70th International Astronautical Congress (IAC), Washington D.C., United States, 21-25 October 2019.

IAC-19-IAC-19-B3.8-GTS.2.3

Designing A Martian Greenhouse as A Habitable Space: Feasibility Studies and Design Approach

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Abstract

Current models of greenhouse design primarily focus on enabling a means for water recycling, air revitalization, and food production. However, the enormous potential of using interior landscaping for positive psychological effects on the crew has been neglected. An indoor garden impacts living conditions within a confined environment of surface habitats in active and passive ways. Actively, from the human factors perspective, it diversifies the crew's diet and adds the enjoyment of on-site gardening to routine activities. Passively, it brings colors, textures, and aromas into the otherwise mundane interior environment.

This research takes its objectives and major design requirements from NASA's Big Idea Challenge competition and begins by discussing a series of research investigations that collect systems and plant requirements, analyzes them, and synthesizes the results into a greenhouse design. This research by design process starts with plant selection based on their nutritional values using recipes from different cultures. Next, environmental requirements are considered for a hydroponic planting system for selected plants such as temperature, pH, and pollination methods. Afterward, the sizes of mature plants are reviewed to generate structural measurements of plant beds. Since architectural elements and design principles are linear, planar, and three-dimensional (3D), the integrated result is characterized into four categories: Plant Bracket, Plant Wall, Plant Trellis, and Plant Box.

Finally, this paper concludes by proposing the criteria for feasibility studies pertaining to the construction of a greenhouse on Mars surface at different stages of infrastructure development. Using a greenhouse as a habitable space that enhances the quality of life during a long-duration mission is also taken into considerations. Design factors for the evaluation of greenhouse module proposals (Figures of Merits) are presented and categorized by the level of their impact on overall mission planning and success.

Keywords: Greenhouse, Architecture, Hydroponics, Plants

1. Introduction

Sustainable human presence and exploration on Mars depend on the development of Earth-independent strategies that include in-situ food production using local greenhouses. There are two approaches to the greenhouse design for the partial gravity of Mars. The first is the over-engineered plant factory, which mostly focuses on the efficiency ratio of the total mass production to the resources consumed per day. In such proposals, the priority is the simplicity of design, enabling autonomous operations. Therefore, the produce selection is limited and consists of a few similar plants. Contrasting with this is the second type of design, in which there are over-optimistic design concepts that suggest having an extra-terrestrial food source for a 600-day mission as a backyard for human leisure.

This paper presents a design approach that combines both tactics — a series of trade studies aimed to find a feasible compromise between human factors and agricultural requirements.

2. Human Factors

Human health has physical and psychological aspects that are influenced by passive and/or active factors. Dynamic elements such as diet and meal diversity interact directly with human physical and mental health and are considered an active factor. Passive environmental aspects, such as aromas and color enrichment, are passive factors that affect cognitive conditioning.

2.1. Active Human Factors

2.1.1. *Diet*

Humans require nutrients and energy supplied in the form of calories. Insufficient calories and inadequate micronutrients trigger distinct health issues; for example, the Apollo 15 crew highlighted how an unexpected deficiency of one or more nutrients in a long-term space mission significantly affected mission success[1]. Therefore, it is essential to provide crewmembers with a required level of nutrition during their missions to prevent health deterioration. "Human-Systems Integration Requirements," section 3.5.1.3.1 in the NASA Constellation Program (C×P) document 70024[2], thoroughly reviews nutritional requirements.

Additionally, the role of the greenhouse as a provider of various fresh food is more critical in long-duration mission scenarios. The use of fresh vegetables on Mars could enhance the nutritional intake of the crew and reduce the risk of vitamin and mineral deficiencies in their diet.

2.1.2.*Menu Diversity and Culture*

Food acceptance depends on the variety and adaptability of the food menu system. An extensive range of food items provides multiple choices to avoid menu fatigue. According to anecdotal reports, "healthier and tastier foods decrease the stress often experienced by the crew. Therefore, taste, menu variety, and an array of textures, colors, and flavors can contribute to the psychosocial wellbeing of the crew."[3]

Overall acceptability of the food is reduced when the food is challenging to prepare and/or eat [4]. Moreover, food acceptance can be affected by the social context and timing of meals. Food and mealtimes offer crews significant psychological and social benefits, such as reducing the stress and boredom of prolonged space missions and stimulating team-building behavior by sharing meals [4].

