

An Analysis of Hybrid Life Support Systems for Sustainable Habitats

by

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B.A., Princeton University (2012)

Submitted to the Department of Aeronautics and Astronautics
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Abstract

The design of sustainable habitats on Earth, on other planetary surfaces, and in space, has motivated strategic planning with respect to life support (LS) system technology development and habitat design. Such planning requires LS system analyses including both high fidelity modeling and high level trade space exploration of candidate architectures. A particularly relevant trade for sustainable, long duration missions exists between the implementation of physicochemical and bioregenerative LS technologies. In the case of the food subsystem, there are distinct advantages and disadvantages to employing either prepackaged food or a biomass production system (BPS). This project investigates the trade between biologically grown food and stored food as part of the broader bioregenerative-physicochemical trade-off in environmental control and life support systems (ECLSS) for isolated and confined environments. Lunar and Mars surface habitats with varying degrees of bioregeneration for food and atmosphere revitalization are simulated using the BioSim advanced life support system simulation. An equivalent system mass (ESM) analysis is carried out, and improvements to crop lighting systems and agricultural system autonomy are considered as two possibilities for reducing infrastructure costs for biological food growth systems. The ESM analysis indicates that reducing lighting costs and increasing autonomy of the food production, processing, and preparation systems associated with the BPS will increase its feasibility and cost-effectiveness for use in long-term space flight. With no technology improvements, mission durations at which the ESM cost of a hybrid system is lower than that of a physicochemical system with similar performance will likely not be less than about 4 years for lunar surface missions and 4.8 years for Mars surface missions; however, with significant improvements to the BPS and its supporting infrastructure needs, these “crossover” times can be more than halved. The H metric is proposed for classification of fully or partially regenerative habitats. The multidisciplinary ECLSS optimization considers 14 design variables and models and evaluates integrated ECLSS’s for non-crew time ESM and crew time. Ultimately the question that is posed is, what is the optimal combination of physicochemical and bioregenerative life support technologies for a given mission or mission campaign, and

how can this drive strategic technology development?

Thesis Supervisor: Olivier L. de Weck

Title: Professor

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Contents

1	Introduction	15
1.1	Motivation and Background	15
1.1.1	Environmental control and life support systems	16
1.1.2	The physicochemical-bioregenerative spectrum	19
1.1.3	The relevance of hybrid life support systems	20
1.1.4	The bioregenerative-physicochemical trade	23
1.2	Review of the Literature	24
1.2.1	Overview of existing and past life support modeling efforts . .	26
1.2.2	Overview of ECLSS bioregenerative technology development .	29
1.2.3	Overview of ECLSS trade studies	29
1.2.4	Overview of other relevant literature	34
1.3	Reductionist vs. Systems-Level Research: a Comparison of Research Methods	35
1.3.1	Closed Ecological Systems Research at NASA	36
1.3.2	Closed Ecological Systems Research at Biosphere 2	37
1.3.3	Applications to hybrid life support development and planning	39
1.4	Thesis Objectives	41
1.5	Chapter 1 Summary	42
2	Approach	43
2.1	Summary of Case Studies	43
2.2	Design Assumptions	45
2.3	BioSim Tool Overview	47

2.3.1	Structure	48
2.3.2	MATLAB postprocessor	51
2.3.3	Biomass production system model overview	53
2.4	Modeling Assumptions	56
2.5	Figures of Merit	57
2.5.1	Equivalent system mass	57
2.6	Chapter 2 Summary	61
3	ESM Analysis of Lunar and Mars Surface Habitat Systems	63
3.1	Infrastructure Costs	64
3.2	Agricultural System Autonomy and BPS Power Demand	64
3.3	Evaluation of ESM For Various Architectures	67
3.4	Discussion	68
3.5	Hybrid Life Support System Classification Metric	70
3.6	Chapter 3 Summary	72
4	Multidisciplinary ECLSS Design and Optimization	75
4.1	Background	76
4.2	Optimization Problem	77
4.2.1	Design variables	77
4.2.2	Parameters and constraints	78
4.2.3	Objectives	79
4.2.4	Assumptions	81
4.2.5	Model structure	81
4.3	Optimization Algorithm Selection	82
4.3.1	NSGA-II	84
4.4	Results	85
4.4.1	Selection of NSGA-II tuning parameters	85
4.4.2	Model sensitivity to crew size	88
4.4.3	Identification of Pareto-optimal architectures	89
4.5	Discussion	91

4.5.1	Merits of multiobjective examination	92
4.6	Chapter 4 Summary	93
5	Conclusion and Future Work	95
5.1	Thesis Summary	95
5.2	Recommendations For Future Work	96
5.3	Final Remarks	100
A	Baseline BioSim .XML Configuration File	101
B	Figures	111

List of Figures

1-1	Consumable flow through systems with different loop closure	16
1-2	Hybrid habitat spectrum	19
1-3	Human Health, Life Support and Habitation Systems Roadmap . . .	22
1-4	Virtual Habitat simulation top-level modules and substructure	27
1-5	EcosimPro graphical model	28
1-6	ALSSAT Block Flow Diagram	30
1-7	Timeline of NASA-funded bioregenerative technology	31
1-8	Laundry system ESM analysis	32
1-9	Waste system ESM analysis	33
1-10	Challenges associated with incorporation of greenhouses	35
1-11	LMLSTP Phase IIA experiment team	36
1-12	Biosphere 2 IAB floor plan	38
1-13	Thesis outline	42
2-1	Baseline habitat architecture used for analyses	44
2-2	Store sizes to support habitat architectures	47
2-3	Structure of the BioSim simulation.	48
2-4	Interaction between the simulation and controller within BioSim. . . .	50
2-5	BioSim GUI showing all visual modules open.	52
2-6	Wheat crop CO ₂ usage	54
2-7	Cumulative edible biomass produced by the BPS	55
3-1	ESM breakdown of lunar ECLSS architectures	65
3-2	ESM breakdown of Mars ECLSS architectures	66

3-3	ESM analysis of lunar ECLSS architectures	67
3-4	ESM analysis of Mars ECLSS architectures	68
3-5	Generalized human-centric consumable flow in a habitat	71
3-6	Classification of habitat architectures on the H-spectrum	73
4-1	Baseline habitat architecture used for ECLSS MSDO analysis	76
4-2	Model block diagram	82
4-3	Convergence of fmincon active-set algorithm	83
4-4	Comparison of Pareto fronts found by the NBI and NSGA-II algorithms	84
4-5	Mutation coefficient tuning for NSGA-II algorithm	86
4-6	Population and generation size tuning for NSGA-II algorithm	87
4-7	Crew size sensitivity analysis	88
4-8	Pareto front design variables for baseline GA optimization	90
4-9	Pareto front design variables for GA optimizations with varied crew size	92
5-1	Atmospheric stability of BioSim Plant Environment module	97

List of Tables

1.1	High-level ECLSS functional decomposition	17
1.2	Bioregenerative ECLSS technologies	18
1.3	ESM analysis for an early Mars mission	34
2.1	Trade-off in food providing subsystem	43
2.2	Subsystem attributes and corresponding ESM conversion factors . . .	58
2.3	Lunar ESM conversion factors	59
2.4	Mars ESM conversion factors	60
3.1	Crossover times for various missions	69
3.2	Computation of H metric	72
4.1	Design vector and list of configurable attributes	78
4.2	Design attributes for Pareto-optimal designs	91
5.1	Mission phases and their durations assumed for a lunar mission . . .	98

Chapter 1

Introduction

1.1 Motivation and Background

Long-duration manned space flight has captured the human imagination for centuries. Numerous works of renowned science fiction (e.g., *Star Wars*, *Star Trek*, 2001: *A Space Odyssey*, *Alien*) and recent initiatives such as Mars One and Inspiration Mars rely on the premise that in the future, technology will enable humans to sustainably live outside of the Earth and to travel to distant star systems and planets. Currently, the farthest reach of the human civilization has been to the Moon orbiting our planet Earth. Humans have not yet developed the technology necessary to safely and affordably travel to Mars or other planets in our solar systems. Meanwhile, interplanetary probes have allowed us to observe much of the solar system, and NASA’s Voyager 1 spacecraft is currently exiting the solar system and heading into interstellar space.

Highly sustainable habitats are required to enable long-duration manned space missions due to the impracticability of frequent logistical resupply. Sustainability in isolated and confined environments can be quantified by the degree of resource loop closure in a system or, similarly, by the maximum time a system can survive between successive resupply missions. A fully sustainable system (“closed-loop”) would have the ability to operate indefinitely if that system were to be materially and energetically closed off from the external environment. In contrast, an entirely unsustainable system, referred to as an “open-loop” system, requires stores of consumables at the in-

put, transforms the consumables into waste products that are stored or removed from the system boundary, and fails sharply once the initial consumable store is depleted if no timely resupply occurs. For example, the habitats inside the Apollo spacecraft were open-loop systems [1, 134-139], whereas the International Space Station US Segment recycles roughly 74% of its waste water via the Water Recovery System (WRS) and recycles consumables to produce oxygen using the Oxygen Generation System (OGS) [2]. Figure 1-1 shows consumable flow through open-loop, semi-closed loop, and closed loop (fully regenerable) systems. m^0 indicates initial consumable store

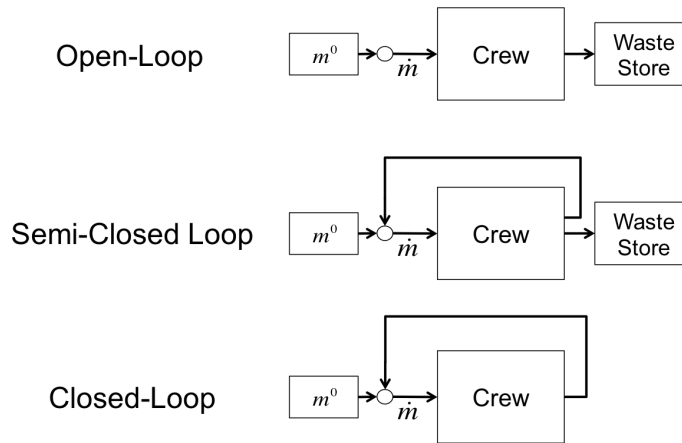


Figure 1-1: Consumable flow through open-loop, semi-closed loop, and closed loop systems.

mass; \dot{m} indicates mass flow rate into the human crew.

1.1.1 Environmental control and life support systems

In the manned spaceflight community, the term Environmental Control and Life Support System (ECLSS) refers to the engineered systems inside a habitat that exist for the purpose of keeping any living beings (i.e., humans and/or animals) alive. ECLSS can be decomposed into the following primary functions: Air Management, Water Management, and Solid Waste Management [3]. These can be decomposed into subfunctions in a variety of ways. For example, NASA's ECLSS Roadmap (2011) decomposes these three primary functions into several subfunctions as detailed in Table 1.1. Note that this functional decomposition excludes the food production/providing sub-

Primary Functions	Subfunctions
Air Management	<ul style="list-style-type: none"> • Circulation • Conditioning • Emergency Services • Monitoring • Pressure Management
Water Management	<ul style="list-style-type: none"> • Potable Water Management • Waste Water Management • Water Quality Monitoring
Solid Waste Management	<ul style="list-style-type: none"> • Trash Management • Metabolic Waste Management • Logistical Waste Management

Table 1.1: High-level ECLSS functional decomposition [3].

system. This decomposition assumes that food providing is decoupled from the other functions; in a scenario where all food is stored for the mission, this is acceptable, but in a scenario with biologically grown food, this is not the case.

In an ECLSS, each of these functions must be accomplished by an architecture that employs an appropriate “technology choice.” The choice of technology can be regenerative or nonregenerative (with respect to consumable processing) and can be based on physical, chemical, or biological processes. Some terms that will be useful for our discussion of ECLSS technologies are as follows:

- **Physicochemical technology:** A technology that relies on physical and/or chemical processes to transform and/or relocate resources. No living organisms such as bacteria or plants are actively used to carry out life support functions.
- **Biological technology:** A technology that relies on biological processes to transform resources. Plants, bacteria, and/or other organisms are actively and intentionally used.
- **Regenerative process:** A process that regenerates consumables such as mass

and energy. Systems can be fully, partially, or entirely not regenerative.

- **Physicochemical life support technologies:** Technologies that exploit physicochemical processes for use in life support systems for sustaining humans. Examples of physicochemical life support technologies include consumable storage canisters, and chemical waste stabilization systems. Physicochemical technologies can be regenerative, as in the case of Sabatier reactors (for H₂O production) and metal oxide absorption beds (for CO₂ removal from air).
- **Bioregenerative life support technologies:** Technologies that exploit biological regenerative processes for use in life support systems for sustaining humans. Examples of biological life support technologies include plant growth chambers and microbial bioreactors (for water filtering or energy production).

A list of types of bioregenerative ECLSS technologies and the subfunctions they can carry out is provided in Table 1.2.

	CO ₂ /O ₂ exchanging	Air filtering	Food producing	Resource recovery	Energy producing
<i>Plants</i>	X	X	X		X
<i>Algal reactors</i>	X	X	X		X
<i>Composters</i> <i>(aerobic/anaerobic)</i>		X		X	
<i>Microbial bioreactors</i> <i>(aerobic/anaerobic)</i>				X	X
<i>Leaching technology</i>				X	

Table 1.2: Types of bioregenerative ECLSS technologies and the ECLSS subfunctions they can perform.

Higher land plants can be used as they are on Earth for air filtering, conversion of CO₂ into O₂, production of food, and, less commonly, energy production (e.g., biofuels). Algal reactors are used in similar ways, though are less appealing and nutritionally complete as a food source. Both aerobic and anaerobic composters can filter air and aid in recycling of inedible biomass. Microbial bioreactors, both aerobic and anaerobic, are useful for water purification and energy production. Lastly,

leaching technologies extract essential nutrients from inedible plant biomass to be used in future food growth.

1.1.2 The physicochemical-bioregenerative spectrum

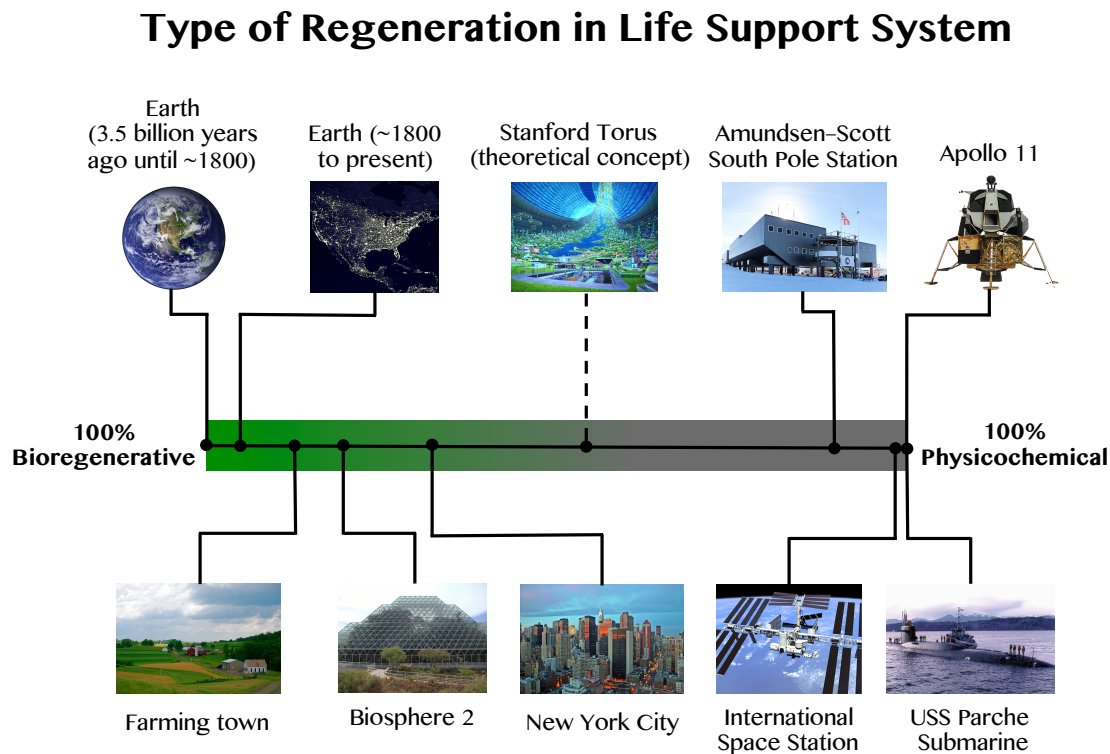


Figure 1-2: Habitats are placed along a spectrum based upon the proportion of life support technologies they employ that are bioregenerative or physicochemical. Mostly or entirely bioregenerative systems (e.g., the planet Earth) fall to the far left; mostly or entirely physicochemical systems (e.g., ICEs) fall to the far right. Hybrid systems are in the middle.

Figure 1-2 notionally classifies several habitats based on the types of life support technologies they employ. Examples of hybrid bioregenerative-physicochemical habitats are shown, as well as some closed ecosystems and fully physicochemical habitats that lie on either end of the spectrum. Throughout most of human history, we have relied on naturally occurring biological processes to sustain ourselves; only relatively recently (ca. Industrial Revolution) has our naturally evolved life support system -

the Earth - been notably altered by the introduction of physicochemical machines [4].

Life support systems for isolated and confined environments (ICEs) such as submarines and spacecraft developed as entirely physicochemical, with any recycling of consumables accomplished by technologies that employ either passive or active chemical and physical processes (e.g., an air filter that uses a metal oxide adsorption bed to remove CO₂ from the air). The incorporation of bioregenerative components in ICEs is notable but relatively recent. Bioregenerative life support technologies that are currently in use in Earth-based isolated and confined environments such as the Antarctic Base include greenhouse-like controlled plant growth chambers that provide the researchers with fresh food [5]. Plant growth has also been tested in space, but almost entirely for scientific purposes, not life support; however, the plants tended by the ISS “farmers” do slightly alter the atmosphere of the ISS, so they can be considered part of the life support system. Bioreactors have also been flown on the ISS for scientific research [6] but not as an integrated part of the life support system.

In the future, habitat concepts such as the Stanford Torus [7] incorporate vast, complex hybrid ecosystems in which many biological components such as microbes, plants, insects, and animals cohabitate with humans “naturally” as they evolved to do on Earth, while at the same time controlling key LS parameters within prescribed limits using physicochemical technologies.

1.1.3 The relevance of hybrid life support systems

The near- and far-term goals of the National Aeronautics and Space Administration (NASA) for manned space exploration motivate a systematic examination of hybrid life support systems to enable long-term habitability in space. NASA is working towards a crewed exploration of the surface of Mars in the 2030s [8, 9]. To this end, NASA has developed roadmaps for the development of necessary technologies. The Technology Area (TA) 06 (Human Health, Life Support and Habitation Systems) roadmap [9] reflects high interest in the development of hybrid habitation systems within NASA’s Exploration Systems Mission Directorate.

Figure 1-3 shows a roadmap timeline for the Human Health, Life Support and

Habitation Systems technology area. The roadmap assumes a crewed highly elliptical orbit (HEO) mission in 2021, a crewed near Earth object/asteroid mission in 2025, crewed Mars Orbit/Phobos and near Earth object missions in 2030, and crewed Mars orbit and surface missions around 2034-2035. To support these missions, the roadmap calls for a flight demonstration of an “integrated, mostly physicochemical ECLSS (full oxygen recovery, nearly full water recycling, and food augmentation with plants) around 2017, a flight demonstration of an augmented hybrid ECLSS (bulk food production and full oxygen and near-full water recovery augmented with crops and biological systems) around 2027, and a ground demonstration of a “primary hybrid ECLSS (oxygen and water recovery principally provided by crops and biological systems and bulk food production systems) around 2028. By 2035, the roadmap expects to demonstrate integrated ECLSS and food production in an Earth-bound testbed.

The TA 07 (Human Exploration Destination Systems) roadmap [10] emphasizes the importance of sustainable and reliable systems to support missions destined for a HEO and Mars, similarly calling for in situ food production by 2020 and a demo of Mars surface logistics including food production systems by 2025. After viewing the TA 06 and TA 07 timelines, one may follow up with questions such as how to decompose these requirements (e.g., what percentage of oxygen should be recycled by plants in each ECLSS?), or which specific technologies we should invest in to meet these goals (e.g., which type of water purification should we fund - microbial or purely chemical?). There is clearly a need for dependable analysis of hybrid ECLSS technologies and habitats to better inform the goals on roadmaps such as these. For example, specifying the proportion of regeneration by biological means would aid scientists and engineers in their efforts to support NASA’s needs. To this end, there are two broad questions we hope to apply to bioregenerative and physicochemical life support systems and address with this work [11]:

1. **Isoperformance Investigation:** What combinations of technologies from a given set of options can meet a given set of mission requirements (mainly defined in terms of crew size and mission duration)?

2. **Technology Development Guidance:** What are the requirements for a specific technological concept in order to reach a given level of system performance?

1.1.4 The bioregenerative-physicochemical trade

Hybrid life support systems are employed in science fiction works (e.g., *Battlestar Galactica*, *Sunshine*) and in futuristic visions of long-term, sustainable space habitats envisioned by the astronautics community (e.g., *Stanford Torus*). However, some point to the importance of high-reliability systems for spaceflight as a justification for excluding biological life support systems from ECLSS. For example, Monsi Roman, chief microbiologist for the Marshall Space Flight Center’s ECLSS project, stated that “While you try to mimic what’s happening on Earth – which is so complicated if you really think about it – we have to use systems that we can control 100 percent.” According to Roman, ECLSSs employ machines over microbes because “if a machine breaks, you can fix it” [12]. Jane Poynter, one of the participants in the two-year Biosphere 2 experiment in Oracle, AZ from 1991-1993, stated that “Until artificial biospheres have undergone extensive testing, I would only bet my life on one that had physical/chemical backup systems” [13, 288].

In addition to concerns about reliability, the low TRL of bioregenerative components could postpone their incorporation into existing heritage physicochemical systems. Hardware heritage is certainly an advantage of the continual employment of purely physicochemical life support systems for manned space flight. Previously used ECLS systems such as those successfully developed for Apollo and the ISS contained almost entirely physicochemical technologies such as Sabatier reactors, oxygen storage tanks, waste stabilization and storage canisters, etc. The TRL of physicochemical technologies certainly surpasses that of bioregenerative components that have been tested in isolated and confined environments on Earth (bioregenerative components generally have TRL lower than 6), such as microbial bioreactors, microbial water filtration systems, and plant growth chambers. Still, visions for crewed Mars missions include bioregeneration (e.g., NASA’s roadmap for achieving a crewed Mars surface mission necessitates the regeneration of consumables partially through biological

means), and many have suggested the incorporation of non-critical bioregenerative systems into missions to not only add redundancy but also provide physiological and psychological benefits to the crew [14]. So it seems that there are competing objectives, and therefore trades to be made, when it comes to choosing biological vs. physicochemical technologies for a space life support system. We hypothesize that there exists, for a given population or crew size and mission duration, an optimal mix of technologies.

