshopper and Karamba in order to explore and evaluate a variety of geometry and structural configurations in an automated fashion, and optimize sizing and structural properties of the greenhouse module. Figure 11 illustrates the Finite Element Model used for the analysis of the shell: the results show that the outer structure is subject to mainly tensile stresses due to the interior and exterior pressure difference of almost 1 atm. The maximum displacement on the membrane is on the order of 5 cm and is therefore acceptable given the maximum displacements that is usually required for roof systems (1/200 of the span – NTC 2018 and Eurocode 0), in this case equal to 7 cm. Moreover, the utilization factor show that the inflatable structure does not reach the yield limit of the used composite material (comprehensive of a bladder and Kevlar mesh). The results for the inner structures show a combination of compressive and tensional forces due mainly to the spiral geometry. The results indicate a maximum deflection of 0.219 cm on top of the cantilevered runway, that is acceptable given the limit of 1/300 of the span, prescribed by NTC 20018, that is equal to 0.8 cm.

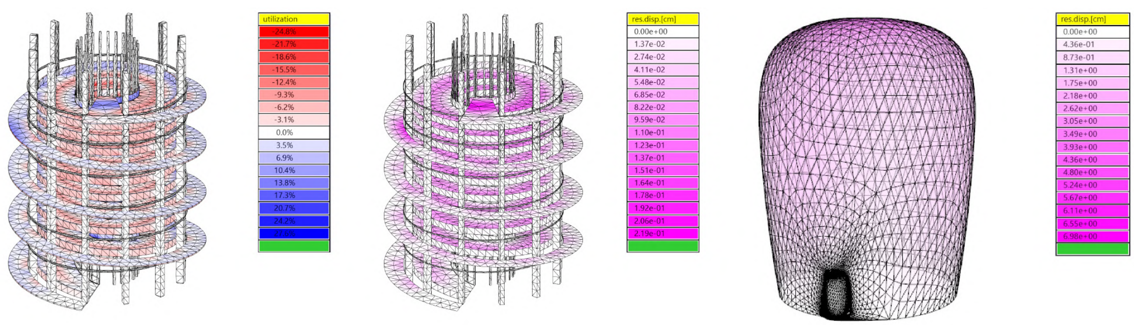

Fig. 11 FEA analysis of BEAVER CAD showing minimal levels of displacement

D. Materials

The greenhouse is designed with an outer structure similar to that of the Mars Ice Home, and integrates many of its systems. Consistently, the outer layers are built with similar materials, such as Beta cloth for covering, with the optional addition of Chromel-R for increased abrasion resistance [38]. The ice, insulation, and water bags are all made with Mylar, which has high strength and is impermeable to both gases and liquids. The interior structural layer is made with Teflon, chosen for its strength and low creep value, and the structure's inner bladders are made with high-density polyethylene (HDPE), which is puncture resistant and flexible at a wide range of temperatures. These levels of shielding are expected to reduce the amount of incoming radiation by between 40% and 60% [39]. Aerogel insulation acts as an additional barrier to the gas insulation layer to minimize heat exchange with the external environment. The interior of the module is made with a combination of plastics such as polypropylene, polycarbonate, and acrylonitrile butadiene styrene (ABS) [40, 41]. In particular, the spiral structures are made with polypropylene, chosen for its strength and flexibility [42]. Table 2 summarizes the materials chosen for the main components of the module.

E. Launch mass

The total launched mass of the greenhouse system, which includes the outer structure, inner spiral structures, central core, upper and lower floors, plant trays, LED fixtures, water and air circulation systems, life support systems, furniture, batteries, plant nutrients, and command and control systems is 11,822 kg. A mass breakdown is shown in Table 3 ??. Over 60% of the mass is from the structure of the system. Therefore, any improvements in the design or material choices for the structural elements would pay significant dividends in reducing the total mass of the greenhouse system. The plant spiral structure accounts for 28% of this structural mass (1143 kg), while the inflatable structure accounts for 24%

(1000 kg) and the carbon fiber inner column accounts for 20% (830 kg). The rest of the structural mass is composed of support columns, plant trays, and floors for the greenhouse.

Component	Material
Structural columns and core	Carbon Fiber
Spiral	Carbon fiber with aluminum structural reinforcement
Trays	Plastic (Plyethylene)
Inner stairs	Carbon fiber with aluminum structural reinforcement
Other inflatables	Kevlar, reinforced with RFP (Reinforced Fiber Polymer)
Water tank	Kevlar, reinforced with RFP (Reinforced Fiber Polymer)
Germination cabinets	Aluminum
Water Tubing	Reinforced Tygon

