PeaPod - Requirements

Outlining the Requirements for a Design Submission to the
NASA/CSA Deep Space Food Challenge

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Contents

1 Introduction

1.1 Purpose

The purpose of this document is to outline both the category requirements (Section 2.2) for a design submission to the NASA/CSA Deep Space Food Challenge (DSFC) [1] and the scoped requirements (Section 1.3) for the design being proposed by PeaPod Technologies Inc.: **PeaPod**.

The goal of the DSFC is for participants to "Create novel food production technologies or systems that require minimal inputs and maximize safe, nutritious, and palatable food outputs for long-duration space missions, and which have potential to benefit people on Earth." [2]

1.2 Framing Structure

This document achieves its purpose via "top-down" framing (Section 2), with each subsection's entries being derived from the entries of the previous[1].

- **2.1 - Opportunity**: A succinct scoped design statement.
- **2.2 - Challenge Requirements**: Categorical/unscoped requirements for *any* submission.
- **2.3 - Stakeholders**: Persons and groups in consideration.
- **2.4.1 - High-Level Objectives (HLOs)**: Conceptual aims/"DfX" derived from Requirements and Stakeholders.
- **2.4.2 - Low-Level Objectives (LLOs)**: Tactical goals derived from HLOs.
- **2.5 - Metrics**: Granular quantitative measures of design success, fit, utility, etc. derived from LLOs.
- **2.6 - Constraints**: *Mandatory* requirements, minimums, and maximums (i.e. true/false, pass/fail) for the proposed design.
- **2.7 - Criteria**: *Graded* (i.e. points-based, more/less is better) requirements for the proposed design.

[1] Each objective and metric has a numbered reference to the entry it was derived from (**S**takeholder **1** : S1, **H**igh-**L**evel Objective **8** : HL8, etc.)

1.3 Scope and Justification

The three underlined criteria in the challenge statement in Section 1.1 have also helped to define the scope of the design:

SC1. The longer the duration of the space mission (up to and including interplanetary travel and permanent colonization) the lesser the feasibility of resupply[2]. The lesser the feasibility of resupply, and the more minimal the input (i.e. launch mass), the less food will be able to be packed at launch, thus the more the design will need to generate net-new food grown on-board during the mission.

SC2. The minimization of inputs (launch mass), the minimization of other negative criteria such as growth time, design complexity, etc. and the maximization of safety (pathogenic and otherwise) means that food animal growth has been deemed not feasible, and is outside the scope of this document. Thus, the design should focus on food-producing plant growth[3].

SC3. Spacecraft are not good plant growth systems (lack of water access, proper lighting and nutrition, etc.), thus the design should encompass a plant growth environment that:

- SC3a. provides of all necessary plant growth inputs (water, nutrients, lighting, etc.);
- SC3b. contains or otherwise encompasses a viable plant growth environment (temperature, humidity, gas concentrations, airflow, etc.);
- SC3c. has control over all parameters of both a) and b) (environment parameters); these together are the (plant growth) environment conditions.

SC4. To maximize safety (of both the plants and the crew) and redundancy, and to minimize inputs (required human interaction), the environment should be automated and isolated from the spacecraft cabin with regards to all environment conditions (thermally, water-tight, etc.) unless beneficial and efficient (i.e no loss).

[2]Minimal resupply is also listed as a constraint directly in the challenge details [2, 3].

[3]This is primarily an issue in-transit; for colonization, non-plant food production systems should definitely be considered.

SC5. A greater degree of nutrition and palatability of food outputs implies a greater variety of plants (incl. leafy greens, fruits, root vegetables, legumes, etc.); as such the food production system should be able to generate a continuous and wide variety of environmental conditions such that any food plants could be grown within.

SC6. The demand for high plant variety, automation, parameter control, efficiency/input minimization (water, nutrients, footprint per plant), etc. implies the use of an aeroponic plant growth method [4].

SC7. Output nutrient and yield maximization in a controlled-environment implies environment parameter optimization. This is best accomplished via data collection of both plant-growth and environment metrics and cross-growth-environment networking (data versatility, sharing, and machine intelligence).