1.2 Review of the Literature

Searching for the optimal combination of physicochemical and bioregenerative life support technologies for a given mission is a multidisciplinary problem that draws from systems biology and from both those who work on technology development and those who perform trade studies within the ECLSS community. Work in the field of systems biology has investigated issues related to complexity and robustness [15][16][17]. Numerous analyses of isolated bioregenerative technology (e.g., crops, microbial reactors) performance have been carried out in order to characterize them and identify feasible opportunities to replace consumable stores and/or regenerative physicochemical technologies with more effective biological elements [18][19][20]. Trade studies have been performed for individual subsystems of a habitat [21][22][23].

The ESM of a system takes into account the mass of the system itself as well as the added infrastructure (power, volume, thermal energy, crew time, and logistics) mass that will be needed to support the system’s operation. There is a mission duration at which the ESM cost of a hybrid system is lower than that of a purely physicochemical system with similar performance; at this “break-even” or crossover mission duration and longer durations, the hybrid system is ESM-optimal, and at shorter mission durations, the physicochemical option is ESM-optimal. Several studies have predicted crossover times when biologically-produced food becomes ESM-optimal to be somewhere between 0.49-20 years [24][25][26] depending on assumptions about mission scenario, improvements to the crop production system, and infrastructure costs. A

common limitation of these studies is the consideration of the food subsystem ESM in isolation and the limited computation of ESM for fixed mission durations (which can only be used for a vague estimate of crossover times). A 2004 study by Alan Drysdale calculated ESM for a 15-year Mars surface base with a large lettuce crop and assumed different improvements to the BPS system and usage of in situ consumables and found crossover times of around or significantly less than 15 years [24]. The study used static estimates of crop productivity and prescribed crop area per crew member from an independent BIO-Plex study. With a separate set of assumptions favorable to bioregeneration (sunlight usage, advanced BPS system, falling infrastructure costs), Drysdale 2005 computed crossover points around 800-1000 days (2.2-2.7 Earth years) for Mars surface and Mars flyby missions [25]. Drysdale 2001 computed a crop metric that indicates ESM-optimality for the food providing system and found the crossover point for most crops to be between 180-5278 days (0.49-14.46 years), but the study did not consider the potential ESM savings in the air and water subsystems due to full plant functionality [26].

Zabel and Schubert [27] have taken an initial look at incorporating physicochemical technologies into greenhouses to improve their performance. Other studies have focused on a single external environment (e.g., the Moon) and performed trade studies for the purpose of making technology development recommendations [28].

However, there is a noticeable lack of general studies with regard to the nature of combined physicochemical and biological processes within space life support systems across external environments. The project described in this paper ultimately aims to aid in the general examination of regeneration that enables sustainable habitats by carrying out trade studies on the integrated habitat system that employ existing validated high-fidelity habitat modeling tools and consider multiple combinations of technologies across subsystems and multiple simulation parameters (i.e., mission duration, external environment, crew size).

1.2.1 Overview of existing and past life support modeling efforts

Several ECLSS modeling tools exist at varying levels of fidelity and for different purposes. This section briefly summarizes three modeling efforts. A fourth modeling tool, BioSim, is used for this research, and will be discussed in future sections.

Virtual Habitat

The Virtual Habitat (VHab) is a dynamic life support system modeling and simulation software developed by students at the Technical University of Munich (TUM) [29]. VHab runs at very high fidelity, and the technologies and system topology are defined by the user [29]. The need for integration of dynamic factors into optimization of life support systems motivated VHab’s creation. VHab enables users to simulate entire mission scenarios (e.g., ISS operations) and provides information about the system to the user, who may wish to quantify system stability, controllability, or robustness. The modular structure of VHab is shown in Figure 1-4. The four main modules are the closed environment module, the crew module, the physicochemical module, and the biological module. The closed environment module is the “backbone” of the simulation: it contains the habitat buffers and consumables and manages boundary conditions, internal interfaces, and life support system control. While it has been demonstrated to be a useful tool, VHab is not open-source and is unfortunately only used by students at TUM and presumably a few others.

EcosimPro

EcosimPro is a multidisciplinary dynamic system modeling and simulation tool that can be used to simulate life support systems of a user-defined topology at very high fidelity [30]. EcosimPro has been used by the European Space Agency and aerospace companies for simulations in various fields, including propulsion, ECLSS, and power systems. The tool can model any system that is represented by a set of differential equations and discrete events. The tool is valued for its object-oriented structure,



Figure 1-4: Virtual Habitat simulation top-level modules and substructure [29].

expandable ECLSS component library, and user-friendly visual environment. Users can “easily” add or edit components in the ECLSS component library, allowing them to achieve the acquired level of fidelity for different applications [30]. The main components modeled are:

- Cabin
- Crew
- Fittings
- Pipes

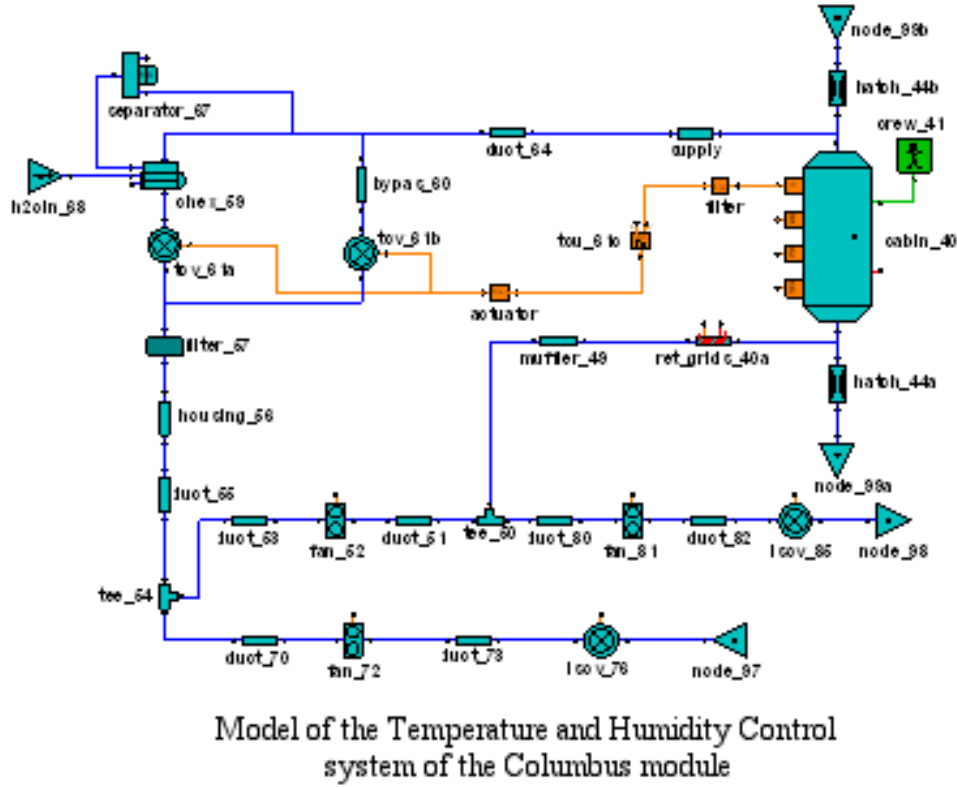


Figure 1-5: EcosimPro graphical model of the temperature and humidity control system of the Columbus module [30].

- Valves
- Boundary Conditions
- Sensors

The tool simulates chemical reactions, mass and energy balance, heat transfer, biological processes, and fluid flow; all of these processes are essential to high-fidelity modeling of ECLSS systems [30].

ALSSAT

Development of the Advanced Life Support Sizing Analysis Tool (ALSSAT) was initiated by NASA Johnson Space Center's Crew and Thermal System Division in 1997 [31]. ALSSAT was intended to meet the ECLSS community's need for a tool to aid in sizing of ECLSS for design, trade studies, and system optimization [31]. The steady-state model operates at medium level of fidelity and allows the user to define

the system topology. The focus on Advanced Life Support (ALS) Systems indicates the intention of the model for use in modeling systems with resource regeneration (regeneration by physicochemical and/or bioregenerative processes). The model has six Exploration Life Support subsystems: Air Management Subsystem, Biomass Subsystem, Food Management Subsystem; Solid Waste Management Subsystem, Water Management Subsystem, and Thermal Control Subsystem. There are also external interfaces for Extravehicular Activity and Human Accommodations [31]. ALSSAT evaluates both short-duration, open-loop and long-duration, closed-loop systems for mass, volume, power, and ESM. Limited system optimization for various mission scenarios can be performed.

1.2.2 Overview of ECLSS bioregenerative technology development

NASA has funded many ECLSS bioregenerative technology development projects over the past 30 years. This includes bioregenerative research and testing for NASA's Controlled Ecological Life Support System (CELSS) and ALS programs, a timeline of which is shown in Figure 1-7.

Several countries' space programs have pursued and funded bioregenerative technology research in the past decade: The European Space Agency continues to fund the MELiSSA Project [33], the Closed Ecology Experiment Facility (CEEF) is run by the Japanese Institute for Environmental Science [34], and the Italian Space Agency runs the CAB project [35]. Numerous other technology development and closed ecological system testing efforts are underway in these countries, as well as in Canada [36], China [37], and Russia [38].

1.2.3 Overview of ECLSS trade studies

Several trade studies that examine the effect of technology selection on ECLSS subsystems have been carried out to investigate the relative merits of ECLSS technologies.

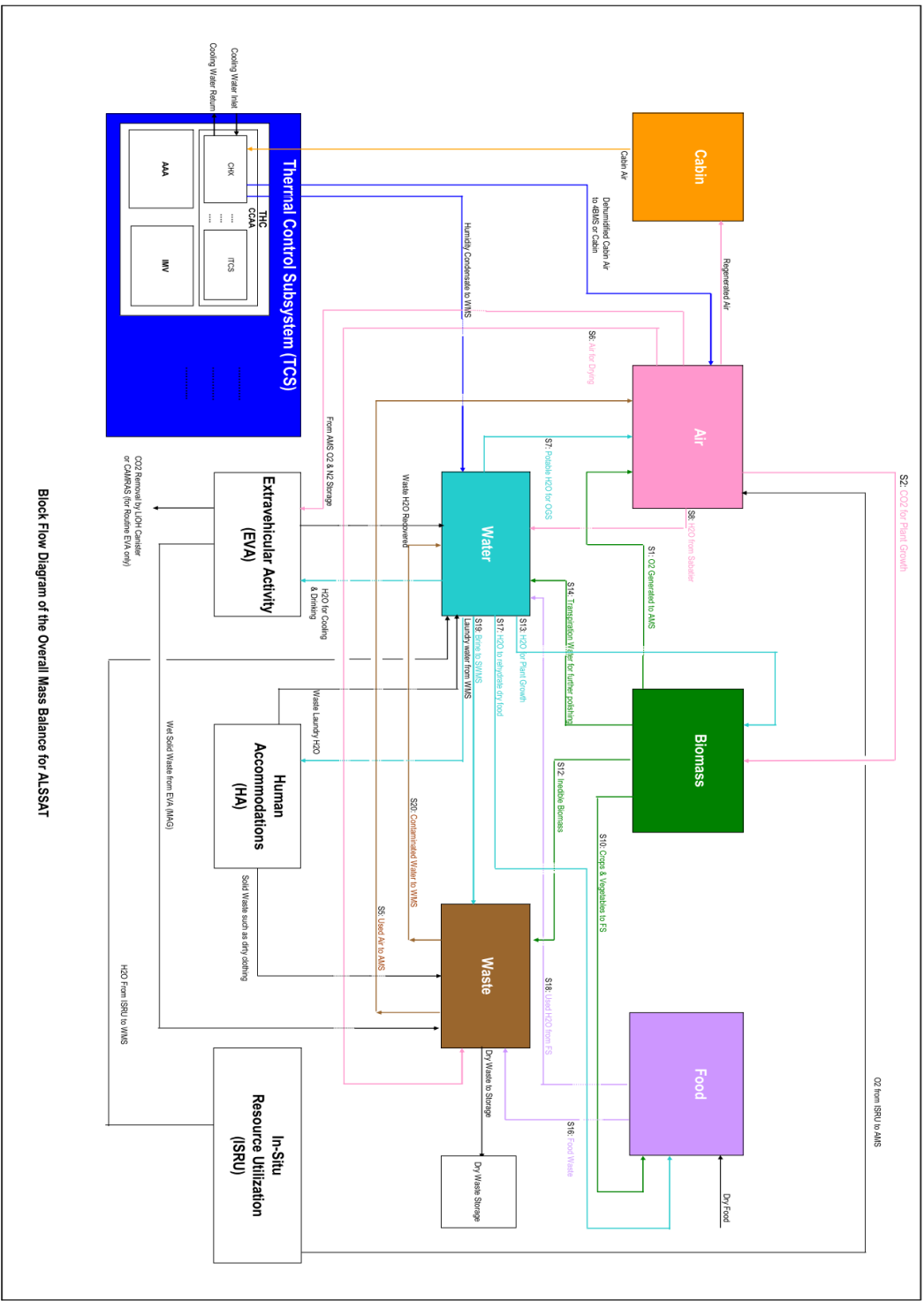


Figure 1-6: Block Flow Diagram for ALSSAT Integration of the ALS Subsystems and External Interfaces [31].

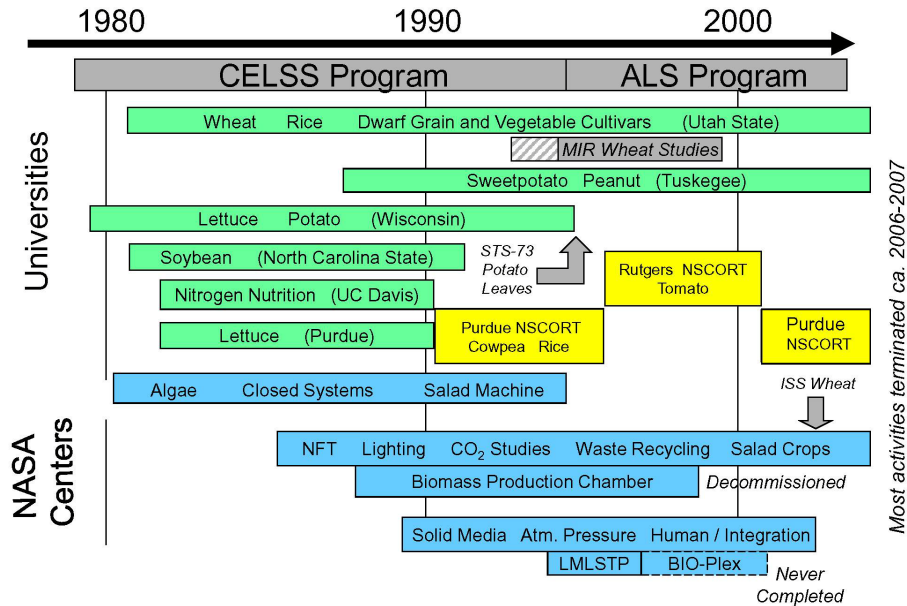


Figure 1-7: Timeline of NASA-funded bioregenerative life support technology research through 2007 [32].

Three examples are summarized in this section.

Laundry subsystem

Maxwell and Drysdale investigated feasibility and usefulness of laundry options [23]. Laundry poses the second-largest logistical load on a long-term mission if it is not recycled (after food); however, different washing methods require sometimes significant consumables from the life support hardware. The authors discuss how terrestrial “commercial-off-the-shelf” (COTS) laundry systems could be modified for use on long-term space missions. Each system is evaluated for ESM, and it is assumed that there will be limited resupply. The laundry subsystem is isolated in the calculation and there are no discrete events considered in the steady-state balance. The authors consider three missions: ISS (low Earth orbit, or LEO), Mars transit, and Mars surface base scenarios. The authors conclude that any of the high efficiency terrestrial COTS laundry systems considered would be cost-effective for each mission considered (see Figure 1-8 for the ESM Analysis); however, at this time, it is not cost effective to introduce laundry for ISS now because ISS already has a 90-day resupply frequency

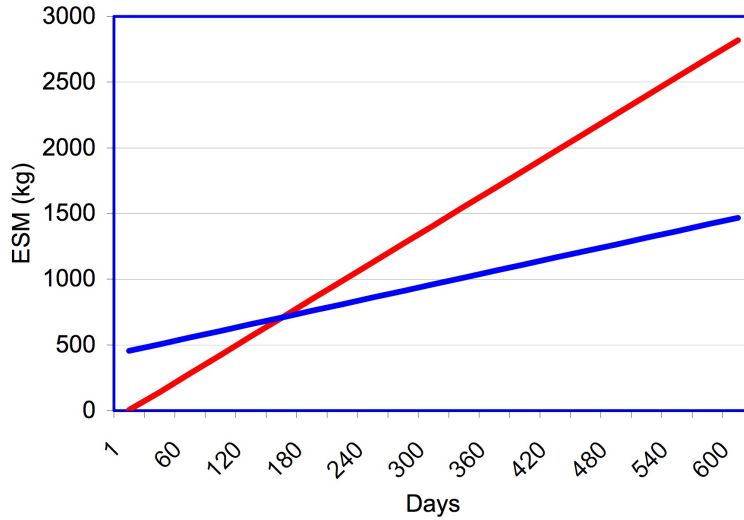


Figure 1-8: ESM Analysis of lowest-ESM laundry option considered by Maxwell and Drysdale (the Comb-O-Matic 2000, shown in blue) vs. stored clothes (shown in red) [23]. The crossover mission duration is about 175 days.

and does not have prohibitive concerns about waste volume or bacterial growth and odors.

Waste subsystem

Drysdale performed a trade study with respect to various waste processing options and similarly evaluated ESM [39]. Mission scenarios considered were of long-duration and beyond LEO (lunar surface and Mars surface). The processes considered were storage, compaction, drying, aerobic and anaerobic biodegradation, chemical oxidation, pyrolysis, and post processing. It is assumed that waste is constantly produced and constantly processed. The author also graphs linear relations between ESM and mission duration based on two points per line (an estimated ESM at $t = 0$ years and an estimated ESM at the baseline mission duration of the mission scenario in question). ESM was only calculated for the isolated waste management subsystem. The author discusses the effect of the chosen waste management system on other subsystems qualitatively (e.g., with regard to the waste water they produce that must then be processed) and notes the tight connection between the waste management subsystem and water management and oxygen production subsystems.

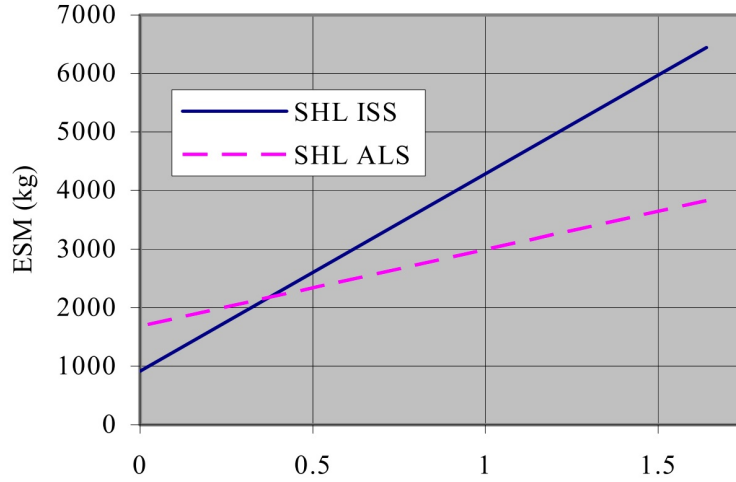


Figure 1-9: ESM Analysis (ESM vs. mission duration in years) of two Mars Surface Habitat waste systems. The solid line shows the first-order ISS ESM for a baseline Mars Surface Habitat Lander (SHL), extrapolated for different mission durations. The dotted line represents the Advanced Life Support (ALS) System SHL [39].

Food subsystem

Levri et al. performed a food system trade study (ESM analysis) for an early Mars mission [21]. The food options considered were the ISS Assembly with some frozen food and four variations of the Shuttle Training Menu. Each option assumes salad crop growth, and one of the Shuttle Training Menu options assumes white potato crop growth. The authors estimate the ESM of the entire ECLSS system for the point design of a 600-day Mars mission with a majority of technologies that are physicochemical. Sizing for the food, air revitalization, solids processing, and water recovery subsystems was performed based on a static mass balance using static estimates of technology consumable flow rates. The salad crops and the potato crop (when included in the food option) growth areas were sized to 7.5 m² for a crew of six. Potatoes were chosen based on the low level of preparation they require. Yields of both the salad and potato BPS shelves were estimated based on an average dry edible biomass growth rate. The authors compute nutritional parameters (energy, protein, carbohydrate, and fat content) for each menu. One of the main focuses of this study is the packaging approaches used for the stored food; the authors consider the merits (both quantitatively and qualitatively) of thermo-stabilized, intermediate moisture,

Sub-system	1 (frozen)	2 (multiple serving)	3 (potato)	4 (indiv)	5 (low mc)
ARS	5,617	5,616	5,568	5,616	5,617
BPS	2,452	2,452	6,310	2,452	2,452
FPS	11,551	6,388	6,414	6,461	5,581
SPS	976	697	969	707	707
WRS	4,371	5,472	5,317	5,469	6,374
HAS & EVA	2,620	2,620	2,620	2,620	2,620
ESM _{NCT}	27,587	23,246	27,198	23,324	23,351

Table 1.3: Non-crewtime ESM analysis of each ECLSS subsystem for the point design early Mars mission [21]. Units are in kg.

natural form, and rehydratable packaging. Table 1.3 shows the breakdown of non-crewtime ESM costs (includes mass, power, volume, thermal energy, and logistical factors) for each subsystem.

1.2.4 Overview of other relevant literature

Zabel and Schubert took an initial look into incorporating physicochemical technologies into greenhouses and hypothesized that greenhouses, when considered with supporting physicochemical hardware, would be more reliable and attractive for use in space flight [27]. The authors note the complexity of greenhouse modules and the high heritage (TRL level) of physicochemical life support technologies such as CO₂ adsorption technologies, electrolysis technologies, water purification systems, and waste recycling techniques. The authors review the challenges faced by life support systems employing greenhouses (see Figure 1-10), some of which can presumably be mitigated by using physicochemical elements with active or passive control. Some horticultural methods, such as continuous planting and harvesting, can be implemented to further mitigate the oscillations in consumable use and atmosphere revitalization rate of higher plants [27].