Table 2 Main components materials of the module

F. Environmental control

The internal pressure of the greenhouse is kept at 14.6 PSI, a slightly lower value compared to that of the Ice Home (14.7 PSI) in order to positively-pressurize the Ice Home and thus prevent contaminants entering it from the greenhouse module [43]. Both modules are kept in the range of Earth atmospheric pressure in order to enable the use of existing technologies and improve the ability to test on Earth prior to launch to Mars. It is much easier to build and test systems at Earth's atmospheric pressure than it would be to test systems that operate at a reduced pressure. In addition, keeping both modules at roughly 1 atmosphere of pressure allows the system to have the same bulk atmospheric composition (79% N^2, 21% O^2) as Earth. In space systems with reduced pressures, the partial pressure of oxygen must remain consistent with Earth's ambient in order to allow astronauts to breathe and function normally. However, increasing the partial pressure of oxygen in an atmosphere means that the composition of the atmosphere swings to higher percentages of oxygen, which increases fire hazards. With ease of testing and safety in mind, the team made the decision to operate the greenhouse at roughly Earth ambient pressure and composition. The same principle is currently adopted on the International Space Station [44].

CO2 levels are maintained in the 800 – 1000 ppm range, twice the concentration on Earth [45–47]. This promotes plant growth while also maintaining a safe level for human health [48, 49]. The internal temperature of the greenhouse is maintained from 23 – 26 ºC to maintain conditions suitable for most crops. Initial calculations show that residual heat from the LEDs and humans is sufficient to counter the small loss of heat through the gas insulation shell of the greenhouse. Table 3 summarizes the environmental conditions designed for the module.

Pressure: 14.69 psia	CO_2 levels: 800-1000 ppm	Temperature: 23-26 °C

Table 3 Internal environmental conditions

G. In Situ Resource Utilization and Power generation

The module is expected to be deployed in an area of Mars with access to water. Research to establish water and ice levels on Mars is ongoing, but it is currently evident that large deposits of water ice exist close to the surface in most of the Northern Hemisphere of Mars in the Arcadia Planitia [50, 51]. The rate of filling of the ice shield is highly dependent on the water ISRU capabilities that will be available at the time of its deployment. In terms of water usage for growing crops, the greenhouse water cycle is closed and should be self-sufficient. However, for the sake of assuming some inefficiencies and losses, the team allocated 0.125 m^3 per day of water usage to the greenhouse growth system. The greenhouse is powered with six Kilopower nuclear reactors that produce 10 kWe each [52]. Nuclear was chosen over solar power for a variety of reasons, chief among them its continuous production even at night and in the event of dust storms. Table 4 shows an estimation of the greenhouse power budget [53]. The estimated peak power demand is 53.5 kW, while the average power demand is 38.9 kW. Therefore, for nominal operation, only four Kilopower reactors will be used and two will serve as spares.

Component	Peak Power	Estimated power budget for the greenhouse system
LED Lighting	48355 W	35520 W
Water Circulation System	325 W	325 W
Heaters	800 W	200 W
ECLSS	800 W	400 W
Power Conditioning	500 W	400 W
Controls and Computing Systems	1000 W	1000 W
Automation Equipment	1350 W	800 W
Exchange System with Mars Ice Home	200 W	200 W
Misc. (Valves, sensors, etc.)	200 W	50 W
Total Requirement	**53.5 kW**	**38.9 kW**

Table 4 Estimated power budget for the greenhouse system

Clearly, the majority of the power requirement comes from the LED lighting used to provide adequate growing conditions to the plants. Standard LED lighting arrays used for indoor greenhouses are employed in this architecture to maximize the Technology Readiness Level (TRL) of this subsystem. While this number is high, it is largely unavoidable; plants require a certain amount of power to grow, and the purpose of the greenhouse is to grow these plants. The power requirements for the LEDs, water circulation system, automation equipment, and exchange system were calculated for the greenhouse, while the rest of the numbers were estimates from the Mars Ice Home design. The total power was minimized through engineering solutions that minimize moving parts and employ dual-use systems. For example, the greenhouse tray system is designed to move with gravity instead of having a mechanized system that would require power. Another example is that the CO^2 scrubbers use passive amine beds instead of a powered system.

H. Risk management and System maintenance

Minimizing risk of power failure or plant disease spreading is essential for continuous and safe operations. A key element to risk mitigation is redundancy; therefore, the greenhouse subsystems were designed with redundant features. There is a primary and a secondary water reservoir for the crops in case one of the water supplies becomes contaminated. Two pumps support pumping water into the reservoirs with motor controllers connected to an automated switching system to ensure that one is always running. In the event that one pump malfunctions, the second is automatically activated and has the capacity to take over and supply the greenhouse while the first is repaired. Furthermore, each section of the tray bed spiral has the capability to be double-isolated from the rest of the greenhouse water supply to prevent the spread of waterborne disease while continuing operation in all other areas of the spiral. All features throughout are double-isolated or have a backup system available to continue food production to the maximum extent possible when faced with a subsystem failure.

Day-to-day operations and maintenance of the greenhouse are planned to be kept to a minimum once the greenhouse is up and running, as described earlier. General maintenance on the pumps and electronics cabinets is conducted as necessary in accordance with a preventative maintenance schedule. When maintenance is conducted, a secondary system is placed online first to ensure continued operation. All of these actions are set up for manual operation, but many of them would be able to be automated by robotic systems if desired to ensure continued food growth even in the absence of humans.