SC8. A solution focussed on palatability (focus on enjoyable plants) and variety (adaptability to many distinct environment requirements) is not suited to high caloric output. Most plants are simply not capable of producing the required daily caloric output in the space allotted (Section 2.6). As such, the scope of our solution places far greater importance on output palatability and variety (both culinary and nutritional) as well as production of critical micronutrients as opposed to pure caloric yield[4].

DSFC Phase 1 development, testing, and assessment is scoped to terrestrial/Earth-like operational constraints [2, 3]:

- Gravity (9.81 m/s^2);
- Ambient atmospheric pressure (101,325 Pa);
- Ambient atmospheric temperature (22 °C);
- Ambient atmospheric humidity (50 %RH);

[4]The solution "need not meet the full nutritional requirements of future crews, but can contribute significantly to, and integrate with, a comprehensive food system." [2]

1.4 Definitions

A number of useful definitions have emerged from the above scoping:

1. **(Plant Growth) Environment** - The holistic environment with which the plant interacts over the course of its growth.

2. **(Plant Growth) Environment Parameters** - The independent quantitative parameters defining the Environment. Inputs to the control system.

3. **(Plant) Growth System** - Includes the physical enclosure isolating the plant and Environment from the surroundings, as well as any infrastructure required to implement the Environment Parameters and generate the Environment by controlling Environment conditions. Satisfies all requirements in this document.

4. **(Plant) Growth Metrics** - The quantitative measures of plant growth, including yield mass, growth rate, compound concentrations (i.e. nutrients, flavour compounds), caloric density, etc.

5. **(Environment) Program** - The to-date most optimized set of Environment Parameters for a given Plant Growth Metric (i.e. Program X maximizes yield mass for lettuce), implemented by the Plant Growth System.

2 Framing

2.1 Opportunity

Design an automated and isolated aeroponic plant growth system for the Deep Space Food Challenge [1], able to generate any environment from a combination of independent environment parameters, with both environment and plant metric data collection.

2.2 Challenge Requirements

The following are the overall challenge requirements compiled from DSFC Applicant Guide details [2], the DSFC Phase 2 Instructions [3], and an excerpt from NASA-STD-3001: Section 7.1 Food and Nutrition [5]:

R1. **Must** help fill food gaps for a *three-year* round-trip mission with *no resupply*:

  (a) **Should** aim to produce food outputs that fulfill **all daily nutritional needs** for a crew of *four (4)* people;

  (b) **Must** maintain food output *safety* and *nutrition* during *all phases* of the mission;

  (c) **Must** output food that is *varied, palatable, and acceptable* to the crew for the *duration* of the mission;

  (d) **Must** produce food outputs that require *no additional processing time*[5];

R2. **Should** improve the accessibility of food on Earth by enhancing local production; in particular, via production directly in urban centres and in remote and harsh environments;

R3. **Must** aim to achieve the *greatest food output* with *minimal inputs* and *minimal waste*;

R4. **Must** transmit *operational data and limited video* to a remote location, and be able to receive periodic *operational commands*;

R5. **Must** operate under Earth-like conditions (See Section 1.3);

[5] It is assumed that fresh (or packaged unprepared) edible plant products are already prepared on existing space missions, and that this preparation meets this requirement.

2.3 Stakeholders

S1. Food Product Consumers - Palatability, output

S2. NASA/CSA Stakeholders - Feasability, input, optimization

2.4 Objectives

2.4.1 High-Level

HL1. Food Output Suitability (S1, R1, R1a, R1c, R1d, R2)

HL2. Environment Control, Automation, and Optimization (S2, R1b, R1d, R2, R3, R4)

HL3. Cross-Contamination (S1, S2, R1b, R2)

HL4. Time and Resource Efficiency (S1, S2, R1d, R2, R3)

HL5. Safety, Stability, Reliability (S1, S2, R1b)

HL6. Feasability (S2, R2, R5)

2.4.2 Low-Level

LL1. Output Food Variety (HL1)