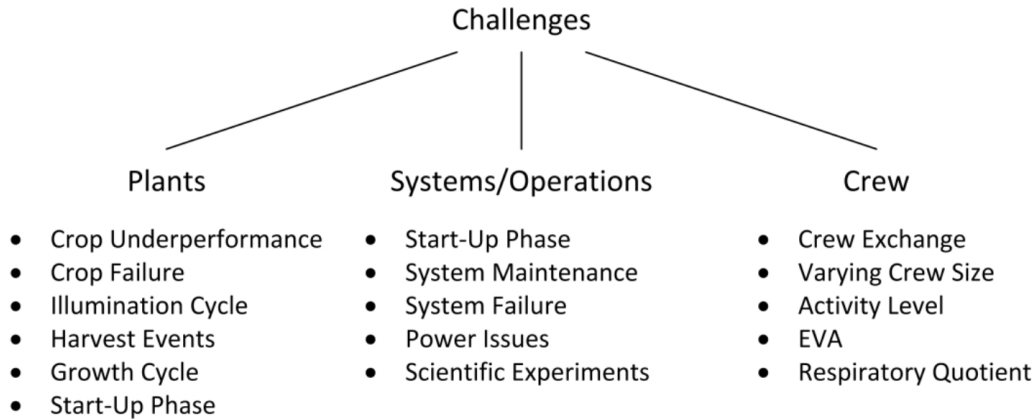


Figure 1-10: Types of challenges associated the the incorporation of greenhouses into life support systems [27].

1.3 Reductionist vs. Systems-Level Research: a Comparison of Research Methods

The complex nature of bioregenerative processes requires special consideration relative to physicochemical processes largely by nature. Bioregenerative life support technologies attempt to exploit biological processes that are the subject of (sometimes ongoing) scientific inquiry for practical purposes (e.g., carbon dioxide removal from mixed-gas air). The governing chemical processes may be understood to varied levels of detail and confidence, and system-level behavior is often measured and tested in various controlled lab settings. However, this approach is largely unstandardized. The bounds of operation of biological processes are often difficult to ascertain because testing every combination of parameters for the surrounding environment is impossible. In contrast, physicochemical technologies are often imagined from the “bottom up,” i.e., well-understood physicochemical processes are combined to achieve a desired effect, creating an arguably more transparent emergent process.

It is relevant to compare the generally reductionist research methods employed by the ECLSS community, at NASA and elsewhere, and the systems research methods followed by the field of systems biology. The approaches to bioregenerative life support technology modeling and testing employed by NASA and Biosphere 2 (as an example of an independent life support research project employing a staunchly sys-

tems approach) have been pointedly different, and the development of long-duration regenerable ECLSS will likely require a closer look into both with the aim of developing an appropriate research methodology and potentially a unified approach (e.g., use of a unified modeling language to map system processes, inputs, and outputs).

1.3.1 Closed Ecological Systems Research at NASA

A series of controlled experiments were carried out in the 1990s at NASA Johnson Space Center that examined hybrid regenerative life support systems for air, water, and solid waste recovery. The Lunar-Mars Life Support Test Project (LMLSTP) had four phases: Phase I was a 15-day, 1-person air revitalization system test using a vari-



Figure 1-11: Crew, backup crew, and other Advanced Life Support personnel of the LMLSTP Phase IIA experiment [40].

able pressure growth chamber (VPGC); Phase II was a 30-day, 4-person integrated physicochemical air revitalization system, water recovery system, and thermal control

test in the life support systems integration facility (LSSIF); Phase IIA was a 60-day, 4-person ISS integrated ECLSS test in the LSSIF (the Phase IIA team is shown in Figure 1-11; Phase III was a 90-day, 4-person integrated physicochemical and biological air recovery system, water recovery system, and trace contaminant control system test in the VPGC and LSSIF. The technologies tested included wheat crops for air revitalization and food production, microbial bioreactors for waste water treatment, an incinerator for carbon recovery from solid waste (straw and feces), and physicochemical CO₂ removal systems, CO₂ reduction systems, and oxygen generation systems [41, 48-49].

The tests demonstrated the controllability of crops with regard to photosynthetic rate and yield, as well as the robustness of plant systems in an integrated hybrid life support system [41, 45]. Crops were shown to be a feasible option for continuous CO₂ removal and O₂ production (11.2 m² of wheat provided continuous air revitalization that would meet the needs for a single human test subject over the duration of a 15-day experiment (LMLSTP Phase I). Integrated biological and physicochemical life support systems were tested in the LMLSTP Phase III experiment at NASA JSC, in which the function of air revitalization was provided 75% by physicochemical systems (molecular sieve CO₂ removal subsystem, CO₂ reduction subsystem, oxygen generation subsystem, and a trace contaminant control subsystem) and 25% by the wheat crop. Wheat was planted in stages to provide more uniform air revitalization and grain production, avoiding the discontinuities resulting from discrete bulk planting and harvesting [41, 47]. This experiment also confirmed that the nutrients required by the crops could incorporate nutrients recovered from inedible plant biomass.

1.3.2 Closed Ecological Systems Research at Biosphere 2

The Biosphere 2 facility in Oracle, AZ contains a potentially closed ecological system with an area of 1.28 ha and a volume of 200,000 m³ [42]. The facility was designed as a scientific laboratory to aid in ecology and biosphere research. The biomes were used as test beds for environmental research and technology development while the closed ecological experiment was underway from 1991-1993, and continues to be used

as such. Seven types of ecosystems (“biomes”) were constructed: an ocean with a coral reef, a mangrove wetlands, a tropical rainforest, a savannah grassland, a fog desert, the intensive agriculture biome (IAB), and the human habitat. The Biosphere 2 “Technosphere” contained physicochemical systems (electrical, plumbing, and mechanical). Air handler units regulated the agricultural area’s temperature levels to approximately 65 – 87 °F and the humidity levels below 45%.

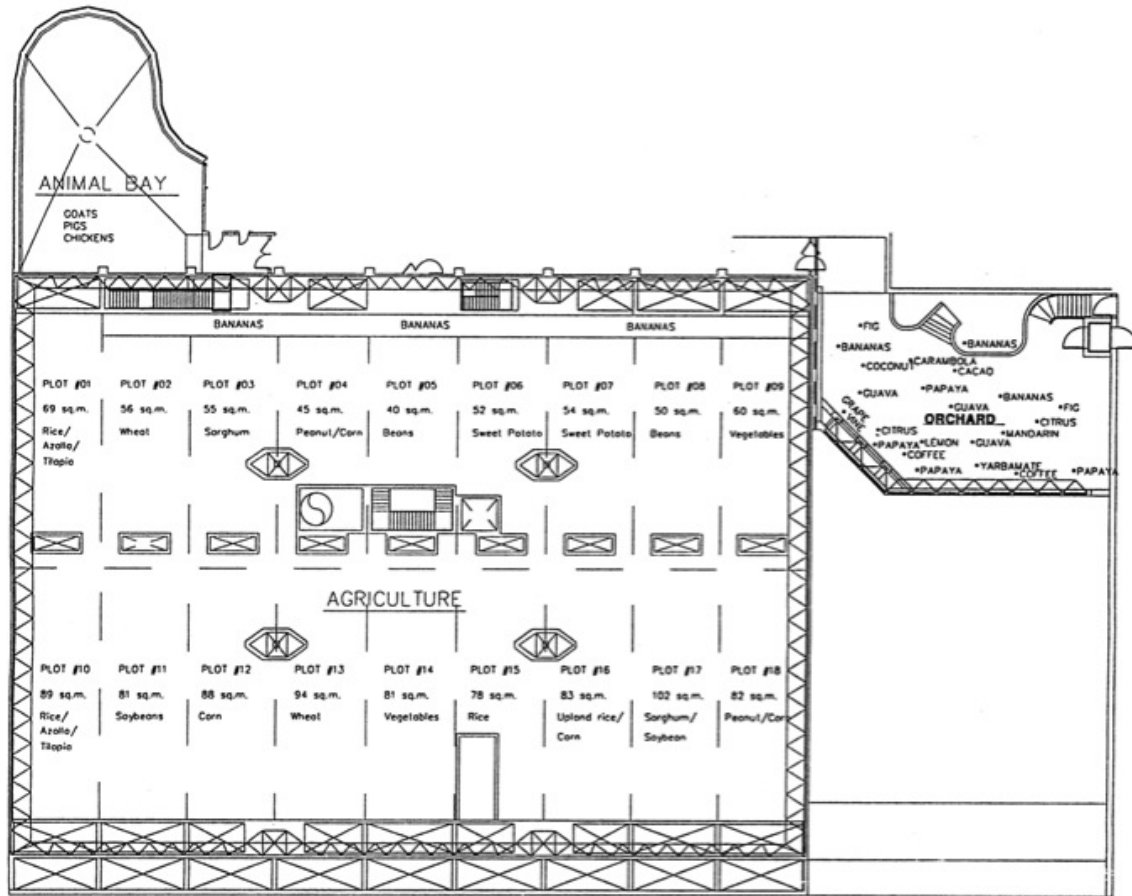


Figure 1-12: IAB floor plan of planting area, orchard, and animal bay. Air handler return vents are located at the center of the IAB [16].

Toxic chemicals could not exist within the closed ecosystem, so the agricultural system was designed to persist without the use of chemical biocides [42]. Creative approaches were taken to keep pests under control (e.g., use of a polycultural agriculture as opposed to a monocultural agriculture, use of non-toxic sprays). Human and animal waste, as well as inedible crop biomass, were processed microbially and the

nutrients were returned to the agricultural system. Trace gases were controlled using the agricultural soil as a microbial soil bed reactor (SBR). When air was pumped through the biologically active soil, trace gases (both produced by the biological elements and other technologies) were metabolized by the microbes [42]. It was found during preliminary development of the SBR that the system is not easily controllable due to the dependence of performance on soil properties (e.g., moisture, composition, ecology) and the air flow rate, plant cover, and other physical characteristics [16].

Agricultural productivity for the approximately 92 crops used in the IAB was reported and was higher than the productivity of the most efficiently run fertile agricultural land on Earth [16]. Light sensors recorded the total daily quantum light in the IAB over time. Atmospheric composition and pressure were measured over time and are reported in constant intervals [42]. However, the atmosphere of the system remained materially mixed for the duration of the closed two-year experiment, so causal relationships for individual technologies and organisms were not obtained, nor were they the scientific goal. Each biome, including the agricultural biome, was treated largely as a unit, and the behavior of each unit was noted in such a way that only high-level causal relationships could be determined. Nelson (1993) states:

The detailed functioning of the agricultural system can be modelled in terms of its interactions with the total ecological system, e.g. its role in biospheric nutrient and water cycles, energy consumption and production, food web structure and maintenance of biodiversity, soil development and seasonal changes [42].

1.3.3 Applications to hybrid life support development and planning

While many who work on long-duration manned space mission planning anticipate the eventual incorporation of bioregenerative components into space ECLSS architectures, this expectation is accompanied by a hesitation to immediately employ these components, likely resulting from the growing risk-averse paradigm in spaceflight

[43, 44]. Physicochemical hardware fails frequently on the International Space Station; however, the perceived risk in the employment of bioregenerative hardware is generally higher than the perceived risk of employing physicochemical hardware. In order to quantify and subsequently reduce risk while increasing reliability for systems employing bioregenerative components, research and evaluation methods for bioregenerative life support components must be further standardized.

One could approach the complication arising from the lack of transparency and predictability of biological processes in two ways: first, by isolating biological elements as much as possible and attempting to achieve high confidence in the underlying chemistry governing the processes in question, or second, by embracing a systems-level approach and noting the behavior of different integrated sets of biological elements in a few varied environments as a way to indirectly ascertain the given element's ongoing processes. The former "reductionist" approach is that generally taken by NASA researchers and engineers, while the latter "systems-level" approach can be observed in the Biosphere 2 project operations.

Ecological systems and physicochemical systems, as well as hybrid systems that employ both, cannot be effectively studied using reductionist approaches or systems-level approaches alone. In scientific research, conclusions must be obtained with high certainty, and causality is often sought after. Ecological systems, by nature, are complex and often display nonintuitive, non-linear behavior, so their characterization requires more than just a reductionist approach [45]. According to those involved in the closed Biosphere 2 experiment, one of the most important and most intriguing scientific challenges of the mission was the "management of shifting equilibria" amongst the atmospheric gases [42]. The Biosphere 2 crew performed a lengthy investigation into one particularly unfortunate cause of inequilibrium, ruling out causes based on both systems-level and direct investigations that targeted specific components of the ecosystem and technosphere. Systems-level analyses of complex systems undoubtedly aids in understanding emergent behavior and optimization; however, it must be performed as methodically as reductionist investigations are. Some recent quotations from the field of biological sciences regarding systems-level approaches are

cited below:

“Systems biology...is about putting together rather than taking apart, integration rather than reduction. It requires that we develop ways of thinking about integration that are as rigorous as our reductionist programmes, but different...It means changing our philosophy, in the full sense of the term” [46, 176].

“The reductionist approach has successfully identified most of the components and many of the interactions but, unfortunately, offers no convincing concepts or methods to understand how system properties emerge...the pluralism of causes and effects in biological networks is better addressed by observing, through quantitative measures, multiple components simultaneously and by rigorous data integration with mathematical models” [47].

1.4 Thesis Objectives

This project poses the question: What is the optimal combination of physicochemical and bioregenerative elements that create a well-functioning system that meets mission requirements? Long-duration manned space missions’ success is heavily dependent on robust ECLSS, yet the ECLSS technologies that will be employed are still under development or, in some cases, have not yet been identified for development and maturation. ECLSS technology development is generally driven by trade studies, and these trade studies must be realistic and must account for the current state of the art technologies and possible improvements. High-fidelity modeling should be applied to ECLSS trade studies, allowing for an analysis of the integrated ECLSS system and habitat that capture non-intuitive issues and emergent interactions and thus providing a more accurate estimate of system consumable and technology requirements. This study determines the optimal integration of bioregenerative technologies into a baseline habitat architecture by using a validated, integrated, time-stepped habitat

simulation. It is hoped that the merits of employing high-fidelity models for trade studies to drive ECLSS technology development will be justified in this study.

1.5 Chapter 1 Summary

To summarize, this chapter introduced and motivated the project that is described in this report. The literature reviewed in this section draws from the field of systems biology and the ECLSS communities at NASA and internationally. The remainder of the report will systematically pursue the thesis objectives (see Figure 1-13 for a graphical representation). Chapter 2 explains the formulation of the project, the baseline habitat architecture, and the approach taken to carry out the case studies. The model used for the case studies is explained in detail, and figures of merit are quantified. Chapter 3 presents results of an ESM analysis for both lunar and Mars surface habitat baseline architectures. The implications of the findings with respect to technology development are discussed. Chapter 4 presents the results of a group project multiobjective ECLSS optimization. Lastly, the findings of this project are summarized in Chapter 5 and detailed areas for future work are described.

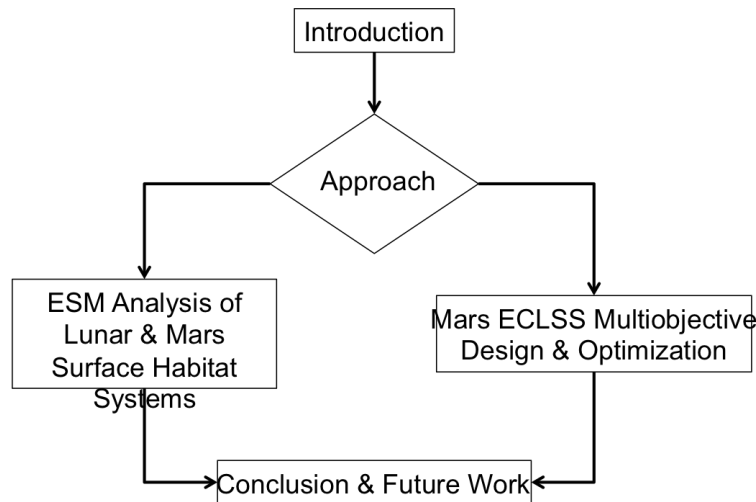


Figure 1-13: Graphical representation of thesis chapters.

Chapter 2

Approach

2.1 Summary of Case Studies

For the analyses present in this paper, we model and simulate lunar and Martian habitats using the open source JAVA-based BioSim modeling tool. The present analysis of these habitats focuses primarily on the food providing and atmosphere management subsystems, with some crossovers into other subsystems. The trade between the choices of stored food and a Biomass Production System (BPS) within the food providing subsystem are summarized in Table 2.1.

	Advantages	Disadvantages
Biomass Production System	<ul style="list-style-type: none">• Self-stabilizing properties• Regenerative• Psychological benefits	<ul style="list-style-type: none">• Crew time potentially high• Risk of crop failure• Supporting hardware/control systems required
Stored Food	<ul style="list-style-type: none">• Little crew time required• Low risk	<ul style="list-style-type: none">• Limited variety• Fixed consumable amount• Limited shelf life

Table 2.1: Trade-off in food providing subsystem.

The baseline habitat architecture that is modeled and simulated for the case studies is shown in Figure 2-1. The directional flow of consumables between environments,

crew groups, stores, and hardware components is shown with arrows. The abbreviations used in the diagram are as follows:

- BPS: Biomass Production System
- Accum.: O₂ accumulator
- Dehumid.: Dehumidifier
- VCCR: Variable Configuration CO₂ Removal System
- CRS: CO₂ Reduction System
- OGS: Oxygen Generation System
- Env.: Environment
- Grp.: Group

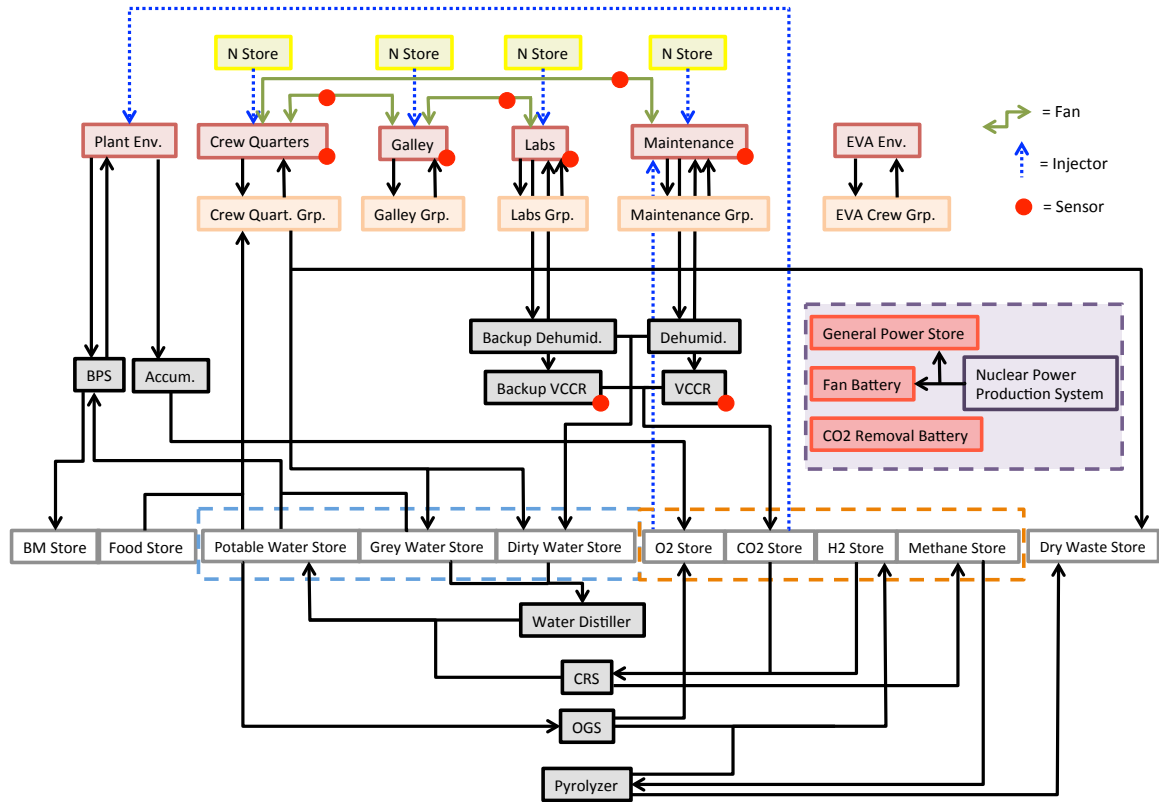


Figure 2-1: Baseline BioSim habitat architecture used for analyses. In this figure, environments are outlined in crimson, crew groups are outlined in peach, physico-chemical and bioregenerative components are outlined in black, stores are outlined in grey, and the power subsystem is diagrammed in the faint purple box to the right.

For both the lunar and Martian surface habitats, the proportion of food providing

and atmosphere providing functions accomplished by the BPS were varied (using the aforementioned architecture as a baseline) to investigate the relative merits of both technologies and, more comprehensively, of different hybrid systems. It was anticipated that the entirely non-regenerable food system (stored frozen/dehydrated foods) would present the lowest-cost option for the food providing function for short duration missions, and a more regenerable hybrid food system option (stored food supplemented with BPS) would present the lowest-cost option for long duration missions. A “crossover point” is anticipated to exist between mission durations of one to several years.

An ESM analysis of lunar and Mars surface habitats is carried out in Chapter 3. For this analysis, the baseline architecture is varied such that varying percentages of the crew’s food needs are met by a biomass production system and stored food systems, respectively. Each architecture that is considered has been designed with appropriate supporting consumable stores and gas exchange rates to achieve atmospheric stability (this is described in detail in the following section). Different levels of autonomy in the BPS management and reduced power demands for the BPS are considered. This work is expanded upon in Chapter 4, which describes and presents the results of a multidisciplinary ECLSS design and optimization project on a simplified architecture based off of Figure 2-1, for which more design variables are allowed to vary.

2.2 Design Assumptions

Changeable parameters in ECLSS architectures with Biomass Production System shelf sizes from 0 to 70 m² were tuned to ensure stable atmospheres in the plant and crew environments and sufficient consumable stores for a mission duration of up to 1000 days (2.7 Earth years). The upper limit of 70 m² was determined such that even with a safety factor of two on crop productivity (a safety factor is not applied in our analysis, but should be in future work), the crew would be fully fed with the maximum BPS shelf area, A_{BPS} . Sizing was performed for the OGS, VCCR, BPS

supporting systems, O₂ store, CO₂ store, potable water store, and grey water store. The driving design variable is A_{BPS} .