2.1.3.*Gardening*

In addition to scientific and life-support value, there is evidence that cosmonauts and astronauts enjoy handling plants and observing them grow. Salyut cosmonaut Valentin Lebedev recalls that for him, plants were "like pets." During his mission, he attached his sleeping bag to the ceiling next to the Oasis greenhouse to be able to look at the plants before falling asleep[5]

Shuttle-Mir astronaut Mike Foale also "loved these experiments" [with the Greenhouse], because they "reduced his irritability" [6]. Attending the plants provides the crew with regular activity and interaction with living material inside a technologically mediated habitat. Even though appreciation of 'gardening' may differ from individual to individual, the presence of growing plants may complement the mental well-being of the whole crew [7].

2.2. Passive Human Factors

2.2.1.*Color, Texture, and Aromas*

The current food strategy for International Space Station (ISS) prevents overly odiferous menus because other crewmembers could be disturbed in the pressure-tight habitat. In contrast, for a Mars mission, the introduction of recognizable and pleasant scents and tastes (through food) is being considered[8].

Documented testimonials about noxious smells in closed ECLSS space capsules suggest another critical function of plants onboard space habitats. Plants that indicate "freshness" can normalize the environment during long-term missions, neutralizing a certain amount of indoor "air pollution" caused by humans.

"The aroma of the Earth" is a term often used by astronauts to describe the feeling of fresh fruit in the missions.[9][10][11]

2.3. Design Factors

Interior design through physical settings satisfies the basic need for shelter and protection, influences the shape of activities, nurtures aspirations and expresses the ideas that accompany the actions, and affect the outlook, mood, and personality of the crew. The purpose of interior design, therefore, is the functional improvement, aesthetic enrichment, and psychological enhancement of the quality of life in interior spaces.[12]

The purpose of design is to organize the parts into a coherent whole in order to achieve specific goals. In interior design, elements are arranged into three-dimensional patterns according to functional, aesthetic, and behavioral guidelines. The relationships among the elements established by these patterns ultimately determine the visual qualities and functional fitness of interior space and influence how to perceive and use it

The geometric elements—point, line, plane, and volume—can be arranged to articulate and define space. In architecture, these fundamental elements become linear columns and beams, and planar walls, floors, and roofs.[13]

In architectural design, these elements are organized to give a building form, differentiate between inside and outside, and define the boundaries of interior space.

3. Agricultural Factors

3.1. Plant Lists

In NASA's report "Nutritional and Cultural Aspects of Plant Species Selection for a Controlled Ecological Life Support System" [14], there are three scenarios of plant selection for a Mars mission: Minimum, Modest and Generous.

The "minimum" version represents the most basic dietary requirements with less than ten plants. Nutritious plants with higher harvest index (ratio of edible portion to total biomass) are on this list, and the number of species has been dictated strictly by nutritional needs without regard for palatability and diversity.

The "modest" list has been derived from a vegetarian diet with 15 plants on the list. The simplicity is the primary driving factor, but the ability to create pleasing dishes was also considered.

The "generous" scenario pays attention to all the previous factors as well as better efficiency of nutrient recycling by the Controlled Ecological Life-Support Systems (CELSS) than the previous lists. This list has more than 35 plants making for the most variety.

Table 1 of the Appendix compares the diversity of the plant list provided by different countries. It categorizes plants into 8 types: Fruit, Grain, Herb and Spices, Leaf and Flower, Leguminous, Root and Tuber, Salad, and

Sugar. The number of plants in each category reflects cultural preferences for flavor profiles in meals. Unexpectedly, the number of shared plants among the lists is not significant. For example, in the minimum list which provides for the basic needs of the crew, only peas, potato, and wheat are shared, 3 out of 13. This ratio increases in the generous list to 17 out of 36, or just above 47%.

3.2. Plant Selection

With just 30% of plants in common, an ultimate selection of plants does not exist and cannot be achieved due to the crew's personal preferences. Table 1 shows the most common plants between all the lists. This paper suggests a public greenhouse for these 24 plants and private chambers for other personal selections.