LL2. Output Food Palatability (HL1)

LL3. Nutrient Output (HL1, HL4)

LL4. Energy Output (HL1, HL4)

LL5. Leaf-Zone Temperature Control (HL2, HL4)

LL6. Leaf-Zone Humidity Control (HL2)

LL7. Gas Concentration Control (HL2)

LL8. Lighting Control (HL2, HL4)

LL9. Insulation, Isolation (HL2, HL3, HL4)

LL10. Air Circulation Control (HL2, HL3)

LL11. Nutrient Solution Control (HL2)

LL12. Root-Zone Temperature Control (HL2)

LL13. Germination Success (HL2, HL4, HL5)

LL14. High Degree of Automation (HL3, HL4)

LL15. Energy Efficiency (HL4)

LL16. Water Usage (HL4)

LL17. Germination Time (HL4)

LL18. Growth Time (HL4)

LL19. Time-To-Harvest/-Reharvest (HL4)

LL20. Potential for Cross-Contamination (HL3)

LL21. Environmental, Process Safety (HL5)

LL22. Output Consumption Safety (HL1, HL5)

LL23. Reliability (HL5)

LL24. Input Stability (HL5)

LL25. Output Shelf Life (HL5)

LL26. Cost (HL6)

LL27. Size (HL6)

2.5 Metrics

#	Metric		Units
M1	Plant Species Variety	(LL1)	Y/N (per plant species)
M2	Palatability of Output	(LL2)	1-9 Hedonic (per plant)
M3	Protein Output	(LL3)	g/kg body mass/crewmember/day
M4	Protein Output Energy	(LL3)	kCal/day/crewmember (%TDEI)
M5	Carbohydrate Output Energy	(LL3)	kCal/day/crewmember (%TDEI)
M6	Lipid Output Energy	(LL3)	kCal/day/crewmember (%TDEI)
M7	Ω-6 Fatty Acid Output	(LL3)	g/day/crewmember
M8	Ω-3 Fatty Acid Output	(LL3)	g/day/crewmember
M9	Saturated Fat Output Energy	(LL3)	kCal/day/crewmember (%TDEI)
M10	Trans Fatty Acids Output	(LL3)	kCal/crewmember (%TDEI)
M11	Cholesterol Output	(LL3)	mg/day/crewmember
M12	Fiber Output	(LL3)	g/day/crewmember
M13	Caloric Output	(LL4)	kCal/day/crewmember
M14	Air Temperature Control Range	(LL5)	min, max °C
M15	Air Temperature Control Rate	(LL5)	Δ°C/sec at each °C
M16	Air Temperature Control Stability	(LL5)	±°C at each °C
M17	Air Humidity Control Range	(LL6)	min, max %RH
M18	Air Humidity Control Rate	(LL6)	Δ%RH/sec at each %RH
M19	Air Humidity Control Stability	(LL6)	±%RH at each %RH
M20	CO_2 Supplementation Range	(LL7)	max ppm CO_2
M21	CO_2 Concentration Control Rate	(LL7)	ppm CO_2/sec at each ppm CO_2
M22	CO_2 Concentration Control Stability	(LL7)	±ppm CO_2 at each ppm CO_2
M23	Light Spectrum Wavelength Range	(LL8, LL20)	min, max nm
M24	Light Spectrum PAR Match	(LL8)	% (each plant)
M25	Light Intensity Control Range	(LL8)	min, max μmol $m^{-2}sec^{-1}$ at each nm
M26	Light Intensity Control Stability	(LL8)	±μmol $m^{-2}sec^{-1}$ at each nm
M27	Light Loss, Capture by Surfaces	(LL9)	%
M28	Outside Light Penetration	(LL9)	%
M29	Heat Loss	(LL9)	±W at each °C
M30	Water Loss due to Leaks, Evaporation	(LL9)	mL/hr
M31	Internal Circulation Airflow Control Range	(LL10)	min, max m^3/min
M32	Gas Exchange due to Leaks	(LL10)	m^3/min
M33	Maximum Intentional Gas Exchange	(LL10)	m^3/min
M34	Nutrient Sol'n Delivery Control Range	(LL11)	min, max mL/sec
M35	Nutrient Sol'n Delivery Control Rate	(LL11)	ΔmL/sec^2 at each mL/sec
M36	Nutrient Sol'n Delivery Control Stability	(LL11)	±mL/sec at each mL/sec
M37	Nutrient Concentrations Control Range	(LL11)	min, max ppm (each nutrient)
M38	Nutrient Concentrations Control Rate	(LL11)	Δppm/sec at each ppm (each nutr.)
M39	Nutrient Concentrations Control Stability	(LL11)	±ppm at each ppm (each nutrient)