The rate of gas exchange between the plants and crew environments were assumed to be a function of the BPS area, and were solved for initially by a trial-and-error procedure using the simulation tool described in the subsequent section to ensure atmospheric stability for 1000 days. In the absence of a control system, a piecewise linear relation between gas exchange rates and store sizes was set and applied to several hybrid architectures (with varied proportion of food providing and atmosphere providing functions accomplished by the BPS). For example, the CO₂ injector and O₂ accumulator rates that transfer each gas between the Plant Environment and each gas store are given in Equations 2.1 and 2.2, respectively, in units of mol/hr.

$$r_{CO_2} = 0.1 + 0.076 \cdot (A_{BPS} - 1) \quad (2.1)$$

$$r_{O_2} = \begin{cases} 0.1 \cdot A_{BPS} & : A_{BPS} \leq 30m^2 \\ 3 + 0.1375 \cdot (A_{BPS} - 30) & : A_{BPS} > 30m^2 \end{cases} \quad (2.2)$$

The OGS and VCCR were linearly sized down from their required size in a baseline physicochemical life support system based on the proportion of O₂ generation and CO₂ consumption, respectively, that the BPS carried out (i.e., if half of the O₂ production was handled by the BPS, the OGS component rate in the simulation and the OGS ESM would be halved). The required initial gas and water store sizes were computed based on the actual observed consumable consumption of the system over the mission duration. Figure 2-2 shows the initial O₂, CO₂, and H₂O store levels required to support the systems needs over the full 1000-day mission duration. The leftmost plot shows the linear decrease in initial O₂ level required to provide oxygen to the crew by physicochemical means over the mission duration. After A_{BPS} exceeds 40 m², it is no longer necessary to have a significant O₂ store because of the constant regeneration of O₂ from CO₂. An O₂ store would only be needed for contingency purposes in the event of BPS failure. The (middle) plot of initial CO₂ level is some-

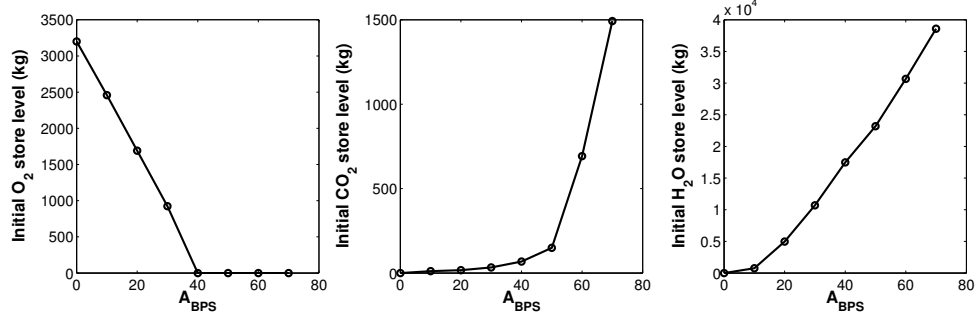


Figure 2-2: Store sizes to support habitat architectures

what less intuitive; the temporal nature of crop CO_2 consumption (see 2-6) and the designed decrease of VCCR rate with increasing A_{BPS} result in a CO_2 store that appears exponential as A_{BPS} is increased. The fixed habitat architecture transfers gas between the Crew Environment using accumulators and injectors; the VCCR can effectively be considered as a CO_2 accumulator that is sized down as A_{BPS} increases. This is an artifact of the fixed architecture in Figure 2 and the design assumption that the VCCR is sized down linearly as the BPS is sized up. A linearly increasing initial CO_2 store level would result if the plants and humans shared the same environment module. Perhaps a more efficient architecture that should be tested in the future would combine the crew and BPS into a shared environment module (in this case, crop layout should be optimized to maximize the psychological benefit to the crew). Lastly, the rightmost plot, initial H_2O store over time, increases approximately linearly with A_{BPS} because the water usage of the BPS dominates over the crews water demand (agricultural water demand on Earth analogously dominates human water consumption). For low A_{BPS} , the crops are able to subsist off of the crews waste water, but for higher crop sizes, a store with dedicated water for the crops must be used.

2.3 BioSim Tool Overview

BioSim is an Advanced Life Support system simulation environment developed at NASA Johnson Space Center in 2003 [48]. BioSim provides a validated dynamic

ECLSS modeling framework that has been used for numerous trade studies, particularly regarding control schemes [49]. The habitat model can be configured to create instances of a general habitat as described in Section 2.3.1. BioSim has many useful features that make it both realistic and user-friendly. During the simulation, the habitat system is accessed through sensors and actuators. Noise and uncertainty are built in, though their use is optional (a deterministic scheme is also possible). The simulation is able to model random and/or scheduled malfunctions and failures of subsystems. The crew members are taskable and can be assigned to perform repair and extravehicular activity, as well as their usual tasks of sleep, exercise, and “ruminating.” Producer/consumer relationships are reflected in the model’s underlying equations [50].

2.3.1 Structure

The top-level structure of the BioSim simulation is shown in Figure 2-3. BioSim

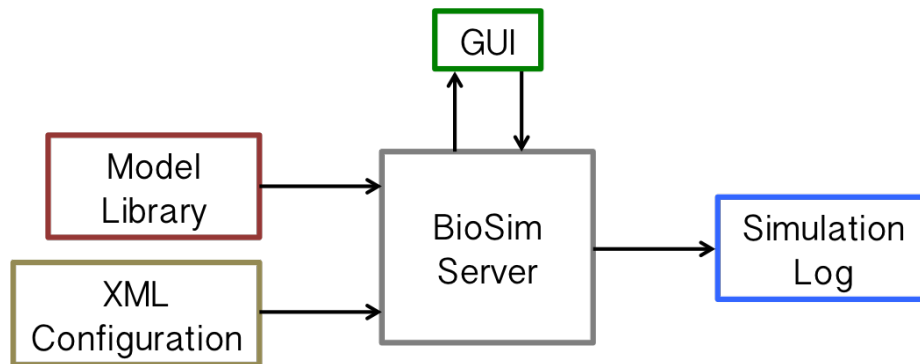


Figure 2-3: Structure of the BioSim simulation.

is a server on which habitat architectures can be simulated. Habitats are designed and initialized using an eXtensible Markup Language (XML) configuration file, in which modules (“BioModules”) representing environments, stores, and technologies are initialized, and the connection between each technology and the environments or stores is defined by maximum and desired flow rates. The types of BioModules roughly map to the subsystems of a habitat, and are as follows:

- Environment (e.g., Plant Environment, Crew Quarters)

- Air (e.g., Nitrogen Store, VCCR)
- Framework (e.g., O₂ Injector, N₂ Injector)
- Water (Water Recovery System, Potable Water Store)
- Power (Power Production System, Power Store)
- Food (e.g., Food Store, Biomass Production System)
- Waste (e.g., Dry Waste Store)
- Crew (e.g., Labs Crew Group, Crew Persons)

The crew members are taskable in BioSim, and their schedule is defined in their module definition in the XML file. The baseline crew schedule is as follows: Sleep (8h), Ruminating (12h), extravehicular activity (2h), exercise (2h). Any activity can be scheduled, and is characterized by an intensity (level 0-5) that describes their metabolic level.

A sample definition of an oxygen generation system, which uses the chemical process of electrolysis to convert potable water into O₂ and H₂, is as follows:

```
<SimBioModules>
  <air>
    <OGS moduleName="OGS">
      <powerConsumer inputs="General_Power_Store"
        desiredFlowRates="1000" maxFlowRates="1000" />
      <potableWaterConsumer inputs="Potable_Water_Store"
        desiredFlowRates="10" maxFlowRates="10" />
      <O2Producer desiredFlowRates="1000" outputs="O2_Store"
        maxFlowRates="1000"></O2Producer>
      <H2Producer desiredFlowRates="1000" outputs="H2_Store"
        maxFlowRates="1000" />
    </OGS>
  </air>
</SimBioModules>
```

```
</air>  
</SimBioModules>
```

In this snippet of the XML configuration file (the full XML file can be found in Appendix A), a module is constructed within the air subsystem of the habitat and it is named “OGS”. Resource inputs and outputs are defined (the OGS is a power consumer, potable water consumer, O₂ producer, and H₂ producer). The source/sink of each resource is defined, as well as the desired and maximum flow rates of each resource. The resources that are tracked in BioSim are power, potable water, grey water, dirty water, air, H₂, nitrogen, O₂, CO₂, biomass, food, and dry waste. Units for the consumable flows can be found in the BioSim User Manual [50].

In addition to these modules, sensors and actuators are initialized in the XML file. BioSim provides a useful platform on which different methods of control can be implemented and compared on baseline habitat architectures. Control systems can access the simulation through sensors and actuators, as would be realistic for a physical system. Malfunctions of hardware and consumable resupply can be inserted into the simulation as specified by the user. The interaction between the server, controller, and malfunctions/resupply is shown in Figure 2-4.

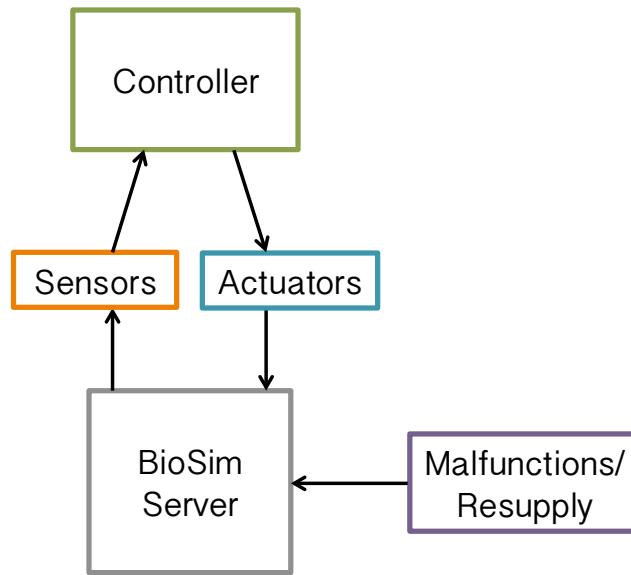


Figure 2-4: Interaction between the simulation and controller within BioSim.

The XML configuration file, containing the habitat topology and technology/environment initializations as described, is read into the BioSim Server, which assembles the models present in the Model Library to construct an integrated habitat system model. The model is then simulated on the BioSim server. The simulation tracks resource flow using a simple producer/consumer model. At each tick (tick duration is one hour), each module takes in resources as consumables from the specified stores and puts resources that are specified as products into their respective stores. If resources are needed by multiple modules in a given tick, the conflict is effectively resolved randomly, and the module that “wins” the resource takes all it needs, and the module that “loses” takes the remainder of the available resource. A future feature allowing for user-specified conflict resolution or prioritization of agents’ needs may be useful.

While the model is loaded on the server, visuals are displayed on the Graphical User Interface, where it can be paused, run tick by tick, and even edited using the GUI. The GUI allows the user to schedule malfunctions and resupply. A screen shot of the BioSim GUI is shown in Figure 2-5.

The BioSim Server outputs a Simulation Log in real time to the user as it runs the model. The type and amount of output is specified by the user in the XML configuration file. The simulation will output the current state of any module that has a `DEBUG` command specified in its initialization.

2.3.2 MATLAB postprocessor

For the analysis present in this paper, a postprocessor was implemented that parses and extracts data from the raw Simulation Log (a .txt file) produced by the BioSim simulation. First, lines of interest (e.g., Plant Environment CO₂ level over time) from the very large Simulation Log are parsed into succinct .txt files (one file per value of interest). Then the data is extracted from each file and assembled into vectors corresponding to environment module atmosphere compositions and consumable store

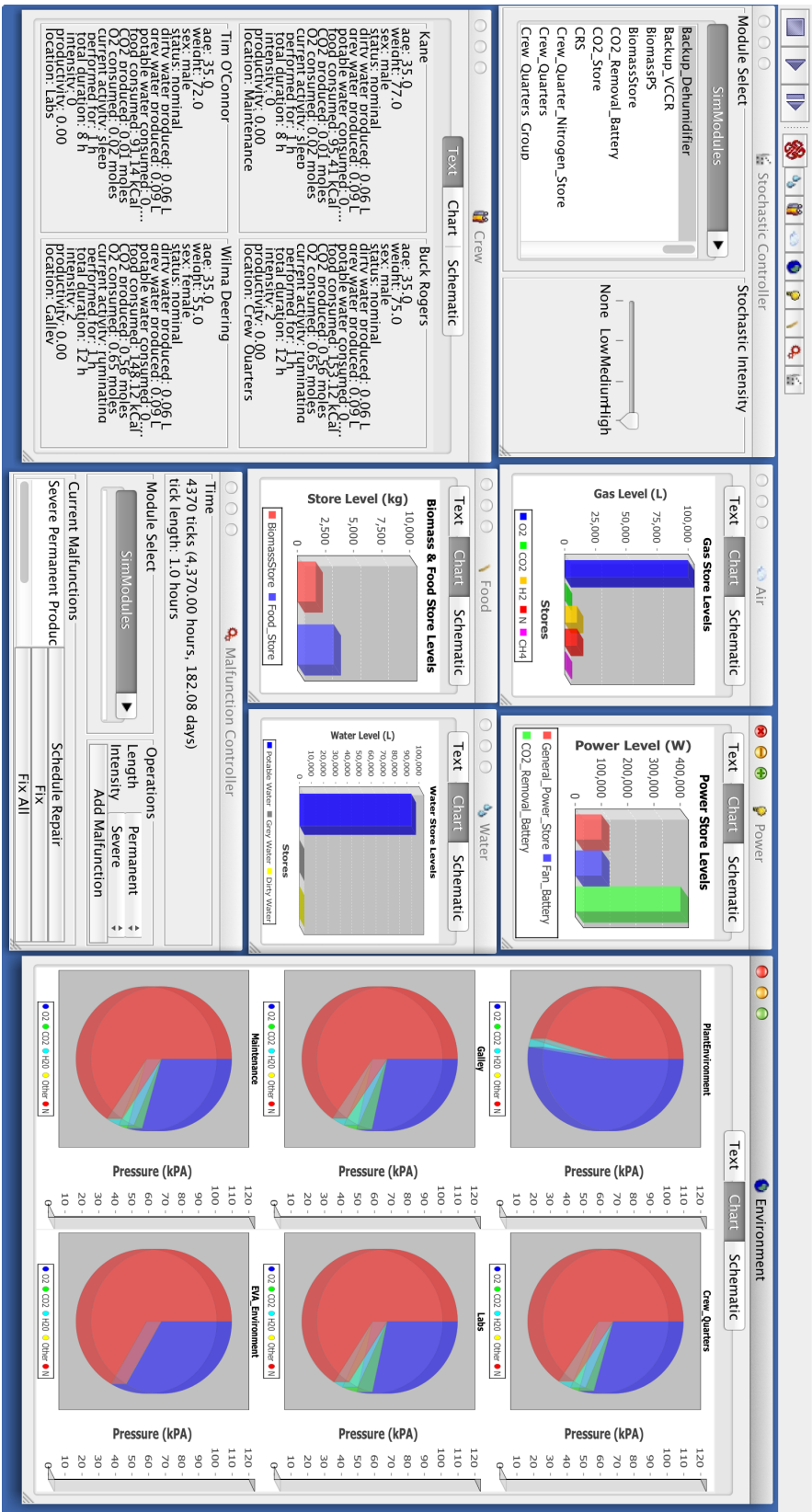


Figure 2-5: BioSim GUI showing all visual modules open.

levels. The postprocessor has been optimized for time at the expense of memory and uses UNIX commands (**grep** and **awk**) through Matlab to parse lines and write to .txt files. The MATLAB postprocessor code can be found in Appendix B.

2.3.3 Biomass production system model overview

One of the technologies modeled in BioSim is a Biomass Production System (BPS), a generic controlled environment plant growth chamber. A model of a BPS was developed in Matlab/Simulink to prepare for the construction of the Bioregenerative Planetary Life Support Systems Test Complex (BIO-Plex). BIO-Plex was a large-scale test and research facility that was initiated in the early 1990s and developed by NASA Johnson Space Center (JSC) for the purpose of testing and maturing ALS technologies and operations for long duration space missions that require a high degree of loop closure [41, 43-45].

A BPS for long-duration space flight, such as the BPS that would be employed for a mission to the Moon or to Mars, is assumed to grow crops hydroponically for mass-efficient delivery of nutrients to plants. The atmosphere, layout, lighting, and nutrient providing systems central to BPS design are optimized to produce maximum crop yield. It is important to note that BPS design has not yet been optimized for mass and infrastructure needs.

The BPS model implemented in BioSim is based off of the dynamic BIO-Plex BPS model that uses energy cascade crop models for high-fidelity simulation of crop system consumable use and yield [51]. The model takes as input any crop mix and planting schedule and provides the resulting consumable (gas and water) exchange and biomass production. The crops modeled are dry beans, lettuce, peanut, white potato, rice, soybean, sweet potato, tomato, and wheat. The crop models were validated with data on lettuce, potato, soybean, and wheat gas exchange and plant growth (no data was available on the other plants) [51]. In the detailed energy cascade crop model, environmental conditions are taken as input (temperature, photosynthetic photon flux from lighting sources, CO₂ level, areal planting density, and photoperiod) and plant developmental parameters are calculated (date of canopy closure, onset of senescence

and plant maturity, and biomass growth rate) [51]. Figure 2-6 shows the CO₂ use of

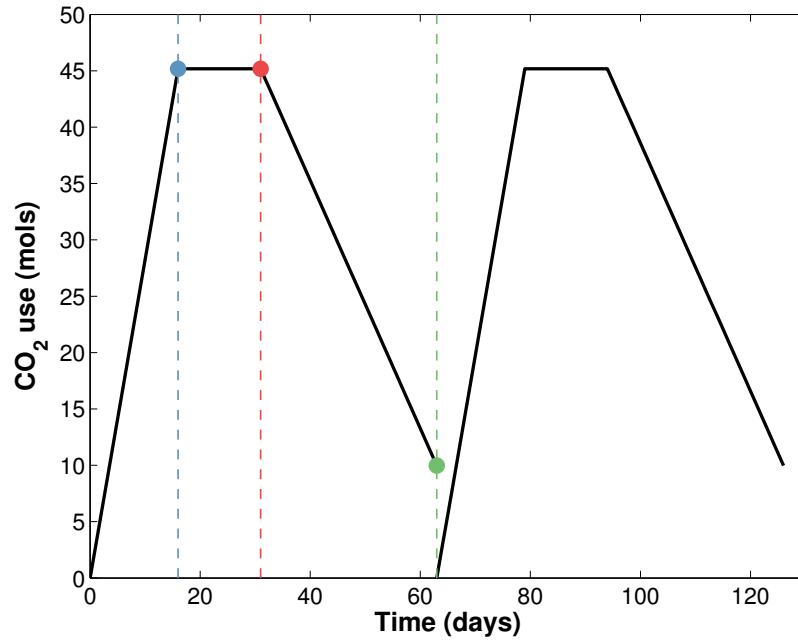


Figure 2-6: CO₂ usage of a 14.2m² wheat crop over three stages of plant growth. The cycle (and time axis of this plot) starts at the time of seedling emergence. The first (blue) point represents the time of canopy closure. The second (red) point marks initial grain setting (onset of senescence). The third (green) point shows the time of maturity or harvest.

a 14.2m² wheat crop, measured experimentally in the BIO-Plex BPS [51]. This time profile also holds for gross photosynthesis, or the CO₂ assimilation rate during light periods.

In the BioSim BPS model, harvests can be scheduled as either discrete or continuous, and new seedlings are planted immediately following a harvest. The BPS directly outputs biomass into the Biomass Store. The amount of dry biomass can be computed from subtracting the water content of the biomass from the total mass. Figure 2-7 shows the edible biomass yield obtained from BPSs of different sizes over 500 days. For simplicity, each BPS contains only soybeans. Also plotted is the 4-person crew's cumulative food demand (note that this is linear). The step-function shape of the yields are due to the 86-day harvest cycle of soybeans and the discrete-time planting schedule. A much smoother yield plot would result from a BPS architec-

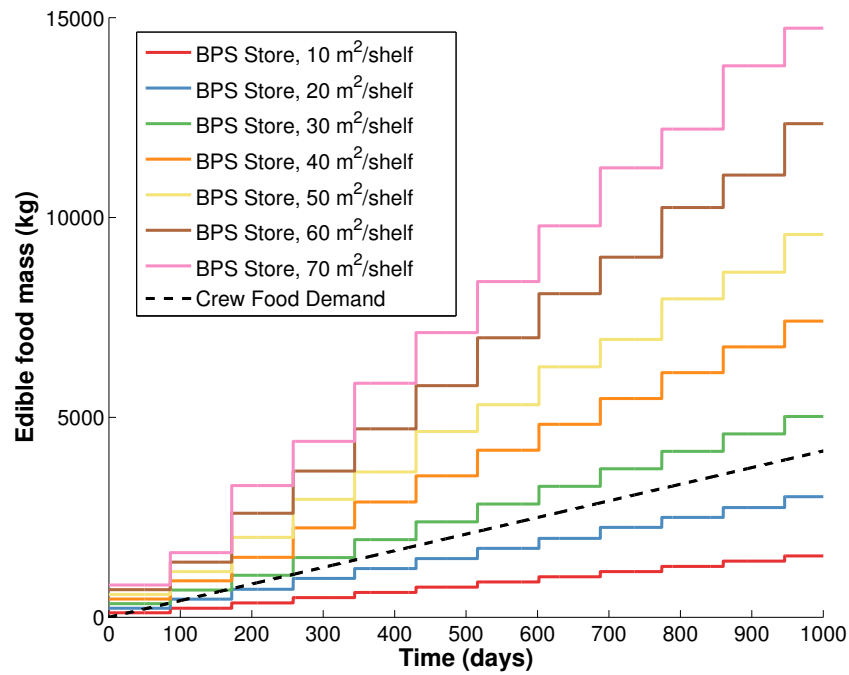


Figure 2-7: Edible BPS store levels for various BPS shelf areas. Also shown is the cumulative crew food demand. A BPS shelf area approximately satisfies crew food demand after the first yield.

ture with varied crops (each with their own harvest cycle time) or with continuous planting and harvesting (this is left to future work). The initial yield happens at $t = 0$ because in practice, the first BPS plants would be planted prior to the start of the mission to avoid an initial reliance on stored food. BPSs with smaller shelf area naturally have smaller yields. The BPS store with 30 m^2 shelf area appears to meet the crew’s food demand over time assuming that, in practice, no crop failure occurs and yields are nominal. Note that crop deaths are modeled in BioSim, but the planned design parameters and simulation of a nominal mission prevented significant crop death from occurring. It is notable that the yields per harvest vary; this is due to plant environment atmospheric gas levels that are not entirely stable over the mission duration. A controller could be implemented to better regulate the atmospheric conditions; however, it has been observed that crops perform quite differently under different atmospheric conditions [42], so this somewhat reflects a realistic scenario.