To simplify the greenhouse systems, these 24 plants should have the most in common with regards to environmental needs.

Table 1 Most Common Plant List

Beans	Kale	Rice
Broccoli	Lettuce	Soybean
Cabbage	Onion	Strawberry
Canola	Peas	Sugar Beet
Carrot	Peanut	Sweet potato
Chard	Peppers	Taro
Cucumber	Potato	Tomato
Herbs	Radish	Wheat

3.3. Plant Requirements

One full life cycle of plants is shown in Figure 1. The cycle starts from seeding to flowering and ripening, then goes back to seeding again. Some plants bypass the formation of seeds to generate new plants by vegetative propagation. For example, potatoes can be divided into pieces, and each piece could germinate a new plant (fruiting to germination). The mature strawberry plant could reach its runners to the ground and germinate (maturing to germination).

There are various studies on genetically modified plants with more compatibility in extra-terrestrial missions[15][16]. For these 24 plants, however, the lack of information restricted this study to the non-genetically modified plants.

Figure 2 shows the agriculture cycle from seed to seed in days. The minimum number of days for each plant cycle happens in the best environmental conditions, where the plant has the highest growth rate. The maximum number occurs in unfit conditions with the lowest rate of production.

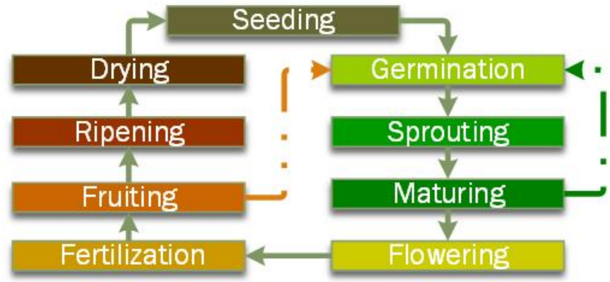

Figure 1 Plant Cycle

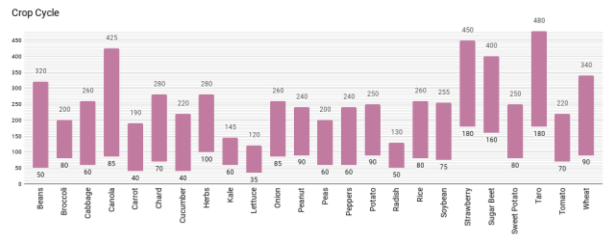

Figure 2 Crop Cycles Durations (Data from FAO[17]**)**

3.3.1.*Pollination*

In a full crop cycle, pollen needs to be transferred from the male flower to the female in order to create the seeds for the next generation. Plants can be self-pollinating or cross-pollinating, which needs a vector (a pollinator or wind) to get the pollen to another flower of the same species.

Figure 3 shows the pollination method for the common plant list. In the minimum plant scenario, only self-pollination plants are included to reduce the complexity of the greenhouse system. However, this approach reduces the diversity of plant types. The only wind pollination in this diagram is chard. Allergic reactions and the low rate of fertilization in a low-density plant greenhouse environment are the main two reasons that wind pollination is not recommended for a Martian greenhouse.

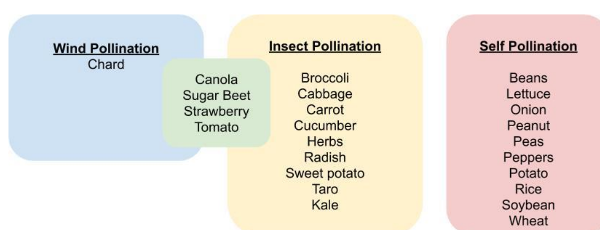

Figure 3 Pollination Method (Data from FAO[17]**)**

3.3.2.*Water*

The hydroponic Nutrient Film Technique (NFT) is chosen for the greenhouse's water system. Compared to other hydroponic systems, NFT needs less growth medium, is more energy-efficient, and has less complicated systems. Additionally, the entire greenhouse, when fully installed, requires less water than other systems.

Since in this closed system, the water is circulated to all plants. It should have a pH level and nutrient value compatible with all plants. Figure 3 shows optimal pH levels for the common plants. Water with a pH level of 6 to 6.2 is suitable for all plants except canola and kale.