2.5 Metrics (Cont'd)

#	Metric		Units
M40	Nutrient Sol'n Temp. Control Range	(LL12)	min, max °C
M41	Nutrient Sol'n Temp. Control Rate	(LL12)	°C/sec at each °C
M42	Nutrient Sol'n Temp Control Stability	(LL12)	±°C at each °C
M43	Germination Success Rate	(LL13)	%
M44	Time Requirement - Maintenance	(LL14)	hrs/week
M45	Time Requirement - Setup	(LL14)	hrs
M46	Energy Efficiency - Power vs. kCal	(LL15)	%
M47	Necessary Water Waste per Day	(LL16)	L/day
M48	Initial Water Requirement	(LL16)	L
M49	Reharvest Period - Fruiting Plants	(LL19)	days (each plant)
M50	Germination Time	(LL17)	hours (each plant)
M51	Time to Harvest	(LL18)	days from planting (each plant)
M52	Potential for Contamination - Germination	(LL20)	% (each event)
M53	Potential for Contamination - Planting	(LL20)	% (each event)
M54	Potential for Contamination - Harvest	(LL20)	% (each event)
M55	Use of Hazardous Compounds	(LL21)	Y/N
M56	Cleaning Hazards	(LL21)	Y/N
M57	Physical, Chemical, Bio Hazards	(LL21)	Y/N
M58	Consumption Safety	(LL22)	%
M59	Loss of Functionality Over 3 Years	(LL23)	%
M60	Input Lifetime while Safe, Useful	(LL24)	Days
M61	Output Shelf Life while Safe, Quality	(LL25)	Days
M62	Cost	(LL26)	CAD
M63	Outer Dimensions	(LL27)	m (W, D, H)
M64	Outer Volume	(LL27)	m^3
M65	Power Consumption	(LL27)	W
M66	Mass	(LL27)	kg

2.6 Constraints

Metric	Constraint	Justification
M2	≥ 6.0	[2, 3]
M3	≈ 0.27g	[2, 3, 5]
M4	≤11.67% TDEI	[2, 3, 5]
M5	50-55% TDEI	[2, 3, 5]
M6	25-35% TDEI	[2, 3, 5]
M7	≈14g	[2, 3, 5]
M8	1.1-1.6g	[2, 3, 5]
M9	<7% TDEI	[2, 3, 5]
M10	<1% TDEI	[2, 3, 5]
M11	<300mg	[2, 3, 5]
M12	21-38g	[2, 3, 5]
M14	Min < 15°C, Max > 30°C	(SC5)
M17	Min < 20 %RH, Max > 90 %RH	(SC5)
M20	>1000ppm (≈600 above ambient)	(SC5)
M23	Min < 300nm[6] (ultraviolet), Max > 800nm (infrared)	(SC5, SC7) [6]
M24	≥ 95% match	(SC5)
M25	Min = 0, Max ≥ typical horticulture	(SC5, SC7)
M31	Min = 0 m^3/min, Max ≥ 2 m^3/min	(SC5, SC7)
M34	Min = 0, Max ≥ max plant requirement	(SC5, SC7)
M40	Min < 10°C, Max > 25°C	(SC5)
M37	Min = 0, Max ≥ max plant requirement	(SC5, SC7)
M44	0.5 hrs/week	[3]
M47	≤4L/day	[3]
M48	≤80L	[3]
M59	≤10%	[2, 3]
M60	≥3 years (1095 days)	[2, 3]
M61	≥3 days	[3]
M63	Fits through 1.07m x 1.90m doorway; W<1.829m, D<2.438m, H<2.591m	[2, 3]
M64	≤ 2 m^3	[2, 3]
M65	Avg. <1500W; Peak < 3000W	[2, 3]

[6] Also for disinfection purposes.