2.4 Modeling Assumptions

The primary assumptions central to this modeling effort are that the crew consists of four people, the mission takes place on either on lunar or on Mars surface, and the mission duration can be up to 1000 days. The biomass production system (BPS) is the bioregenerative food providing option; stored food is the physicochemical and nonregenerative food providing option. For the ESM analysis, the BPS grows only soybeans, and complete nutritional requirements of crew diet are not accounted for (in BioSim, the crew food requirements and rate of consumption are specified only in terms of mass); however, for the ECLSS multidisciplinary optimization problem, the BPS grows three types of crops (soybean, lettuce, rice) for nutritive purposes. For each food providing subsystem design instantiation, stored food supplements BPS-produced food, and the initial level of stored food is retroactively calculated based on the BPS sizing and corresponding cumulative biomass yield. Additionally, the assumed horticulture scenario is that all crops are harvested at the same time (discrete, not continuous, harvesting). Simulation of a continuous harvesting/planting

cycle is left to future work. It is expected that achieving atmospheric stability will be easier with a continuous harvesting and planting cycle.

2.5 Figures of Merit

The case studies carried out as part of this analysis will distinguish between architectures by quantifying Equivalent System Mass (ESM) as the primary figure of merit. ESM can be used to evaluate technologies based on lowest launch cost, as related to the mass, volume, power, cooling, and crewtime needs [52]. In the ESM analysis presented in Chapter 3, ESM is reported to include crew time mass equivalency. In the multidisciplinary ECLSS optimization presented in Chapter 4, however, non-crew time ESM is reported, as crew time used as a separate metric as a proxy for a mission’s science or resource return value, and evaluates life support system subsystems based on their crew operations and maintenance needs.

2.5.1 Equivalent system mass

The conversion values used for the ESM calculations in these case studies are taken from the 2004 Baseline Values and Assumptions Document [14]. ESM of the food providing subsystem, as well as the CO₂ and O₂ management functions to keep the crew atmosphere livable, are calculated; all other subsystem ESMs are assumed to be the same.

Crop yields are highly sensitive to seed quality, planting density, lighting source, lighting schedule, and irrigation schedule. For this analysis, the BPS power usage has been adjusted to model the use of tunable LEDs instead of the high-pressure sodium lamps that are assumed in the Baseline Values and Assumptions document [14].

The food providing subsystem is architected such that stored food is brought to complete the mass of food needed by the crew over the mission duration. Simply put,

$$m_{stored} = m_{demand} - m_{EBM} \quad (2.3)$$

Subsystem Attribute	Unit	Conversion Factor	Unit
m	kg	C_m	kg/kg
V	m ³	C_V	kg/m ³
P	kW	C_P	kg/kW
TE	kW	C_{TE}	kg/kW
CT	crew-hr	C_{CT}	kg/crew-hr
L	kg	C_L	kg/kg

Table 2.2: Table of subsystem attribute and corresponding ESM conversion factor units. Conversion values are taken directly from the 2004 Baseline Values and Assumptions Document.

where m_{stored} is the mass of stored food, m_{demand} is the crew’s cumulative food demand over the mission duration, and m_{EBM} is the cumulative edible biomass grown by the BPS. m_{EBM} is equal to product of the cumulative crop yield and the harvest index, which is a crop type-specific fraction representing the ratio of edible biomass to total biomass.

The form of subsystem ESM calculations is shown in Equation (2.4). This equation converts the subsystem mass (m), volume (V), power (P), thermal energy (TE), crew time (CT), and logistical (L) needs into the ESM units of kg using conversion factors (C_m , C_V , C_P , C_{TE} , C_{CT} , and C_L , respectively). The units for each of these factors is shown in Table 2.2. Note that the case studies in this thesis do not take into account ESM due to typical logistical needs because the missions assume no resupply for the entire duration.

$$ESM = m \cdot C_m + V \cdot C_V + P \cdot C_P + TE \cdot C_{TE} + CT \cdot C_{CT} + L \cdot C_L \quad (2.4)$$

Nominal ESM conversion factors (“infrastructure penalties”) reported in the Baseline Values and Assumptions Document [53] are accompanied by best-case and worst-case scenario conversion factors. These are reproduced in Tables 2.3 and 2.4 for lunar and Mars surface missions, respectively. The nominal conversion factors are “conser-

vative” and refer to the current technology with little to no improvement; the best-case conversion factors consider infrastructure-saving methods (e.g., fuel cell power storage with solar photovoltaic power generation vs. nuclear power generation, flow-through radiators for thermal heat dissipation vs. lightweight flow-through radiators with solar vapor compression heat pump) [53]. A reduction in the current (conservative) infrastructure costs is probable by the 2020s and 2030s [25], as is a reduction in the infrastructure requirements and yields of the crop production system [24]. Therefore, our results consider improvements to the BPS infrastructure requirements (specifically, increased autonomy and reduced power usage) as well as lower-bound infrastructure costs. The upper-bound infrastructure costs are much more similar to the nominal values than are the lower-bound values, so this analysis only considers the lower-bound and nominal scenarios. Future work should compare all three cases.

Conversion Factor	Unit	Lower	Nominal	Upper
C_m	kg/kg		1.0	
C_V	kg/m ³		9.16	13.40
C_P	kg/kW	54	749	749
C_{TE}	kg/kW	97	102	246
C_{CT}	kg/crew-hr		TBD	
C_L	kg/kg		TBD	

Table 2.3: Table of ESM conversion factors for a lunar surface mission taken directly from the 2004 Baseline Values and Assumptions Document.

There are a few notable differences in lunar and Martian conversion factors. The nominal power infrastructure conversion (“cost”) for a lunar surface mission is roughly 3.3 times that of a Mars surface mission due to the raised potential for in situ power production on Mars. Also, no conversion factor for crew time is listed for lunar surface missions, so for our analysis, the nominal crew time conversion factor of 1.25 kg/crew-hr is used for both lunar and Mars surface habitats. Lastly, logistics “costs” are not provided; however, this does not affect our analysis, because our case studies

Conversion Factor	Unit	Lower	Nominal	Upper
C_m	kg/kg		1.0	
C_V	kg/m ³		9.16	13.40
C_P	kg/kW	54	228	338
C_{TE}	kg/kW		146	170
C_{CT}	kg/crew-hr	1.25	1.25	1.50
C_L	kg/kg		TBD	

Table 2.4: Table of ESM conversion factors for a Mars surface mission taken directly from the 2004 Baseline Values and Assumptions Document.

consider only mission scenarios with no resupply. Only consideration of a campaign analysis would include a logistical contribution to ESM (see Grogan et al. 2011 and Siddiqi et al. 2009 for the use of matrix-based methods in logistical planning [54][55]).

Crew time

Note that the crew time (CT) ESM term does not directly map to actual increased system infrastructure mass. The CT value includes any time the crew spends on maintenance and operations of the life support system [52]. All of the ESM factors are converted into units of mass by a mapping to a fraction of the infrastructure cost. The ratio of resource cost (in mass units) to resource use is the ESM conversion factor [52]. The notion that mass equivalency for crew time assumes a mission requirement of a science or resource return objective that must be accomplished during the mission duration [52]. It is implicitly assumed that the less crew time available for non-maintenance and operations work, the bigger the mission’s crew must be to ensure that fixed mission-oriented work is completed [52]. The first case study in this thesis, performed in Chapter 3, abides by this assumption and includes CT in the ESM calculation. The second case study, described in Chapter 4, optimizes for both minimum non-CT ESM and maximum CT, allowing for an independent examination of these objectives.

2.6 Chapter 2 Summary

This chapter summarized the case studies, modeling tool (and assumptions inherent in the use of the tool), added assumptions in the mission scenario and calculations, and figures of merit that distinguish between habitat architectures. The next chapter will present some of the results of these case studies and discuss the conclusions and findings of the project.

Chapter 3

ESM Analysis of Lunar and Mars Surface Habitat Systems

This chapter presents the results of the lunar and Mars surface mission case studies described in Chapter 2 and discusses the implications of the findings.

For both the lunar and Mars case studies, ESM was computed of the following technologies that vary in size based on architecture:

- *Oxygen Generation System (OGS)*: baseline of ALS OGS
- *Variable Configuration CO₂ Removal System (VCCR)*: baseline of the ISS Carbon Dioxide Removal Assembly
- *Stored food*: baseline ISS heritage system; accounts for packaging and hardware for cold storage and preparation
- *Biologically grown food*: baseline NASA's Biomass Production System; accounts for BPS and preparation hardware

The simulated architectures with A_{BPS} ranging from 0 to 70 m² were used as the basis for building architectures with different proportions of food provided biologically vs. stored. For this discussion, architectures will be identified by the percentage of crew food demand that is biologically grown using a BPS within the habitat system boundary. A system with no BPS (employing only stored food to nourish the crew) is identified as having 0% of the food provided by BPS; a system with mostly stored food and a small BPS might have 10% of the food provided by the BPS; a system where

the crew relies entirely on biologically grown food has 100% of the food produced by the BPS.

The ESM of each architecture was calculated using the current BVAD ESM estimates for the ECLSS technologies and the lunar and Martian surface ESM conversion factors as described in Section 2.5.1. Nominal and best-case ESM conversion factors were tested (note that the worst-case infrastructure costs closely resemble the nominal costs, so we do not consider worst-case equivalencies here).

3.1 Infrastructure Costs

Infrastructure costs are considered at both the lower bound and nominal values as listed in the 2004 Baseline Values and Assumptions Document. Lower-bound conversion factors reflect the possibility of using in-situ resources, “low cost” power options such as nuclear power production, and of infrastructure technology development that may reduce the mass of infrastructure and other materials needed from Earth. Table 2.3 lists the conversion factors at nominal, lower-bound, and upper-bound values and Figures 3-1 and 3-2 show the contributing ESM factors (mass, volume, power, thermal energy management, and crew time) for various lunar and Mars surface habitat architectures. The total ESM for 1000-day missions ranges between about 9 and 22 metric tons across all scenarios. Recall that this mass includes the integrated ECLSS and food production system mass; structural, airlock, and power systems are not included.

3.2 Agricultural System Autonomy and BPS Power Demand

Other aspects of the trade between biological food production and stored food that are investigated are the percent of autonomous assistance given to the crew in carrying out farming tasks (crop planting, maintenance, irrigation, harvesting, and processing) and the percent reduction in the BPS’s power requirement (the majority of this

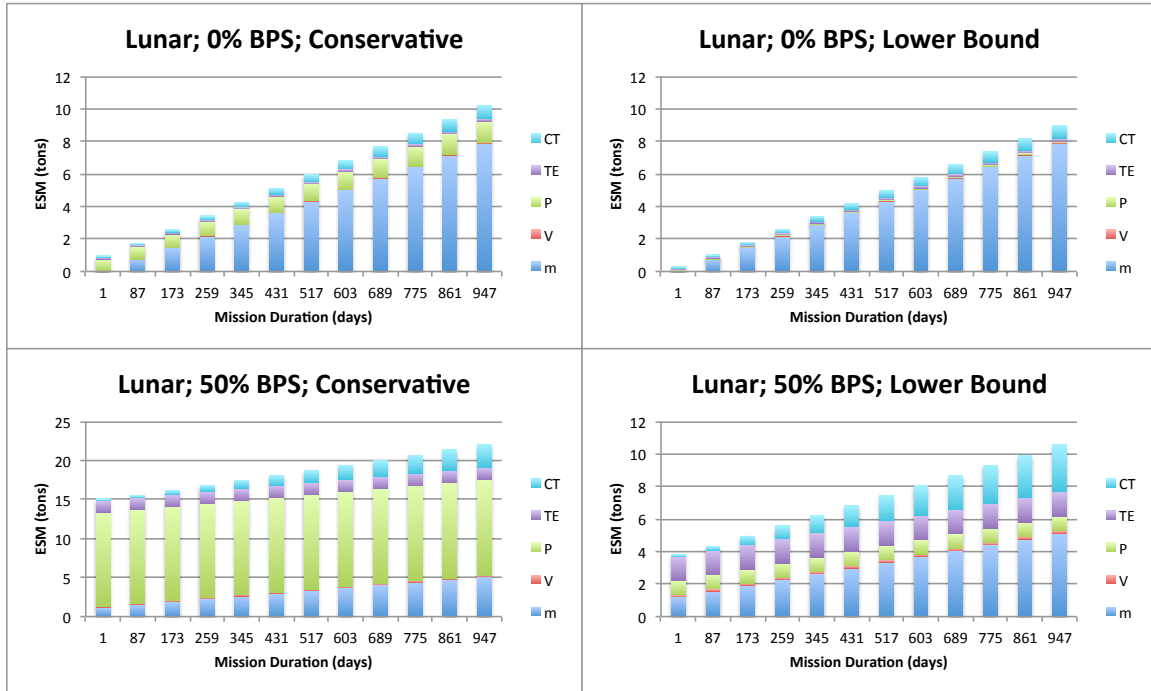


Figure 3-1: ESM of lunar ECLSS architectures for different mission durations. The top two panels show architectures with no BPS, and the bottom two panels show architectures with a BPS that supplies 50% of the crew's food needs. The ESM calculation used for the left panels assumes the nominal infrastructure penalties; those used for the right panels assumes the lower bound infrastructure penalties.

requirement is derived from the lighting needs per unit area of crops). It is essential to consider improvements to the supporting infrastructure costs for the BPS because the stored food supporting hardware (thermoelectric freezer, packaging) has been optimized for use in space, while the BPS hardware has not. BPSs have mostly been optimized for plants per unit shelf area and yield. The powering, lighting, and nutrient providing systems of the BPS have not been the primary focus of BPS design. It is expected that the biggest contributor to ESM for a BPS, the factor that reflects the BPS power draw (see Figures 3-1 and 3-2), would be greatly reduced with optimized lighting systems. Another promising, and likely, option is using direct solar light for part of the necessary light.

The crew time needed to maintain and harvest the crops is the second largest contributor to ESM for BPS with nominal infrastructure penalties and the largest contributor to ESM with lower bound infrastructure penalties. It is likely that large-

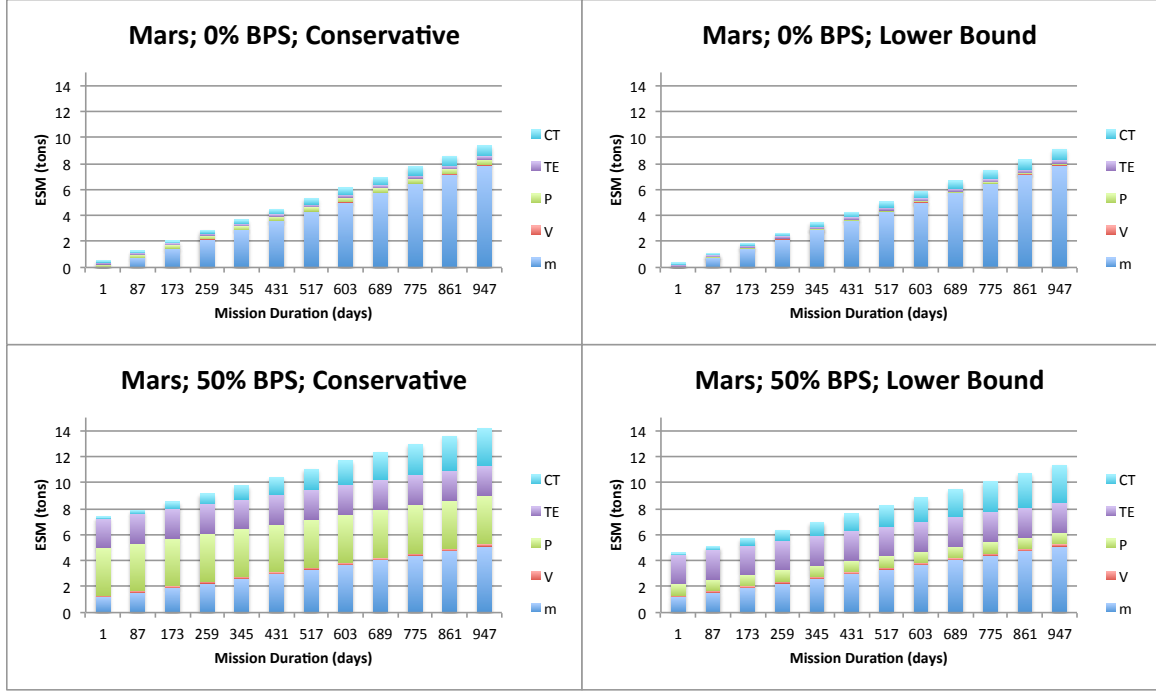


Figure 3-2: ESM of Mars ECLSS architectures for different mission durations. The top two panels show architectures with no BPS, and the bottom two panels show architectures with a BPS that supplies 50% of the crew’s food needs. The ESM calculation used for the left panels assumes the nominal infrastructure penalties; the calculation used for the right panels assumes the lower bound infrastructure penalties.

area BPSs will require manual crew labor to complete the tasks of maintenance and harvesting (for example, the Biosphere 2 crew spent the majority of their time on tasks related to agriculture and food processing and preparation [13]). A more likely architecture would employ semi- or fully-autonomous systems and greatly reduce the crew time impact on BPS ESM. Examples of projects funded to develop autonomous agriculture maintenance systems include the Distributed Robotic Garden at MIT’s Computer Science and Artificial Intelligence Laboratory [56] and the Robotic Gardening System [57], which is funded by NASA JSC Advanced Exploration Systems and aims to reduce the crew time requirement for a biological food production system in space.

Architectures with different percent autonomous crop maintenance (p_A) and harvesting and percent power reduction in BPS lighting systems (p_{PR}) are therefore considered in the following discussion.

3.3 Evaluation of ESM For Various Architectures

An ESM analysis was carried out for surface habitat architectures on the Moon and Mars. The fixed (minimum) ESM of each architecture can be read as the ESM at $t = 0$; other costs are directly or indirectly a function of mission duration, and higher BPS usage decreases the rate at which costs increase with mission duration.

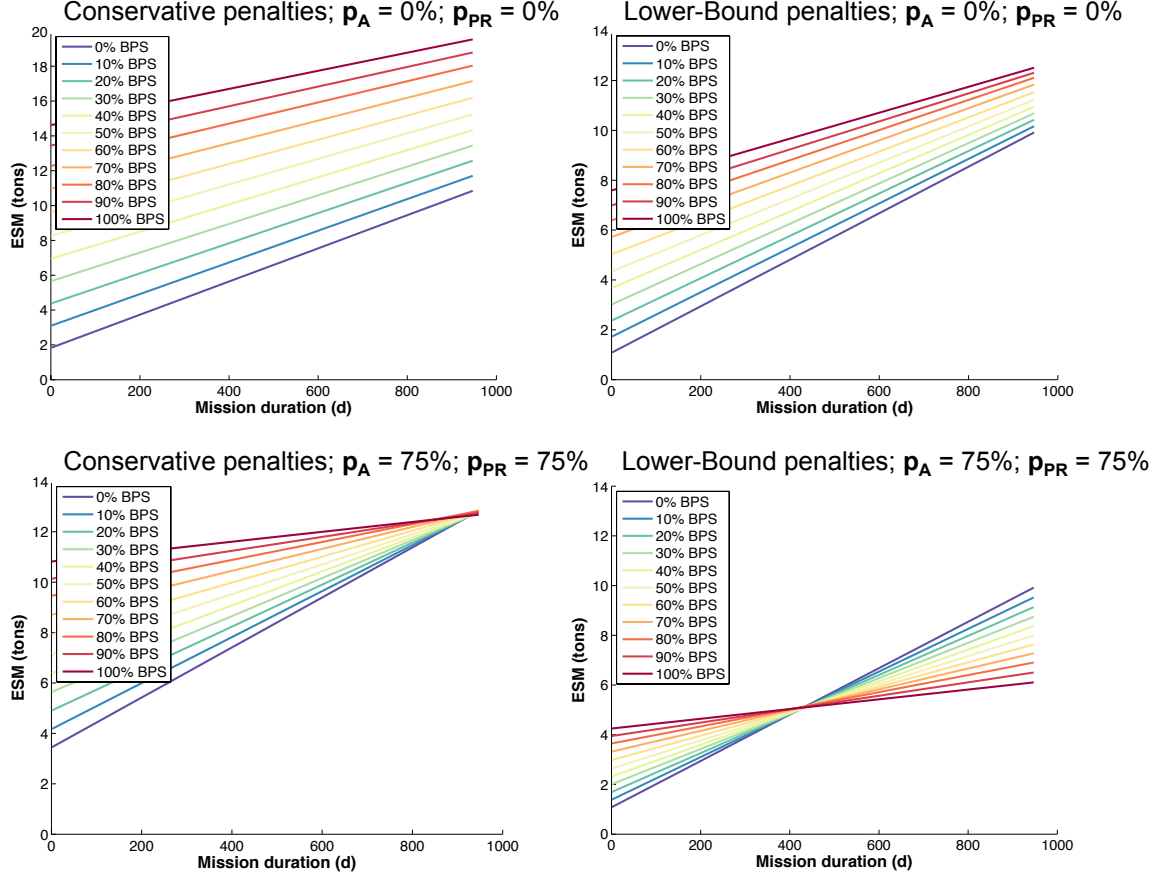


Figure 3-3: ESM analysis of lunar surface ECLSS architectures for nominal and best-case infrastructure penalties and different percentages power reduction in BPS lighting systems and autonomous crop operations.