I. Summary of system trade-off

Table 5 presents a breakdown of the major design decisions for the greenhouse module through the application of principles of Ecology, Architecture and Systems Engineering. The key criteria that drove the choice among different design alternatives relate to the overall module efficiency and the crew well-being. At the matter of fact, these objectives translate into design search directions towards higher crop productivity to guarantee food supply to the crew, lower ratios of occupied space over available volumes to allow for a better comfort of the crew, and system redundancy to guarantee a reliable implementation of all the critical functions. In response to Ecology driven requirements, the hydroponic technology is identified as the most appropriate among the alternatives because it is a well-established and reliable technology used on Earth. In response to the architecture-related requirements, our design permits to optimize surfaces and volume distribution in the deployed configuration, while minimizing the weight and the space occupied in the packed configuration. In response to the requirements related to the functioning and integration of systems and equipments, energy production, supply and distribution constitute a critical aspect. For our greenhouse concept, nuclear power is preferred over solar power for its better performance in guaranteeing production continuity, independently on day-night cycles and external environmental conditions; in addition, nuclear discourses require less maintenance interventions.

Table 5 Most significant design alternatives considered for the greenhouse

Requirements	Options	Motivations
Growing system efficiency	NFT Hydroponics	Low cargo occupation, high yield rates, high control
	Medium Based Hydroponics	High cargo occupation, scientific uncertainty
	Aeroponics	High risk of desease spread
System productivity and mental benefits in harvesting	Partially integrate human interaction	Balance between productivity and mental benefits
	Totally integrate human interaction	Minimizes productivity, maximizes mental benefits
	Do not integrate human interaction	Maximizes productivity, minimizes mental benefits
Stability and functionality of the shape	Cylinder	Best volume and surface optimization
	Torus Sphere Hemisphere	Insufficient volume and surface optimization
Internal space optimization	Vertical layout	Low cargo occupation, more compact systems
	Horizontal layout	High cargo occupation, larger systems needed
Energy supply	Kilopower	More reliable, more compact
	Solar panels	High cargo occupation, high maintenance needs

VI. Concluding Remarks and Future Developments

This paper proposes an innovative greenhouse module to guarantee self-sufficiency and to support a safe manned exploration on Mars. The specific features of the proposed module are (a) the exploitation of in situ resources, (b) the compatibility with the Ice Home residential module, (c) the novel food production system which allows to fulfill entirely the nutritional needs of the crewmembers, (d) the attention to the psychological well-being of the astronauts during a long-term mission. The greenhouse provides enough food to satisfy 100% of the nutritional requirements of a crew of four members through an innovative hydroponic system; the original helical layout shapes and optimizes the distribution of internal volumes and spaces for both the efficient growth of plantations and the comfort of the crew. The module also provides full compatibility and efficient coupling with the Ice Home residential module designed by NASA through the implementation of similar engineering design solutions. The residential Ice Home module and the proposed greenhouse create a closed loop ecosystem with an interchange of data, energy and resources between humans, plants, machines and the Martian environment. A specific characteristic of the proposed study is the large attention dedicated to the mental and physical needs of the exploration crew. Differently from consolidated approaches to current space programmes, our design strategy largely emphasizes human-centered solutions addressing crew well-being in an holistic manner. The module proposes a solution which integrates an optimized and efficient food production system with relaxation, physical activity, ergonomics and flexibility of the workplace. This approach to the design of the space mission combines the integration of technologies largely adopted on Earth for higher reliability, the original spiral layout optimized for the hydroponic system, the structural design optimized for high-pressure resistance and automated deployment, the integration of environmental-control, power supply and water recycling system with an innovative flexible and adaptable interior layout to enhanced space liveability for the crew. Future developments will relate to the simplification of the deployment procedure and the refinement of the design of the piping system. In addition, the design of automation strategies for the motion and flow of the plantation trays, and for the pollination and harvesting processes will be explored. Technologies and design solutions developed for the greenhouse concept can be adopted for applications on Earth, for instance, those can be of great help to address emergency situations arising in urban environment. This opportunity paves the way for a broader discussion towards new solutions to support the concept of self sustainability of cities and face the increasing scarcity of resources.

Acknowledgments

This work was supported by the Space Architecture for Extra-planetary Exploration (SAEXE) Project under the Alta Scuola Politecnica Program of Politecnico di Torino and Politecnico di Milano, and by the 2019 Breakthrough, Innovative and Game-changing (BIG) Idea Challenge under the NASA Game Changing Development (GCD) Program awarding the second place to the Biosphere Engineered Architecture for Viable Extraterrestrial Residence (BEAVER) project team. Additional acknoledgments to Confartigianato di Vicenza and Digital Innovation Hub for the support to Dr. Valentina Sumini and to the Visiting Professor Program of Politecnico di Torino for the support to Dr. Laura Mainini.

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