2.7 Criteria

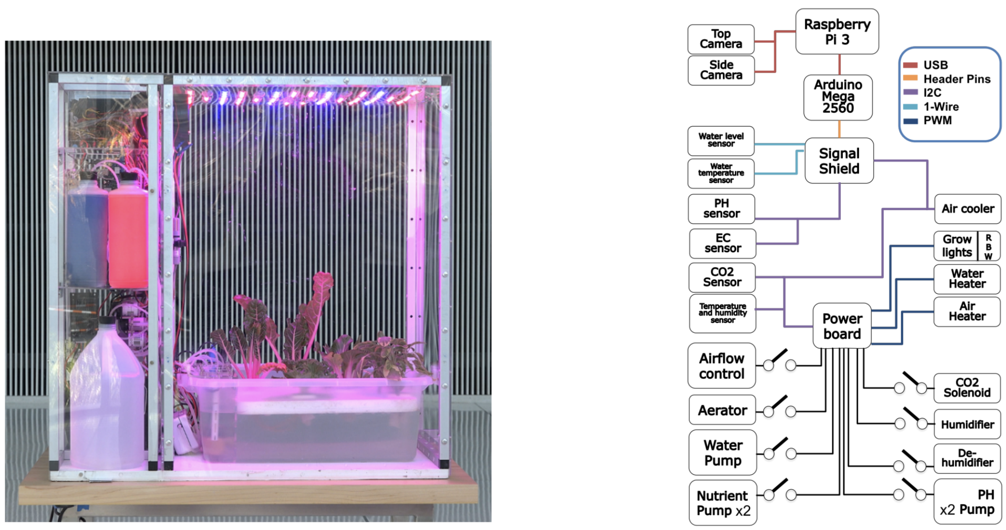
Metric	Criteria	Justification
M1	Should Maximize	(R1c, R3)
M13	Should Maximize	(R1, R1a, R3)
M15	Should Maximize	(SC5, SC7)
M16	Should Minimize	(SC5, SC7)
M18	Should Maximize	(SC5, SC7)
M19	Should Minimize	(SC5, SC7)
M21	Should Maximize	(SC5, SC7)
M22	Should Minimize	(SC5, SC7)
M26	Should Minimize	(SC5, SC7)
M27	Should Minimize	(R3)
M28	Should Minimize	(SC5)
M29	Should Minimize	(R3)
M30	Should Minimize	(R1b)
M32	Should Minimize	(R3)
M33	Should Maximize	(SC5, SC7)
M35	Should Maximize	(SC5, SC7)
M36	Should Minimize	(SC5, SC7)
M41	Should Maximize	(SC5, SC7)
M42	Should Minimize	(SC5, SC7)
M38	Should Maximize	(SC5, SC7)
M39	Should Minimize	(SC5, SC7)
M43	Should Maximize	(R1, R1b)
M45	Should Minimize	(S1)
M46	Should Maximize	(R3)
M49	Should Minimize	(R1b, R3)
M50	Should Minimize	(R1b)
M51	Should Minimize	(R1b)
M52	Should Minimize	(R1b)
M53	Should Minimize	(R1b)
M54	Should Minimize	(R1b)
M55	Should Avoid, Mitigate	(R1b)
M56	Should Avoid, Mitigate	(R1b)
M57	Should Avoid, Mitigate	(R1b)
M58	Should Avoid, Mitigate	(R1b)
M62	Could Minimize	(S2)
M66	Should Minimize	(R3)

3 Reference Designs

3.1 Open Agriculture Initiative - Personal Food Computer

The Open Agriculture Initiative (OpenAG) is a project launched by the MIT Media Lab with the goal to "Build open resources to enable a global community to accelerate digital agricultural innovation."