Note that the architecture with 100% biologically grown food is not very realistic. Even the Biosphere 2 closed ecological experiment brought a limited quantity of stored food on their mission, as a food “buffer” for contingency purposes. Similarly, a resupply-free architecture for mission durations higher than a year is usually envisioned as employing some biologically produced food for psychological and nutritional

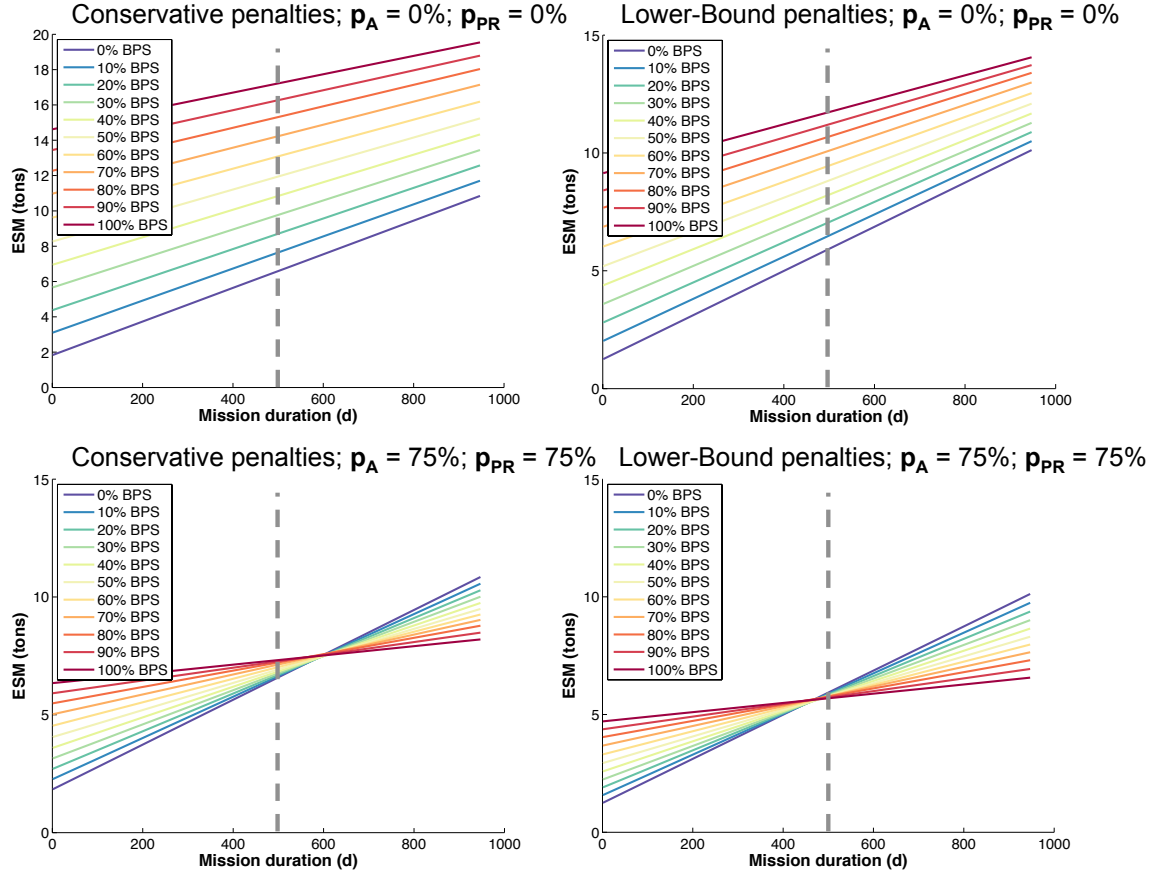


Figure 3-4: ESM analysis of Mars ECLSS architectures for nominal and best-case infrastructure penalties and different percentages power reduction in BPS lighting systems and autonomous crop operations. The 500-day mission duration is marked by the vertical dashed line and represents the Mars DRA 5.0 mission duration.

reasons (though this is disputed by some, e.g., [44]), so the 0% BPS architectures are also less realistic. Table 3.1 shows the approximate crossover times computed for both environments, both sets of infrastructure penalties, and the improved vs. current crop production system.

3.4 Discussion

It is evident in both the lunar and Mars surface ESM analyses (Figures 3-3 and 3-4, respectively) that lower-bound infrastructure penalties, if achievable, would increase the attractiveness of ECLSS architectures that have a high degree of biological re-

	Crossover time - No BPS improvements		Crossover time - Significant BPS improvements	
	Lower-Bound Penalties	Conservative Penalties	Lower-Bound Penalties	Conservative Penalties
<i>Lunar Surface</i>	4.0	5.5	1.2	2.7
<i>Mars Surface</i>	4.8	6.2	1.2	1.6

Table 3.1: Crossover times, reported in Earth years, for different improvements to BPS infrastructure requirements and different assumed infrastructure penalties. A four-person crew is assumed.

generation of nutrients and the atmosphere. This agrees with intuition, as a BPS requires more supporting infrastructure than does the stored food and atmosphere revitalization hardware. The results of the ESM analyses also show that increasing the percent autonomy of the farming and food processing/preparation procedures lowers the “crossover” mission duration at which bioregeneration becomes attractive. Decreasing the crop systems’ usage of electric power for lighting (by optimizing lighting and/or partially employing sunlight) for the crop systems also reduces the crossover time.

In comparing the lunar and Mars mission scenarios, we see that the crossover points at which bioregeneration is less “expensive” occur at lower mission durations for Mars with nominal infrastructure penalties, but at higher mission durations for Mars with lower-bound infrastructure penalties when compared to the lunar surface plots. An examination of the nominal and lower-bound infrastructure penalties justifies this observation, as the reduction in power and thermal management infrastructure penalties for the lower-bound case is much higher for a lunar surface scenario than it is for a Mars surface scenario.

The results of ESM analysis show that reducing lighting costs and autonomy of the food production, processing, and preparation systems associated with the biomass production chamber (BPS) will increase its feasibility and cost-effectiveness for use in long-term space flight. Lighting and other supporting systems must be optimized for the BPS in addition to the crop yield per growing area. Without improvements to

these systems, crossover points at which bioregeneration starts to become competitive (based on ESM) will likely not be less than about 4 years for lunar surface missions and 4.8 years for Mars surface missions; however, with significant improvements to the high-cost BPS requirements, the crossover times can be more than halved. This could have implications for the Mars Design Reference Architecture 5.0 [58] for which a 500-day Mars surface stay is assumed. If the improvements made to the BPS have a similar effect to those assumed with high p_A and p_{PR} , significant bioregeneration may be ESM-optimal. In this case, prepackaged, stored food could and probably should still be part of the life support system design for contingency purposes. However, if improvements to the BPS are less significant and lower-bound infrastructure penalties do not apply, any food that is produced biologically would be an extra luxury for purposes such as entertainment, scientific experimentation, diverse and interesting diet, and/or other psychological purposes.

3.5 Hybrid Life Support System Classification Metric

The variations of the baseline habitat architecture considered in this analysis have been identified by the cumulative amount of edible biomass produced biologically, as a percentage of crew food demand. It is useful to formally define a hybrid life support system classification metric, H , such that these habitats (and others in the future) can be placed along a spectrum similar to the spectrum shown in Figure 1-2. This metric could reflect a variety of factors (e.g., relative number of bioregenerative and physicochemical processes, relative number of subsystems that use each type of process). A more rigorous metric might quantify the cumulative percentage of mass flow through the system that is accomplished by regenerative biological or physicochemical processes:

$$H = \frac{-(\int_0^{t_f} \dot{m}_{BR} dt - m_{BR}^0) + (\int_0^{t_f} \dot{m}_{PC} dt - m_{PC}^0)}{\int_0^{t_f} \dot{m}_{crew} dt} \quad (3.1)$$

Here, t_f indicates the mission duration, \dot{m}_{BR} and \dot{m}_{PC} are the mass flow rates of physicochemically- and biologically-produced consumables into the human crew or population, respectively, m_{BR}^0 and m_{PC}^0 are the initial consumables provided at the start of the mission to support the biological and physicochemical technologies, respectively, and \dot{m}_{crew} is the mass flow rate of consumables required by the human crew. A generalized consumable-flow representation of a life support system is shown in Figure 3-5. Equation 3.1 is normalized such that $H = -1$ for an entirely regenerative biological system (e.g., the Earth before the introduction of widespread physicochemical machines) and $H = 1$ for an entirely regenerative physicochemical system (e.g., a fully regenerative form of ISS). Open-loop systems would have $H = 0$ based on Equation 3.1; however, this metric is not particularly useful or relevant for classification of open-loop or near-open loop systems (in this sense, the spectrum on which habitats would lie using the H metric would look somewhat different from the spectrum shown in Figure 1-2). This metric is useful for comparison of significantly regenerative habitats. For our 1000-day mission scenario, the four-person crew's con-

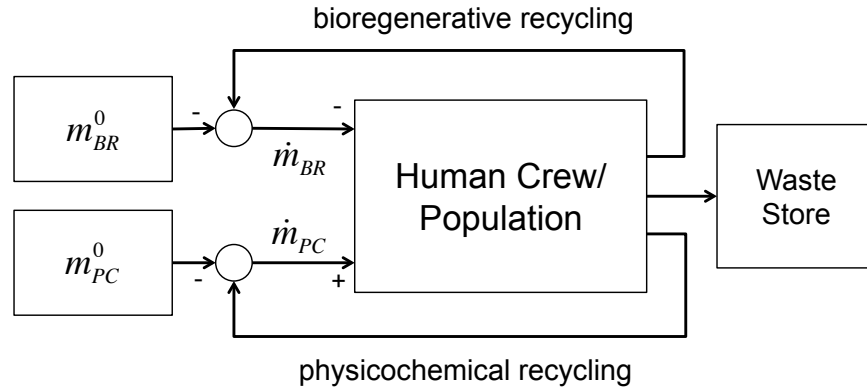


Figure 3-5: Generalized human-centric consumable flow in a universal habitat.

sumable needs of O_2 , H_2O , and food are approximately 3200 kg O_2 , 7260 kg H_2O , and 4000 kg food. Table 3.2 specifies the approximate consumable flows from bioregenerative and physicochemically-regenerative elements and the mass of consumables in the stores required as inputs at the start of the mission to support each type of hardware for fully bioregenerative and fully physicochemically regenerative habitats, as well as the 0% BPS, 50% BPS, and 100% BPS architectures on which the ESM

	1	2	3	4	5
	Fully bioregenerative	100% BPS- grown food	50% BPS- grown food	0% BPS- grown food	Fully physico- chemically regenerative
$\int_0^{t_f} \dot{m}_{BR} dt$	4000 kg food 3200 kg O ₂ 7260 kg H ₂ O	4000 kg food 1500 kg O ₂ 5000 kg H ₂ O	2000 kg food 700 kg O ₂ 1000 kg H ₂ O	–	–
$\int_0^{t_f} \dot{m}_{PC} dt$	–	1700 kg O ₂ 2260 kg H ₂ O	2000 kg food 2500 kg O ₂ 6260 kg H ₂ O	4000 kg food 3200 kg O ₂ 7260 kg H ₂ O	4000 kg food 3200 kg O ₂ 7260 kg H ₂ O
m_{BR}^0	–	17 kg CO ₂ 5000 kg H ₂ O	12 kg CO ₂ 1000 kg H ₂ O	–	–
m_{PC}^0	–	1700 kg O ₂	2000 kg food 2500 kg O ₂	4000 kg food 3200 kg O ₂	–
<i>H</i>	-1.00	-0.22	0.25	0.50	1.00

Table 3.2: Computation of H for classification of habitat architectures by type of regeneration.

analysis was performed in Section 3.3. The H metric is computed; Figure 3-6 shows the placement of the five habitats along the H -spectrum based on the computed H values.

3.6 Chapter 3 Summary

This chapter presented the results of an ESM analysis for habitat architectures with a varied proportion of regeneration from a BPS for lunar and Mars surface missions of durations up to 1000 days. The hybrid life support system classification metric was introduced and habitats were placed along the H spectrum based on the relative amounts of human consumable requirements met by bioregenerative or physicochemically-regenerative systems.

ESM has been shown to be a good indicator of cost; however, it has limitations, and other metrics are relevant in any life support system trade study. The next chapter will present the results of a multiobjective system optimization that optimizes a Mars surface mission’s ECLSS system for both non-crew time ESM and crew time.

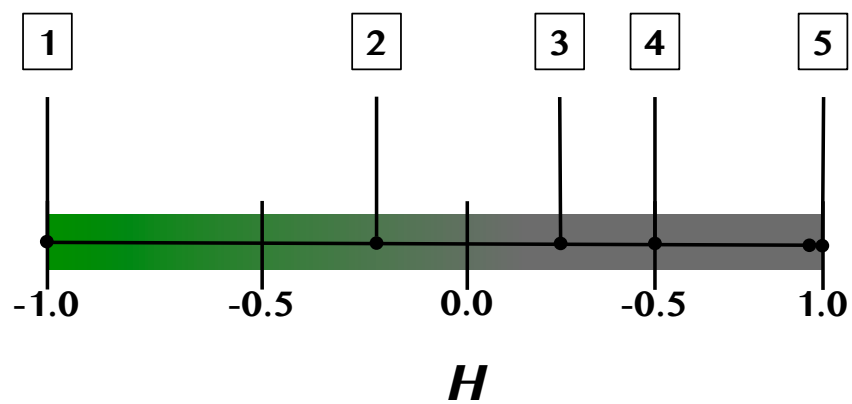


Figure 3-6: Classification of habitat architectures (numbered 1-5) placed along the H -spectrum. The detailed data is shown in Table 3.2

Chapter 4

Multidisciplinary ECLSS Design and Optimization

This chapter examines the question of optimal level of bioregeneration due to crops in a life support system. The results presented here were obtained in the Spring 2014 Multidisciplinary System Design and Optimization (MSDO) class as part of a three-person project along with Andrew Owens and Ioana Josan-Drinceanu. The study is described in more detail in Shaw et al. 2014 [59]. The habitat architecture that is optimized is shown in Figure 4-1. The architecture has two environment modules: the Plant Environment, which contains the Biomass Production System (BPS), and the Crew Quarters, in which the crew remains for the mission duration. Life support components are outlined in black; these include the BPS, an O₂ accumulator, dehumidifiers, a VCCR, a water distiller, a CRS, an OGS, and a Pyrolyzer. The power subsystem consists of the Nuclear Power Production System and three power stores. Consumable stores (outlined in grey) exist for biomass (BM), prepackaged food, potable water, grey water, dirty water, O₂, CO₂, H₂, Methane, and dry waste (ash). O₂ and CO₂ are transferred between the Plant and Crew Environments using gas accumulators and injectors; the system could be simplified by merging these two environment modules together.

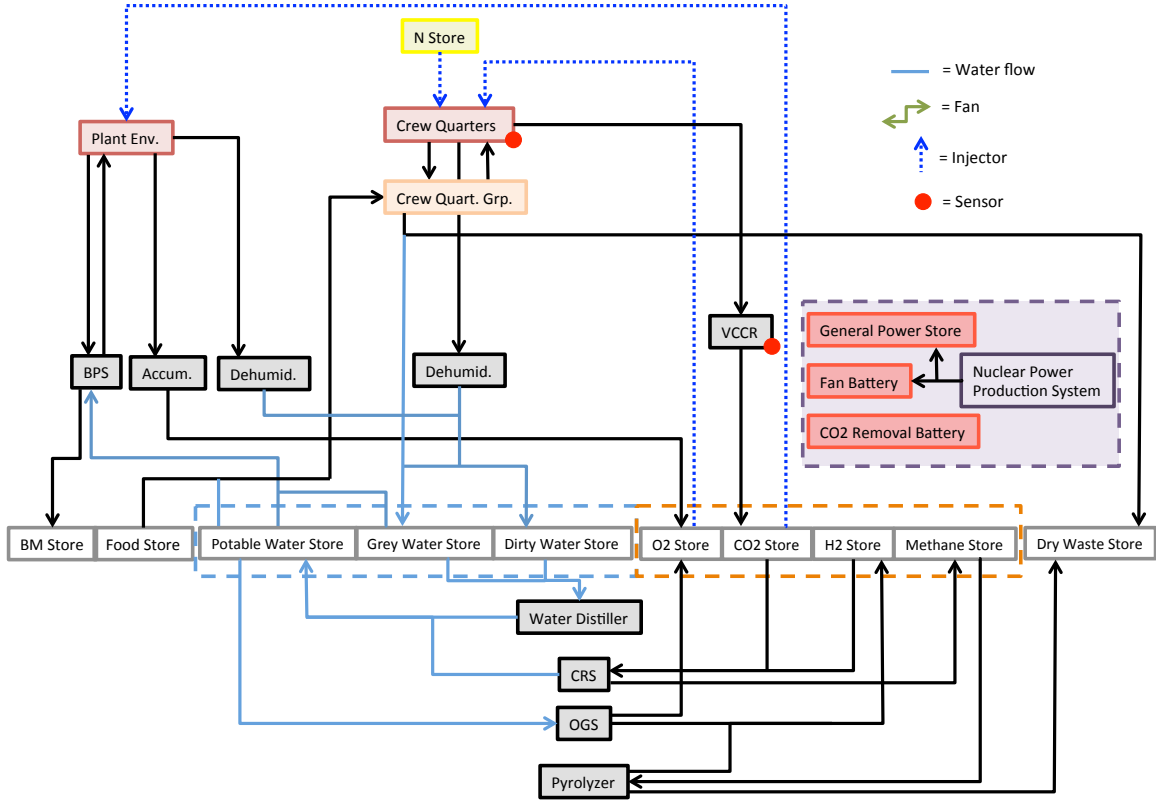


Figure 4-1: Baseline BioSim ECLSS architecture used for MSDO analysis. In this figure, environments are outlined in crimson, crew groups are outlined in peach, physicochemical and bioregenerative components are outlined in black, stores are outlined in grey, and the power subsystem is diagrammed in the faint purple box to the right.

4.1 Background

The design and optimization of ECLSS is a multidisciplinary problem by nature, as ECLSS can contain integrated chemical, biological, and electromechanical systems. Multidisciplinary design and optimization of ECLSS has been performed in past studies [60] [48] [61] using tools such as BioSim [48], ALLSAT [62] and EcosimPro [30]. These studies choose an appropriate optimization algorithm and apply it to a system architecture. Other studies have focused on optimization of one engineering aspect (e.g., control systems) and provided a comparison of multiple optimization algorithms (e.g., genetic algorithms and stochastic hill-climbing approaches) [63]. One study of relevance applied a genetic algorithm to find the ESM-optimal habitat configuration

for a 90-day lunar surface mission, varying between 12 and 20 attributes for five different scenarios. The attributes that were varied are O₂ injector flow rate, OGS, Variable Configuration CO₂ Removal (VCCR), and water recovery systems power consumption, O₂, power, food, and water store capacities and initial levels, BPS shelf sizes for tomatoes and lettuce, and two of the environment module volumes [61]. Our analysis is distinct in its scope and configurable design attributes, as the authors only considered bioregeneration for supplementation of a packaged food diet (the crops grown were salad greens only). The study optimized the habitat configuration for a simplified ESM metric.

4.2 Optimization Problem

Key drivers of ECLSS optimality are examined through an optimization utilizing the high-fidelity modeling tool BioSim. The model captures emergent system properties as a function of component and subsystem design characteristics and allows for the identification of key drivers of optimality in ECLSS design. For our analysis, we develop a model that utilizes the BioSim simulation to explore a tradespace of ECLSS options for a surface habitat.

4.2.1 Design variables

We varied four multipliers on the ECLSS design parameters for this study.

1. Multiplier on area of 3 BPS crops (each type of crop has an equal area)
2. Multiplier on initial level of 4 gas stores
3. Multiplier on initial level of 3 water stores
4. Multiplier on processing rates of 4 regenerative components (analogous to sizing)

These design variables affect multiple aspects of the ECLSS design; the number of configurable attributes is 14, but each attribute is not independent. A full list of configurable attributes is shown in Table 4.1. The employment of non-independent configurable attributes reduces the runtime of the optimization, but also limits the absolute validity of the work, i.e., our optimum will not be the global optimum that

would be found if each of these 14 design variables were independent.

Each design variable selected for optimization is continuous. This allows us to attempt to apply gradient methods on the continuous design space and allows for a more straightforward configuration of the heuristic and gradient based methods. Each of these design variables is confined to a domain of zero to one.

Design Variable	Baseline Value	Attribute
x_1	25 m ²	Area of soybean crop
	25 m ²	Area of lettuce crop
	25 m ²	Area of rice crop
x_2	86000 mol	O ₂ store initial level
	50 mol	CO ₂ store initial level
	0 mol	H ₂ store initial level
	0 mol	CH ₄ store initial level
x_3	18000 kg	Potable water store initial level
	1000 kg	Grey water store initial level
	0 kg	Dirty water store initial level
x_4	0.25 · BioSim nominal	OGS component rate
	0.25 · BioSim nominal	CRS component rate
	0.25 · BioSim nominal	Pyrolyzer component rate
	0.25 · BioSim nominal	Water Distiller component rate

Table 4.1: List of configurable attributes in the life support system architecture, mapped to the design variable x_i that controls each attribute’s value. Baseline values for these attributes is provided.

4.2.2 Parameters and constraints

Several parameters were fixed in the optimization; ideally all of these would be considered as design variables, but optimization would have been extremely computationally expensive.

- There are four crew members: two women and two men
- The mission duration is 600 days
- The area of the plant environment is fixed to 1000m²
- The level of redundancy for regenerative components is set to 9

- The total habitable volume, or the volume of the internal atmosphere of the habitat, is fixed at 6500 m³
- The recycling efficiencies of the regenerative components are fixed at the BioSim default values

The ESM constituent values for each component (mass, power, etc.) are fixed to the 2004 LS Baseline Values and Assumptions Document values [53].

We impose the constraint that all simulation mission durations must be greater than or equal to the nominal mission length (600 days). Designs that resulted in system failure (crew death) prior to reaching nominal mission duration are not considered valid habitat designs.

4.2.3 Objectives

The metrics considered in this optimization problem are non-crew time equivalent system mass (ESM_{NCT}) and crew time (CT).

Equivalent System Mass

ESM is a commonly used metric that captures both the mass of the system itself as well as impacts on the mass of the overall system due to thermal and power loads in order to provide a mass “cost” of a given system [52]. This metric is described in Section 2.5.1, though for our analysis, we use non-crew time ESM (ESM_{NCT}). The infrastructure penalties used are the Mars surface nominal values (refer to Table 2.4).

ESM_{NCT} and is quantified for the following technologies:

- *Oxygen Generation System (OGS)*: baseline of ALS OGS
- *Variable Configuration CO₂ Removal System (VCCR)*: baseline of the ISS Carbon Dioxide Removal Assembly
- *Food Production System*: baseline of NASA’s heritage stored food systems and Biomass Production System (BPS), includes hardware for preparation
- *Dehumidifier*: baseline of ISS dehumidifier
- *Water Distiller*: baseline of combined ISS urine and waste water assemblies

- *Carbon Reduction System*: baseline of ISS Sabatier Reactor
- *Pyrolyzer*: baseline of ISS Methane Pyrolyzer Assembly
- *Batteries*: baselined on COTS Polymer Li-Ion batteries
- *Stores*: masses computed for each gas based on molar mass conversions

Note that the model assumes a nuclear power production system will be used, but the ESM_{NCT} of this is not computed as it would be the same for each architecture given BioSim’s assumption that the power source can provide infinite power. Each component ESM_{NCT} was sized appropriately from the corresponding baseline values for number of crew, mission duration, and load. The OGS, CRS, Pyrolyzer, and Water Distiller are sized by the component rate multiplier, x_4 , which in turn determines its ESM_{NCT} . The OGS and VCCR are sized down linearly based on how much of their functionality is taken care of by the BPS.

Crew Time

The ESM reported is non-crew time ESM, as crew time available for science/resource return is considered separately. As discussed in Section 2.5.1, the conversion of crew-hours to kg of ESM implicitly assumes a requirement of crew work time (on science/resource return) for the mission to be successful. There are several problems with this, including the fact that crew size is a discrete variable, so the increase in the CT ESM factor with increasing CT should really be a step function-type relationship instead of the linear relation that is currently used. Also, it could be that the mission objective of a mission is simply a demonstration of the capability of a habitat to sustain humans for the mission duration, so the assumption that less available crew time for mission activities will necessarily increase crew size might be faulty to begin with. Instead of making this assumption, this optimization considers CT as a separate metric so the reader can consider architectures with more information and fewer implicit assumptions than the scalar ESM value alone offers.