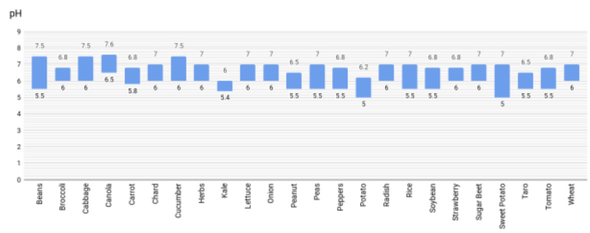

Figure 4 pH of Water (Data from FAO[17]**)**

3.3.3.*Air Temperature, Pressure And Humidity*

A temperature range of 18 to 22 centigrade is comfortable for humans. Figure 4 shows that most plants, except herbs and lettuce, can be productive in this temperature range. Since these plants are essential for menu diversification, considering a more cooling zone or plant pots within a greenhouse could solve this issue.

The overall humidity level should be 60-80% for healthy plant transpiration, and the pressure should be 101 kPa, the same as it is on Earth[18].

Figure 5 Crop Temperature (Data from FAO[17]**)**

3.4. Plant Size

The part of the plant above the surface is called the shoot zone, and the part that is below the surface is the root zone. The junction of the root tissue and the shoot tissue is the crown of a plant. A crown exists at the interface of the medium and the air (in the NFT method, Rockwool is the medium)

Figure 6 describes the variety of plants size in the elevation. This chart reveals that a single plant pot module could not be compatible with all the plants. Previous studies suggest customizable plant racks to change the distance between pots vertically[19][20][21]. However, harvesting the root vegetables with a deeper zone would not be productive.

Figure 7 defines three factors. The green circles represent the horizontal expansion of the individual plant. The rectangle describes the actual space that each plant needs through the whole crop cycle. Moreover, the distance between the rectangles shows the density of the crops. For example, onions can be planted extremely close together because they do not produce much foliage, and the foliage they do produce generally grows vertically. In contrast, broccoli grows a central flower that is surrounded by a lot of large leaves.

Insufficient spacing between plants reduces development speed, extends the growing period, and lowers the vegetative and reproductive development. Also, individual plant dry weight generally decreases as plant spacing decrease[22].

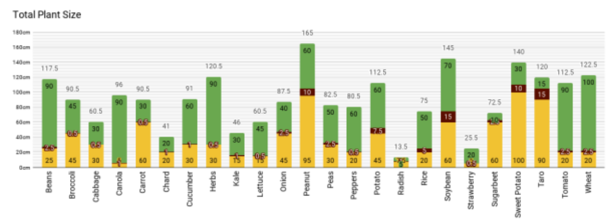

Figure 6 Plants Size in Elevation (Data from FAO[17]**)**

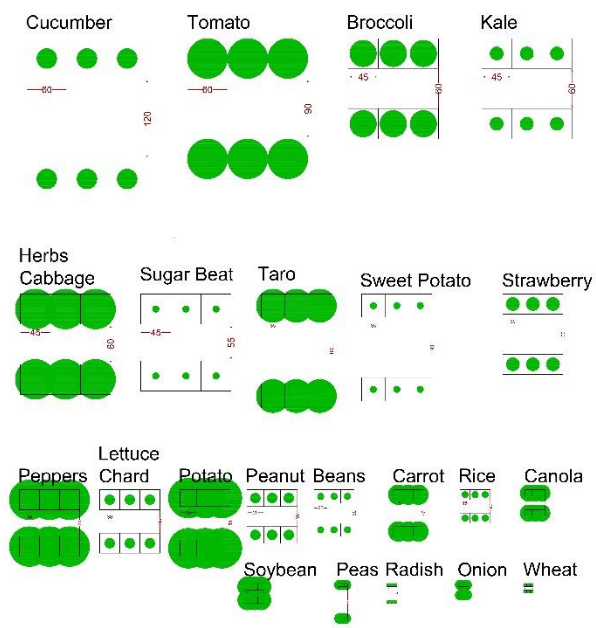

Figure 7 Plants Size and Spacing in Plan

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4. Results

By excluding canola, chard, and kale, the proposed public space plant list contains 21 plants. Since a one-size modular plant pot for the public space list would not be practical, dimensions driven from human factors are considered.