One of their primary developments was an open-source controlled-environment agriculture micro-greenhouse, the Personal Food Computer. The PFC controls all environmental growing parameters and collects data during the growth cycle. Data can be collected by users and shared between members of the open-source community. This allows for the creation of reproducible "climate recipes" where other devices with similar abilities can reliably generate the same environment and attain the same plant growth results.



(a) Assembled PFC v1. (b) Component diagram.

Figure 1: From [7].

One of the design's major flaws is in its implementation. Despite the claim that the PFC focusses on SC3 and SC5, in practice, it failed to meet R3 [8]. In addition, the PFC utilizes Deep Water Culture (DWC) hydroponics [7], as opposed to aeroponics, resulting in a lowered water efficiency.

The PFC is also much more focussed on SC3 and SC5 than R1 and R1a, meaning that they valued optimization and data collection over bulk yield of food outputs. This shows in that their design did not account for scalability of output [9].

However, the array of sensors included in the design (both plant-growth and environmental) as well as the principle of plant phenomenology optimization is informative in meeting R3 and their attempts can serve as a basis for understanding SC3 and SC5 [10].

Attempted: LL1, LL2 (via SC5), LL5. LL6, LL8, LL10, LL11, LL14

Did Not Consider: LL4, LL9, LL13, LL15, LL16, LL17, LL18, LL19, LL20

Appendices

A Requirements Graph

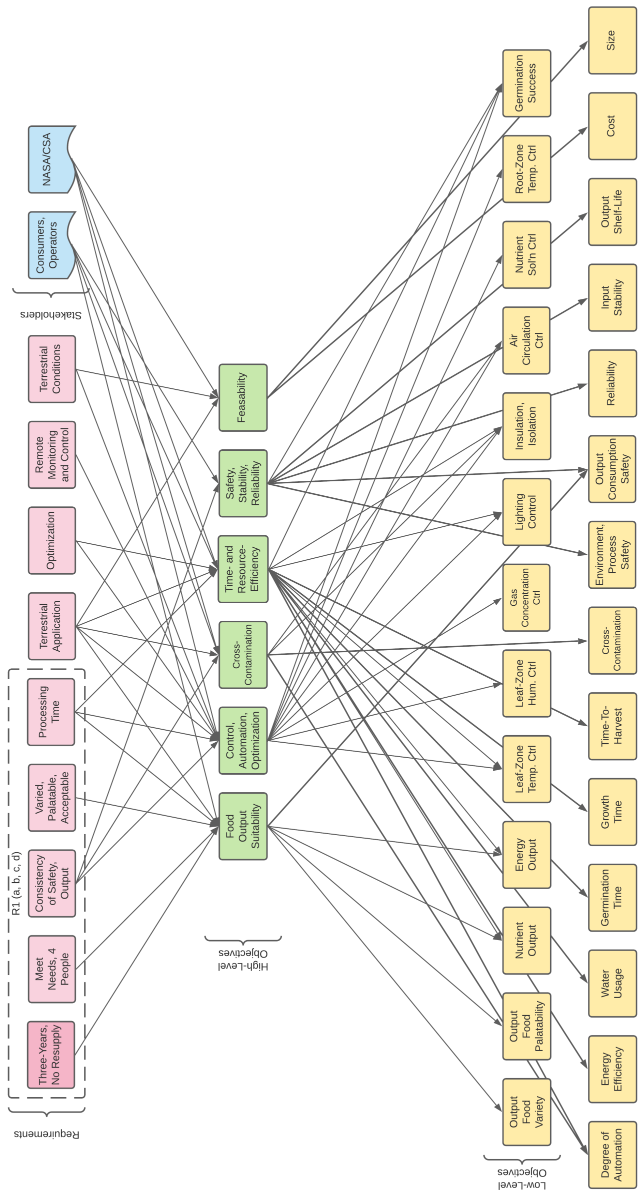


Figure 2: Requirements inheritance graph.

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