The crew time is reported as the percentage of crew time available for science/resource return. The amount of time the crew is awake is estimated as 16 hours per day. The total crew-hours of work available from a crew of n_{crew} crew members over

the duration of the mission ($CT_{nominal}$) is then

$$CT_{nominal} = 16 \frac{hours}{day} \cdot t_{mission} \cdot n_{crew}, \quad (4.1)$$

where $t_{mission}$ is the mission duration in days. The time that the life support system (LSS) equipment requires for maintenance and operations, CT_{LSS} , must be less than or equal to $CT_{nominal}$. The available crew time after LSS maintenance and operations time is spent, expressed as a percentage of available crew time, is then

$$CT = \frac{CT_{nominal} - CT_{LSS}}{CT_{nominal}}. \quad (4.2)$$

4.2.4 Assumptions

This study has similar BioSim-related assumptions to those described in Section 2.4 that were applied to the ESM analysis; however, as mentioned, we model and simulate missions with six crew members for 600 days. Also, three crops (lettuce, soybean, rice) are assumed to exist in the BPS.

4.2.5 Model structure

Our model consists of BioSim as the primary tool, and an XML Generator (written in Matlab) constructs XML configuration files based on a set of design variables x and parameter list pp and feeds them to BioSim simulation, the output logs of which are processed by the Postprocessor. The Postprocessor extracts relevant data from the simulation log that is passed to the Calculator, which computes the objective values and constraints described in Sections 4.2.3 and 4.2.2, respectively. The model block diagram is shown in Figure 4-2. BioSim is written in JAVA; all other modules are written in MATLAB.

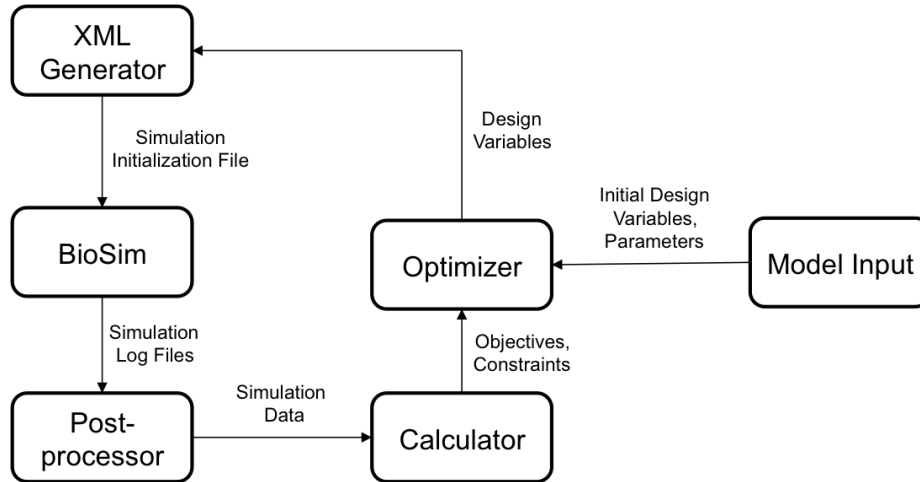


Figure 4-2: Block diagram showing model modules (Model Input, Optimizer, XML Generator, BioSim Simulation, Postprocessor, and Calculator).

Model Runtime

The total runtime of the model is around 50 seconds for a 600-day mission on a 2.3 GHz Intel Core i7 processor. The BioSim simulation takes the majority of this time (25-40 seconds), while the XML Generator, Postprocessor and Calculator combined can take between 15-25 seconds (the majority of this time is spent in the Postprocessor due to the large (437 MB) size of the BioSim output log files). The runtime varies based on the type of computer used and CPU usage for other activities during model runs. The BioSim simulation also varies in runtime and is significantly increased by the optional use of the simulation GUI.

4.3 Optimization Algorithm Selection

Gradient-based and heuristic-based optimization methods were tested for use in optimizing our Mars surface habitat. Gradient-based optimization is generally faster and, when used on a well-formulated problem for which gradients in objective space can be computed with a reasonable initial guess, locate the optimum using a deterministic procedure. However, when the model users have little information or intuition about the objective space and/or infeasible regions in the design space, heuristic methods can be particularly useful as they do not require the user to have much intuition; also,

heuristic methods generally do not succumb to local extrema, while gradient-based methods sometimes do due to use of a gradient and/or curvature check to determine convergence.

Starting with a single-objective optimization of ESM_{NCT} , we applied both the gradient-based `fmincon` active-set algorithm (see MATLAB Documentation Center) and the heuristic-based NSGA-II genetic algorithm [64]. Figure 4-3 shows the converged-upon points for three different `fmincon` starting points and the genetic algorithm ESM_{NCT} minimum value. The convergence of `fmincon` at three different convergence points for three different starting points indicate the presence of multiple local minima in the objective space; this hinders `fmincon`'s performance. We also carried out a coarse partial enumeration and found regions of infeasibility on the interior of the design space, which will similarly decrease `fmincon`'s ability to compute gradients at various points in the design space.

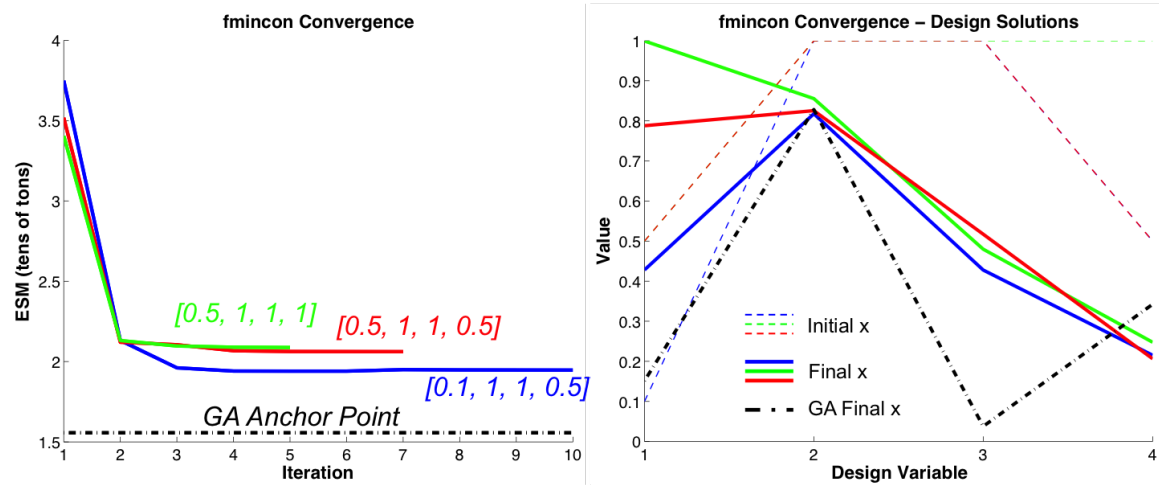


Figure 4-3: Convergence of `fmincon` active-set algorithm for three different initial points (left) and parallel coordinate plots showing the values of each design variable at the initial and final point of the optimization (right). ESM_{NCT} is minimized by `fmincon` and a multiobjective genetic algorithm (shown for comparison), for which the ESM_{NCT} -optimum is chosen as the anchor point that minimized ESM_{NCT} .

We also compared `fmincon` and NSGA-II's performance in a multiobjective optimization of both ESM_{NCT} and CT, and, as predicted from the comparison of ESM_{NCT} -optima selected in each algorithm's single-objective optimization, the NSGA-II performs significantly better. The Normal Boundary Intersection (NBI) method applies

fmincon to a two-objective problem by feeding it a several single-objective functions that have differential weighting on each objective (i.e., $J_{temp} = w_1 \cdot J_1 + w_2 \cdot J_2$, where J_{temp} is the temporary single objective, J_1 and J_2 are the two objectives that are optimized, w_1 and w_2 are weightings on J_1 and J_2 , respectively, and $w_1 + w_2 = 1$) [65]. The NBI optimizations are carried out along evenly spaced lines that are normal to the line between the anchor points, so the algorithm nominally finds a set of points on the Pareto front that are evenly spaced out. The Pareto fronts for both multiobjective optimizations are plotted in Figure 4-4.

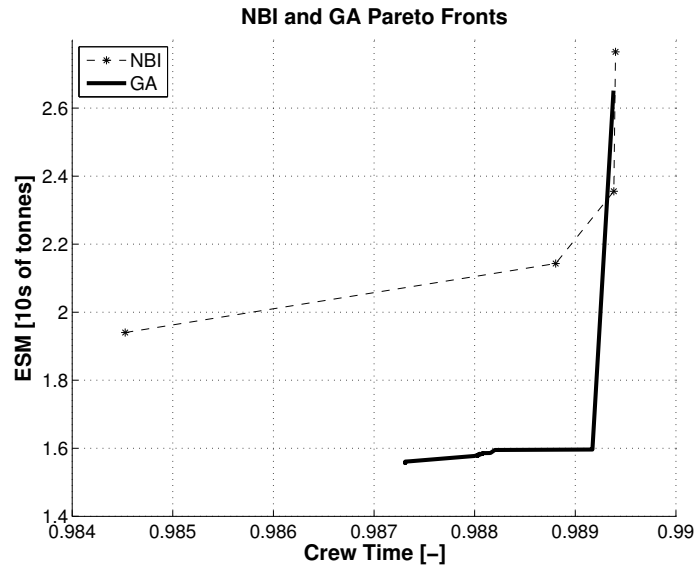


Figure 4-4: Comparison of Pareto fronts found by the NBI and NSGA-II algorithms.

Due to regions of infeasibility and local minima in our design and objective spaces, respectively, and the lower ESM achieved by the NSGA-II, we selected the NSGA-II for our multiobjective optimization.

4.3.1 NSGA-II

Genetic algorithms mimic the process of species evolution. “Individuals” (designs) in the “population” (set of designs) are evaluated for their “fitness” (a score based on their objective values), and the “fittest” (most optimal) individuals survive and “reproduce” (are crossed with each other), creating a set of designs that moves toward

the optima. NSGA-II is a multiobjective genetic algorithm that evaluates a design points fitness based upon a nondominated sorting of the tradespace as well as the “crowding” distance between different points (crowding is undesirable; the algorithm aims to achieve a Pareto front with points that are evenly spaced). Constraints in genetic algorithms can be applied using a penalty function (see Equation 4.3) - if a design does not meet constraints, it is not thrown out; rather, its fitness becomes very high due to the penalty.

$$J_p = J + \rho \cdot \frac{t_{mission} - \min(t_{mission}, t_{system})}{t_{mission}} \quad (4.3)$$

Here, J_p is the penalized objective function value, J is the raw objective function value, ρ is the penalty coefficient, which can be set based on how hard the constraint is, $t_{mission}$ is the nominal mission duration (this is set as a parameter), and t_{system} is the amount of time that the designed mission actually survived for. The penalty term is always positive, as the genetic algorithm minimizes objectives J by default. Thus designs that violate constraints are seen by the optimizer as having very high objective values and, as a result, very low fitness.

4.4 Results

We carry out a multiobjective optimization of the Mars baseline habitat architecture shown in Figure 4-1. A multiobjective examination allows us to examine the Pareto-optimal designs based on ESM_{NCT} and CT as separate metrics, therefore removing some of the assumptions contained in the single objective of ESM. We do not aim to determine the single optimal design.

4.4.1 Selection of NSGA-II tuning parameters

We tuned the NSGA-II parameters of mutation coefficient and the population and generation size to find the combination of these parameters that would result in the best Pareto front that would take a manageable amount of time.

Mutation coefficient

The mutation coefficient in the NSGA-II algorithm is the distribution index in the polynomial mutation performed to mimic random genetic mutations amongst individuals in the population [66]. We chose a baseline population size of 40 and number of generations of 40 to test out three different mutation coefficients: 10, 20, and 30. The three Pareto fronts for NSGA-II runs with each of these mutation coefficients are shown together in Figure 4-5. We observe that a mutation coefficient of 20 pro-

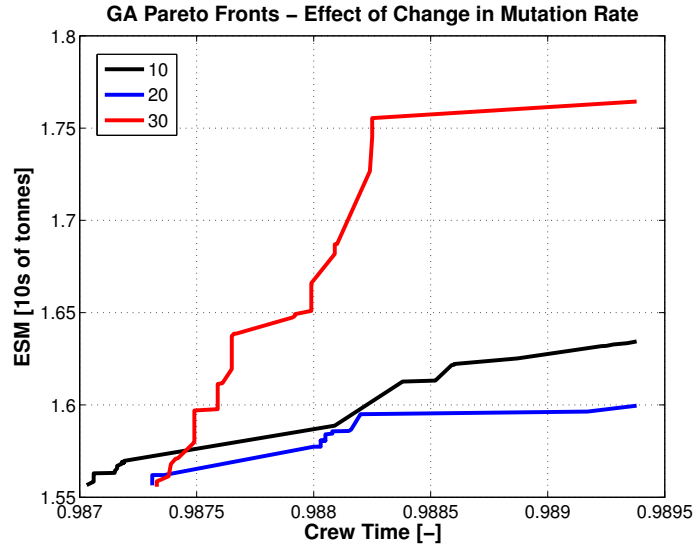


Figure 4-5: Comparison of Pareto fronts found by varying the mutation coefficient tuning parameter.

duces the best Pareto front (it almost entirely dominates the other two). The lowest mutation rate, 10, produces a similar Pareto front; however, the individuals in the population had a low probability of random improvements due to mutation. The highest mutation coefficient, 30, resulted in a Pareto front that was quite varied in terms of ESM_{NCT} , but the individuals on the Pareto front failed to reach ESM_{NCT} values competitive with the individuals in the run with a mutation coefficient of 20.

Population and generation size

As discussed in Section 4.2.5, evaluation of one design takes roughly 50 seconds. We set the requirement that a NSGA-II run must take no more than 24 hours to run; this

translates to a maximum of 1600 function calls. We performed the following three combinations of population size and number of generations that each execute 1600 function calls:

- Population size = 20; Number of generations = 80
- Population size = 40; Number of generations = 40
- Population size = 80; Number of generations = 20

We assume a mutation coefficient of 20. The three Pareto fronts for NSGA-II runs with these sets of tuning parameters are shown together in Figure 4-6. The baseline

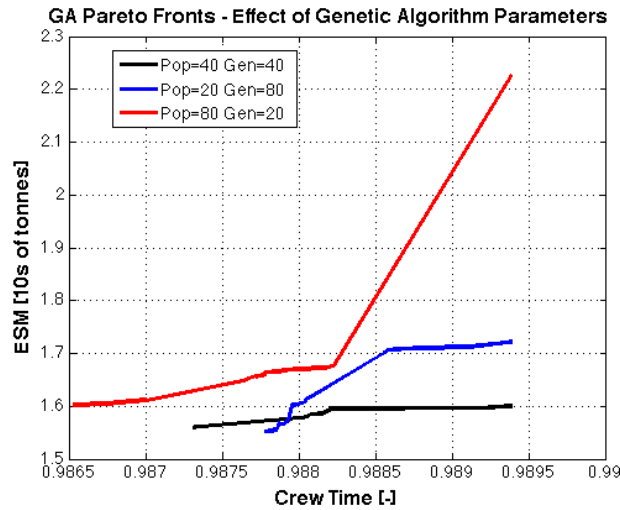


Figure 4-6: Comparison of Pareto fronts found by varying tuning parameters of population size and number of generations.

run with 40 generations of 40 individuals each performs the best (this could be because we selected the mutation rate used based on its performance for this number of generations and population size; ideally every combination of tuning parameters should be tested), as the Pareto front for this optimization almost entirely dominates the other two. The run with 80 individuals per generation has the largest spread across the Pareto front, which makes sense because each generation is permitted to maintain a large degree of diversity. For smaller population sizes, only the fittest individuals are allowed to survive, which shrinks the spread of the Pareto front, but also appears to move the designs toward optimality. Ideally, the higher the population size and number of generations used, the better the Pareto front would be; however,

for our purposes, a run with higher population sizes and more generations (e.g., 80 individuals for 80 generations) is computationally prohibitive.

4.4.2 Model sensitivity to crew size

The effect of changing the crew size from the baseline value of 6 to either 4 or 8 crew members can be seen in Figure 4-7. It appears that the ESM_{NCT} expense of

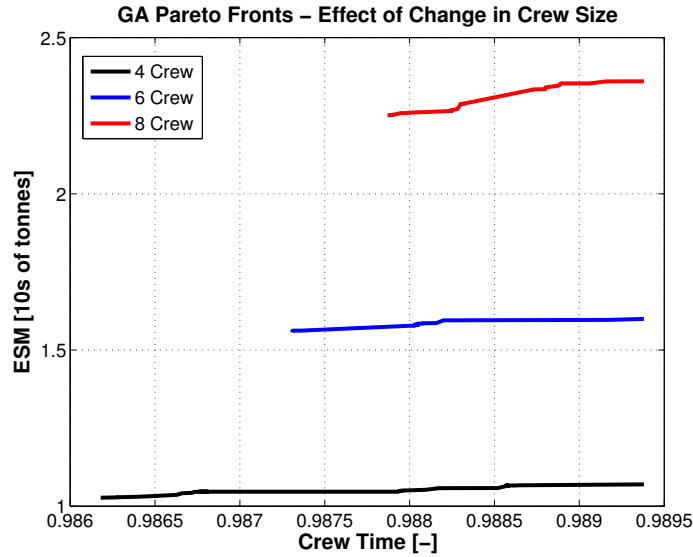


Figure 4-7: Comparison of Pareto fronts found for missions with 4, 6, and 8 crew members.

adding a crew member is around 2.5 tonnes due to more consumables needed; the cost of adding an additional crew member dwarfs the increase in ESM across the Pareto-optimal designs. Also, it is intuitive that the Pareto fronts shrink in their range of CT with increasing crew members, because CT is measured as a percent of total available crew-hours, and the operations costs do not increase as quickly with increasing crew size as do the available crew-hours.

Note that the range of CT values is small (approximately 98.6%-99.0%). This is discussed in the following section.

4.4.3 Identification of Pareto-optimal architectures

One purpose of this multidisciplinary optimization problem is to inform the design of integrated ECLSS similar in form to our Mars surface habitat architecture. To this end, the design attributes of the Pareto-optimal solutions of our baseline and of crew sizes of four and eight are identified in this section.

Figure 4-8 shows a visualization of the design variable values along the Pareto front of the baseline NSGA-II optimization. The three plots show the baseline Pareto front (top left), and the mapping of design variables to ESM_{NCT} (right) and CT (bottom) objective spaces. The BPS shelf area multiplier is shown in green, the gas store multiplier is shown in red, the water store multiplier is shown in blue, and the component rates are shown in black. From an examination of this figure, we see that the maximum value of A_{BPS} occurs at the low ESM_{NCT} /low CT anchor point of the Pareto front, and is accompanied by a relatively high level of gas stores. This intuitively reflects the plants' need for CO_2 in order to grow. At the other anchor point (high ESM_{NCT} and high CT) A_{BPS} has been minimized. This agrees with our predictions, as the BPS is a major contributor to operational crew time requirements (planting, harvesting, irrigation, and food processing and preparation). Water stores and component rates for Pareto-optimal designs vary little; this suggests that a particular level of stored water and component rates is optimal for this architecture across the Pareto front.

Table 4.2 shows the actual range of store levels and component rates present in the Pareto fronts for a crew size of six (baseline) as well as four and eight. Pareto design variable visualizations for the three crew sizes are shown in Figure 4-9; these tables and figures give insight into the optimal design variables for various crew sizes, thereby enabling system designers to focus in and gain a clear understanding of the impact of design variables on the overall system performance. For example, it is clear that the absence of a BPS maximized CT for all three crew sizes, and the minimum ESM was obtained for all crew sizes when $A_{BPS} \approx 11 \text{ m}^2$. Intuitively, an increase in the amount of stored consumables and the necessary regenerative component processing

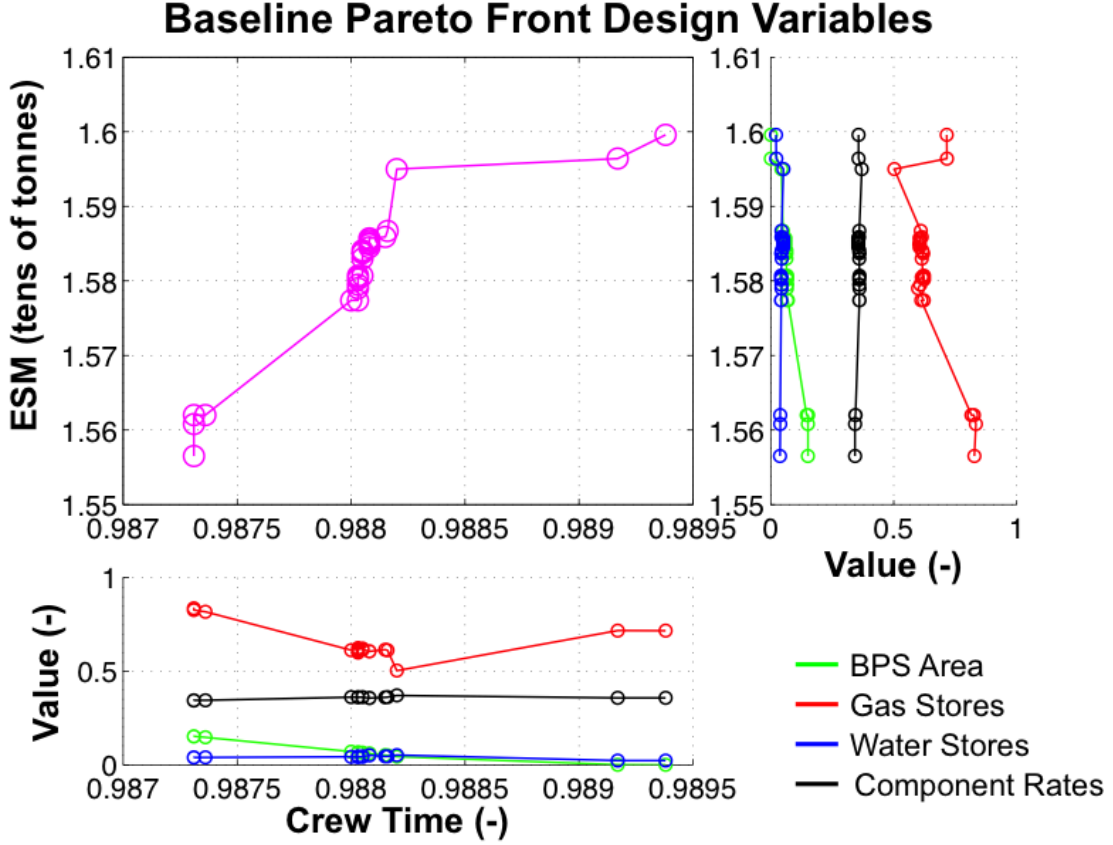


Figure 4-8: Visualization of the values of the design variables along the Pareto front of the baseline GA optimization. The upper left plot shows the Pareto front in objective space; the lower left and upper right plots show the values of the design variables at each point on the Pareto front at the corresponding value of crew time and ESM (respectively).

rates was necessary as crew size increased.