Table 2 groups the plants by their dimensionality and shape, forming four groups: Bracket, Trellis, Wall, and Box. These groups were obtained by considering the height of the plant, the depth of the plant, and the spacing required. For example, low growing, low depth, and high-density plantings naturally form a wall structure. On the other hand, the high height plants naturally form a columnar structure.

Table 2 Public Space Plants Grouping

	Bracket	Trellis	Wall	Box
Height	Low Medium	High	Low	Low
Depth	Low Medium	Low Medium High	Low	Low Medium High
Spacing	Medium	Low Medium High	Low	Low Medium High
Plants	Potato Peanut Sweet Potato Taro	Beans Cucumber Peas Soybean Tomato Peppers	Herbs Radish Lettuce	Carrot Onion Sugar Beet Broccoli Cabbage Rice Wheat Strawberry

The drawing in Figure 8 shows how all plant pots can be expanded out of the envelope.

Figure 9 shows height lines to divide the space into horizontal zones based on the height of humans[23]. Each plant grouping ranges over multiple horizontal zones. For example, the pot of plants in the trellis grouping is in zone D, but the plant grows from C to B. This natural division of the space allows for forming different interior design elements.

Proposed plant pots based on the zones are shown in Figure 10. The yellow color represents Rockwool for the plant bed in the NFT method. Blue is the transparent cap for the boxes used for the pollination period. The horizontal lines on the body of pots represent the foldability of the pots for ease of deployment.

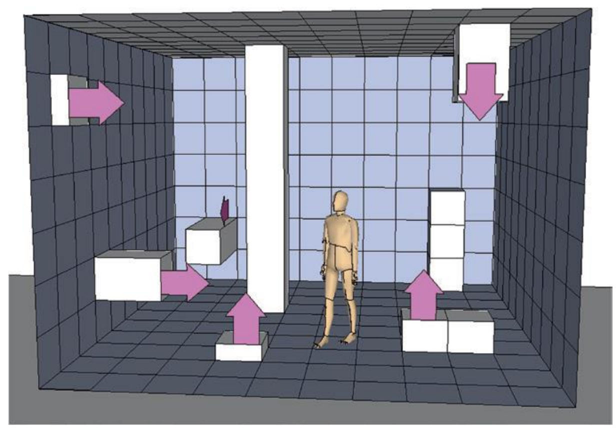

Figure 8 Conceptual 3D Origins [23]

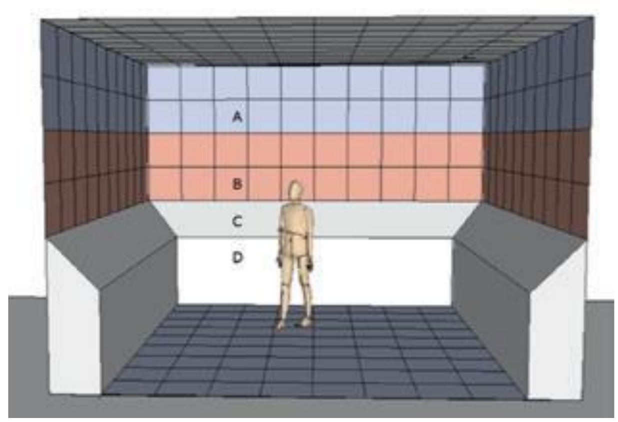

Figure 9 Height Lines and horizontal zones [23]

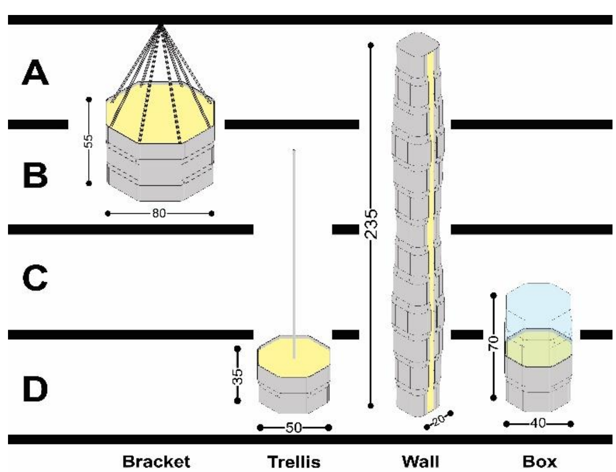

Figure 10 Proposed Plant Pots

5. Conclusions

Industrial mass production of food, which is the approach previously taken, might show an impressive number in theory but ignores human needs. Typically, the mass production approach has used a small plant list to achieve these goals. One might think that increasing the number of same plants might help the situation. However, changing the plant list alone does not address human needs unless accompanied by responsive interior design, especially when cultural differences are taken into account. Additionally, by considering plant geometry, we have categorized the plant lists so that their pots can convert the over-engineered industrial interior into a comfort hub with a unique interior perspective in the extra-terrestrial world.

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Appendix

Table 1 Various Plant Lists

Russian Academy of Sciences [24]	NASA [25]	ESA/Canada [26]	University of Utah [27]	NASA [28]	Institute for Environmental Sciences in Japan [29]	ESA/Canada [26]	NASA [25]	University of Utah [27]
Beets	Beans	Beans	Broccoli	Beets	Beans	Alfalfa	Banana	Beans
Carrots	Broccoli	Beets	Canola	Broccoli	Cabbages	Beans	Barley	Beets
Cucumber	Corn	Broccoli	Carrots	Corn	Carrots	Beets	Beans	Broccoli
Dill	Kale	Cabbages	Chilies	Cucumber	Cucumber	Broccoli	Beets	Cabbages
Earth Almond	Mustard Greens	Carrots	Kale	Kale	Komatsuna	Cabbages	Broccoli	Canola
Kohlrabi	Oats	Cauliflower	Lentil	Lettuce	Lettuce	Carrots	Cabbages	Carrots
Onions	Peanuts	Kale	Lettuce	Mustard Greens	Mitsuba	Cauliflower	Cantaloupe	Chard
Peas	Peas	Lettuce	Onions	Oats	Onions	Chard	Carrots	Chilies
Potato	Potato	Onions	Peas	Onions	Peanuts	Chilies	Cauliflower	Chives
Radishes	Rice	Potato	Peanuts	Peanuts	Peas	Cucumber	Celery	Fennel
Tomato	Soybeans	Rice	Rice	Peas	Peppers	Herbs	Chard	Flax
Wheat	Turnip	Soybeans	Soybeans	Potato	Radishes	Kale	Chives	Garlic
	Wheat	Spinach	Sweet Potato	Rice	Rice	Lettuce	Corn	Ginger
		Sweet Potato	Tomato	Soybeans	Shiso	Mushrooms	Garlic	Kale
		Wheat	Wheat	Spinach	Shungiku	Onions	Grape	Lentil
				Strawberries	Soybeans	Peanuts	Kale	Lettuce
				Sugar Beets	Spinach	Peas	Lettuce	Melons
				Sweet Potato	Sugar Beets	Peppers	Mint	Millets
				Tomato	Tomato	Potato	Oats	Mushrooms
				Wheat	Turnip	Rice	Onions	Oats
						Soybeans	Parsley	Onions
						Spinach	Peanuts	Oregano
						Squash	Peas	Parsley
						Sweet Potato	Peppers	Peanuts
						Tomato	Potato	Peas
						Wheat	Rice	Potato
							Rye	Pumpkin
							Soybeans	Quinoa
							Spinach	Radishes
							Strawberries	Rice
							Sugar Cane	Sage
							Sweet Potato	Sorghum
							Taro	Soybeans
							Tea	Squash
							Tomato	Strawberries
							Wheat	Sunflower
								Sweet Potato
								Thyme
								Tomatillo
								Tomato
								Wheat

Fruit	0	0	0	0	1	0	0	4	3
Grain	1	4	2	3	4	1	2	6	6
Herb and Spices	1	0	0	1	0	4	4	6	9
Leaf and Flower	0	3	5	2	4	3	7	6	6
Leguminous	1	4	2	4	3	4	4	4	6
Root and Tuber	6	2	4	2	3	3	4	5	5
Salad	3	0	2	3	4	4	5	4	5
Sugar	0	0	0	0	1	1	0	1	1
Total	**12**	**13**	**15**	**15**	**20**	**20**	**26**	**36**	**41**