The small range of CT values (approximately 98.6%-99.0%) is due to the formulation of the CT metric. Recall that CT is reported as a percentage of awake crew time. This indicates that minimizing ESM_{NCT} (by raising crop area) reduces the crew's available time for non ECLSS-related activities by 0.4%. Assuming this decrease in crew time is acceptable to the mission designers, the ESM_{NCT} optimal point is of interest. The design vector that minimizes ESM_{NCT} for a crew of four is

Design Variable	Attribute	Unit	Range of Values		
			4 Crew	6 Crew	8 Crew
x ₁	Area of soybean crop	m ²	0-3.8950	0-3.8125	0-3.6725
	Area of lettuce crop	m ²	0-3.8950	0-3.8125	0-3.6725
	Area of rice crop	m ²	0-3.8950	0-3.8125	0-3.6725
x ₂	O ₂ store initial level	mols	2109.6-3099.4	4320.6-7178.4	78733-96587
	CO ₂ store initial level	mols	12.2650-18.0200	25.12-41.7350	45.775-56.155
x ₃	Potable water store initial level	kg	288-730.8	397.8-934.2	478.8-1013.4
	Grey water store initial level	kg	16-40.6	22.1-51.9	26.6-56.3
x ₄	OGS component rate	frac. nom.	0.0609-0.0638	0.0856-0.0926	0.1157-0.1262
	CRS component rate	frac. nom.	0.0609-0.0638	0.0856-0.0926	0.1157-0.1262
	Pyrolyzer component rate	frac. nom.	0.0609-0.0638	0.0856-0.0926	0.1157-0.1262
	Water Distiller component rate	frac. nom.	0.0609-0.0638	0.0856-0.0926	0.1157-0.1262

Table 4.2: Range of values for system attributes found along the Pareto front. Units are given, where “frac. nom.” indicates the fraction of the nominal BioSim value.

$$x = \begin{pmatrix} 0.16 \\ 0.26 \\ 0.04 \\ 0.26 \end{pmatrix}$$

This point has a total crop area of 11.7 m², an initial O₂ store level of 2109.6 mols, an initial CO₂ store level of 12.3 mols, an initial potable water store level of 730.8 kg, an initial grey water store level of 40.6 kg, and OGS, CRS, pyrolyzer, and water distiller component rates of 0.638 BioSim nominal rates.

4.5 Discussion

The multiobjective optimization of our 600-day Mars surface habitat revealed that a degree of bioregeneration using BPS crops was ESM_{NCT}-optimal; however, the employment of crops comes at the expense of crew time. The attractiveness of bioregeneration from crops was expected to increase with a higher number of crew members; however, the opposite was true. This is likely due to the limited degrees of freedom employed in this optimization problem; future studies could free up more design attributes to vary independently or add others that were not varied here.

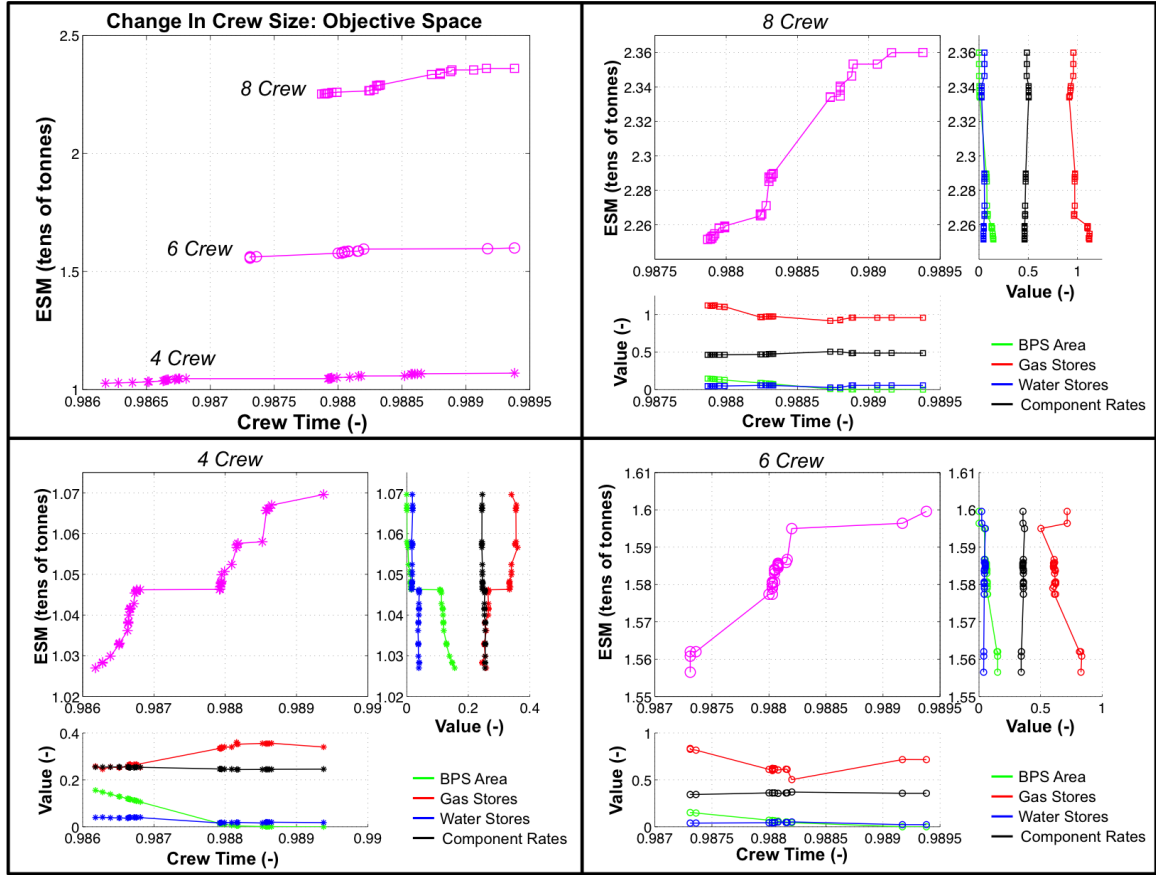


Figure 4-9: Visualization of the design variable values along the Pareto fronts for all cases in a sensitivity analysis investigating crew size. Clockwise from top left, the quadrants are: the objective space showing all 3 Pareto fronts, and the isolated Pareto fronts and design variables for the 8, 6, and 4 crewmember cases, respectively.

4.5.1 Merits of multiobjective examination

Multiobjective optimization gives the decision-maker a richer view of the system performance when compared to single-objective optimization. The separation of CT from ESM (and subsequent multiobjective optimization of CT and ESM_{NCT}) removes implicit assumptions about mission CT requirements and the mission objectives. Visualizations that map the Pareto-optimal solutions in the objective space to the design characteristics of each point can aid in informed design decisions based upon identification of Pareto-optimal systems' attributes and in the examination of the effect of changes in those attributes as objectives are traded. General heuristics about the system being optimized can be formed, and new architectures can be intelligently

generated by examining trends in design variables as they vary across the Pareto front.

The multiobjective optimization methods applied in this analysis and the visualizations used are readily extensible to other problems and other objectives. It is hoped that the community that architects ECLSS, selects ECLSS designs, and generates ECLSS hardware will continue to employ more multiobjective system design and optimization methods in its decision-making; however, this relies on the availability of high fidelity, validated modeling and simulation tools.

4.6 Chapter 4 Summary

To summarize, this work carried out multi-objective optimizations of non-crew time ESM and CT. For single-objective ESM_{NCT} , we attempted both a gradient-based `fmincon` optimization and a NSGA-II genetic algorithm; the genetic algorithm provided better performance. The cause of `fmincon`'s poor performance was mapped to regions of infeasibility in the design space and local minima in the objective space. Next, when we considered both the ESM_{NCT} and CT as objectives, the Pareto front generated by a gradient-based NBI optimization was nearly entirely dominated by the Pareto front obtained from a multiobjective genetic algorithm. After selecting the genetic algorithm as the appropriate optimization method, we tested genetic algorithm parameters including mutation coefficient, number of generations, and population size and selected the genetic algorithm baseline run from which we performed a sensitivity analysis to crew size.

Chapter 5

Conclusion and Future Work

5.1 Thesis Summary

To summarize, this research investigated the trade between biologically grown food and stored food as part of the broader bioregenerative-physicochemical trade-off in environmental control and life support systems (ECLSS) for isolated and confined environments using BioSim, a high-fidelity ECLSS simulation. This trade is particularly relevant for sustainable, long duration missions like those that NASA plans to deploy in the 2030s. An ESM analysis investigated ESM-optimality of lunar and Mars surface habitats, considering architectures with varying degrees of bioregeneration for food and atmosphere revitalization. A key part of this analysis was the quantitative consideration improvements to the electric lighting infrastructure and crew time demands of the BPS. The analyses predictably indicate that reducing lighting costs and increasing autonomy of the food production, processing, and preparation systems associated with the BPS will increase its feasibility and cost-effectiveness for use in long-term space flight. Crossover points at which a hybrid system becomes “cheaper will likely not be less than about 4 years for lunar surface missions and 4.8 years for Mars surface missions in the absence of technology improvements; however, with significant improvements to the BPS and its supporting infrastructure needs, these crossover times can be more than halved. The vague estimates of crossover times in previous studies give the same order of magnitude for ESM-optimality; however,

this study considers more factors in the ESM computation, is based on high-fidelity simulation of each architecture, and solves directly for the crossover mission duration.

The multidisciplinary ECLSS optimization described considered 14 design variables and modeled and evaluated integrated ECLSSs for non-crew time ESM (ESM_{NCT}) and crew time (CT). The ESM_{NCT} /CT Pareto front found using a 40-generation genetic algorithm with 40 individuals per generation is identified and described. ESM_{NCT} -optimal points for various crew sizes were identified; for a crew of four, the ESM_{NCT} -optimal design has 11.7 m² of crops, an initial O₂ store level of 2109.6 mols, an initial CO₂ store level of 12.3 mols, an initial potable water store level of 730.8 kg, an initial grey water store level of 40.6 kg, and OGS, CRS, pyrolyzer, and water distiller component rates of 0.638 BioSim nominal rates. This point is a recommended habitat design if the level of CT of 0.4% less than the maximum possible value is acceptable to the designer.

5.2 Recommendations For Future Work

This research is expandable in many directions. Some topics for future work are discussed here, but follow-up research is certainly not limited to this list. First, research to increase confidence of these results should directly follow this work. The results could be replicated with another modeling tool. In particular, Ecosim Pro seems promising due to its large technology library and the availability of a free trial version on the company website. Other tools, like VHab, ALSSAT, and a more evolved version of HabNet, could be used if available. The results should also be replicated for mixed crops. BioSim contains models for nine crop types, so a first step toward creating a more realistic biomass production system would be to assign a fraction of shelf area to each of these crop types. Also, in this analysis, infrastructure costs were considered only at the lower-bound and nominal values; future work should test the upper-bound (most conservative) values for completeness.

Second, follow up research can be carried out using the same general approach detailed in this paper to expand the implications of this work. The temporal nature

of crop yields with discrete planting and harvesting in this study caused fluctuations in atmosphere composition and pressure (see Figure 5-1); a case study should be carried out to demonstrate the differences in ESM optimality and crop productivity with continuous planting and harvesting. Other assumed parameters for the crop growth environment (e.g., type of lighting, lighting schedule, irrigation schedule) should be considered as well. Additional hardware testbeds could be valuable for testing different combinations of these parameters. In addition, there are several

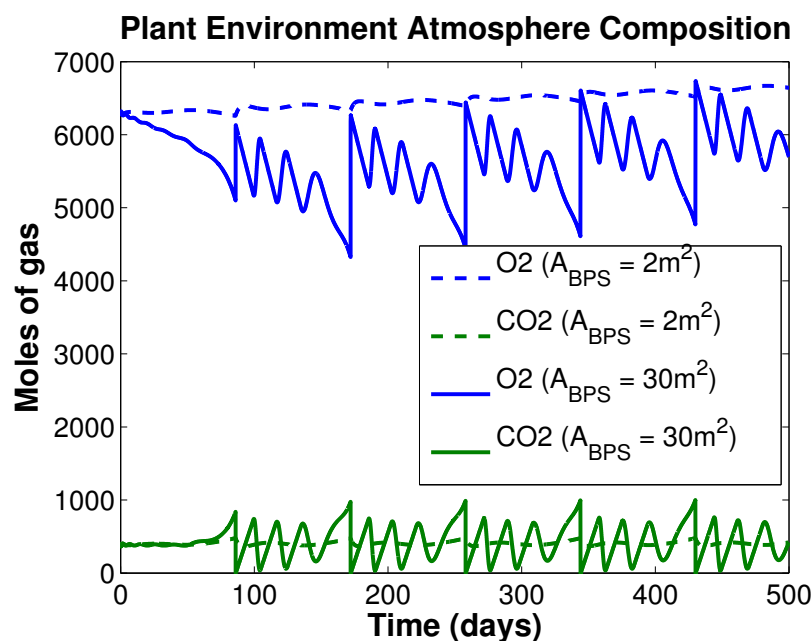


Figure 5-1: Comparison of O_2 and CO_2 levels in BioSim Plant Environment module for BPS shelf areas of 2 and 30 m^2 .

promising bioregenerative components that should be considered in trade studies of the type performed in this thesis. Examples of bioregenerative technologies that have been or should be modeled are algae, microbial fuel cells, microbial bioreactors, and composters. With the exception of algae, these technologies are not intended to affect ECLSS on the full-system level as are crops, but rather are being developed to “plug and play” with existing ECLSS architectures. These technologies, as well as genetically modified crops, could be included in ECLSS analyses similar to the ones performed in this thesis.

Additionally, for this study, we only considered long-duration surface habitats on

the Moon and on Mars. There are three representative mission types described in NASA’s ECLSS Roadmap [3]:

1. Short-duration microgravity mission (Multi-Purpose Crew Vehicle/Space Exploration Vehicle-like)
2. Long-duration microgravity mission (ISS-like with low/zero resupply)
3. Long-duration partial-gravity (surface) exploration mission

This project investigated only the third type because it was hypothesized that biological crop growth systems would be most relevant for longer-duration surface missions; however, there would certainly be positive gains to be had in including BPSs on short-duration missions as well. Also, other mission phases (transit and descent/ascent - see Table 5.1 for details) should be considered to see if it would be feasible to run the BPS continually or just for certain phases of the mission. Our study solely carried

Parameter	Units	Minimum	Nominal	Upper
<i>Crew Size</i>	people	4	6	9
<i>Lunar Transit Phase</i>	d	3	6	7
<i>Lunar Descent/Ascent Phase</i>	d	5	8	8
<i>Lunar Surface Phase</i>	d	3	3 or 30	30
<i>Mars Transit Phase</i>	d	110	180	180
<i>Mars Descent/Ascent Phase</i>	d	7	7	30
<i>Mars Surface Phase</i>	d	540	600	619

Table 5.1: Table of mission phases and their durations assumed for lunar and Mars surface missions [53].

out an ESM analysis for the surface habitat leg of the mission. Power/mass needs are much more costly for the trip than once on the surface, which is reflected in the infrastructure penalties provided for all of the mission phases in the 2004 Advanced Life Support Baseline Values and Assumptions Document [53]. It would be informative to see if the benefits of a BPS on-board for the other 390 days of travel would be worth the added cost. However, in a scenario where BPS is only employed for the surface habitat leg of the journey, the feasibility of keeping seeds intact for over a year should be considered.

Third, contingency factors and redundancy of components should be considered to design for different levels of reliability. This would likely increase the attractiveness of stores of food as a backup option in case one or more crop harvests fails to produce as expected. The necessary redundancy of a full stored food system is well-understood, as stored refrigerated/frozen food has high heritage for space flight applications.

Fourth, other metrics in addition to ESM should continue to be investigated. Most within the ECLSS community recognize that the ESM metric alone is not fully sufficient for evaluation of life support system architectures and subsequent design selection and technology development recommendations. A crew productivity metric would be useful as a proxy for mission science and/or resource return. One attempt at crew productivity quantification was implemented in the BioSim simulation. In BioSim, crew productivity can be “artificially” measured from simulated levels of consumables and mission schedule that affect crew health and happiness (e.g., sleep, nutrition/variety of diet, leisure time, sufficient O₂ and water availability). Crew productivity accrues as mission tasks are completed in the simulation; this measure is multiplied by a factor constructed from equal weightings of several of these factors. This metric has not been applied to published life support studies, perhaps due to its subjectiveness; however, it identifies a few important quantifiable life support simulation parameters that would affect crew productivity in reality. The Virtual Habitat life support system simulation similarly allows crew productivity to accrue during the mission, though it is calculated differently with separate productivity factors based on psychological and physiological parameters. The form of the metric constructed from the relevant simulation parameters (as well as appropriate differential weighting of each factor) can be debated but should be theoretically and empirically investigated by experts in human physiology and psychology. Ultimately, a crew productivity metric would be useful to distinguish between architectures that would better support a crews ability to contribute to science/resource return through their activity.

Another metric that would be useful to quantify is the risk, or probability of loss of crew (P(LoC)). The quantification of P(LoC) would have enriched the ESM analysis and multidisciplinary ECLSS optimization, as the objectives of ESM, crew time, and

P(LoC) roughly map to the three ultimate objectives of cost, science return, and risk often used in early concept development and tradespace exploration. Quantifying the risk of crop failure or of BPS supporting hardware failure would be particularly interesting because of the (perhaps justified) stigma around bioregenerative technologies that they are risky.

Lastly, this work and its continuation should be validated with experimental testbeds. Several isolated technology development and testing efforts have been carried out in the United States and internationally [32]; however, a sensitivity analysis of an integrated advanced life support system that employs biological and regenerative components should be performed to validate the results seen in models such as BioSim, Ecosim Pro, VHab, and ALSSAT. There is a noticeable dearth of experimental testbeds that take a systems-level look at complex ECLSS with a reductionist approach.

5.3 Final Remarks

ECLSS technology development must be driven by realistic trade studies that account for the current state of the art technologies and possible improvements. The introduction of high-fidelity models into trade studies allows for an analysis of the integrated ECLSS system and habitat that capture non-intuitive issues and emergent interactions, allowing the user to obtain a more accurate estimate of system consumable and technology requirements. Integrated system modeling is crucial for complex systems that display nontrivial interactions across subsystem modules. High-fidelity modeling is also able to capture dynamic system behavior that is excluded by steady-state models. It is hoped that the merits of employing high-fidelity models and multidisciplinary system optimization for trade studies to drive technology development have been alluded to and justified in this study and that follow-up studies will be conducted to further the implications of this work.

Appendix A

Baseline BioSim .XML Configuration File

```
1 <?xml version="1.0" encoding="UTF-8"?>
2 <?xml-stylesheet type="text/xsl" href="../../style/table.xsl"?>
3 <biosim xmlns="http://www.traclabs.com/biosim" xmlns:xsi="http://www.w3.org/2001/
  XMLSchema-instance"
4   xsi:schemaLocation="http://www.traclabs.com/biosim ../../schema/BiosimInitSchema.
    xsd">
5   <Globals driverStutterLength="0"
6     crewsToWatch="Crew_Quarters_Group Galley_Group Labs_Group Maintenance_Group"
7     runTillCrewDeath="false" runTillN="24000" startPaused="false"
8     exitWhenFinished="true">
9   </Globals>
10  <SimBioModules>
11    <environment>
12      <SimEnvironment moduleName="PlantEnvironment"
13        initialVolume="1000000" logLevel="DEBUG">
14        <percentageInitialization waterPercentage="0.01"
15          nitrogenPercentage="0.690" otherPercentage="0.001" o2Percentage="
16            0.28"
17          totalPressure="55" co2Percentage="0.019" />
18      </SimEnvironment>
19      <SimEnvironment moduleName="Crew_Quarters"
20        initialVolume="2700000" logLevel="DEBUG">
21        <percentageInitialization waterPercentage="0.01"
22          nitrogenPercentage="0.659" otherPercentage="0.001" o2Percentage="
23            0.33"
24          totalPressure="55" co2Percentage="0" />
25      </SimEnvironment>
26      <SimEnvironment moduleName="Galley" initialVolume="2700000">
27        <percentageInitialization waterPercentage="0.01"
28          nitrogenPercentage="0.659" otherPercentage="0.001" o2Percentage="
29            0.33"
30          totalPressure="55" co2Percentage="0" />
31      </SimEnvironment>
32      <SimEnvironment moduleName="Labs" initialVolume="1900000"
33        airlockVolume="80000">
34        <percentageInitialization waterPercentage="0.01"
35          nitrogenPercentage="0.659" otherPercentage="0.001" o2Percentage="
36            0.33"
37          totalPressure="55" co2Percentage="0" />
38      </SimEnvironment>
39      <SimEnvironment moduleName="Maintenance"
40        initialVolume="19000" airlockVolume="80000" logLevel="DEBUG">
41        <percentageInitialization waterPercentage="0.01"
42          nitrogenPercentage="0.659" otherPercentage="0.001" o2Percentage="
43            0.33"
```

```

38         totalPressure="55" co2Percentage="0" />
39     </SimEnvironment>
40     <SimEnvironment moduleName="EVA_Environment"
41         initialVolume="2700000">
42         <percentageInitialization waterPercentage="0"
43             nitrogenPercentage="0.659" otherPercentage="0.001" o2Percentage="
44                 0.33"
45             totalPressure="55" co2Percentage="0" />
46     </SimEnvironment>
47     <Dehumidifier moduleName="Main_Dehumidifier">
48         <airConsumer inputs="Maintenance" desiredFlowRates="1000"
49             maxFlowRates="1000"></airConsumer>
50         <dirtyWaterProducer desiredFlowRates="1000"
51             outputs="Dirty_Water_Store" maxFlowRates="1000" />
52     </Dehumidifier>
53     <Dehumidifier moduleName="Plant_Dehumidifier">
54         <airConsumer inputs="PlantEnvironment" desiredFlowRates="100"
55             maxFlowRates="100"></airConsumer>
56         <dirtyWaterProducer desiredFlowRates="100"
57             outputs="Dirty_Water_Store" maxFlowRates="100" />
58     </Dehumidifier>
59     <Dehumidifier moduleName="Backup_Dehumidifier">
60         <airConsumer inputs="Labs" desiredFlowRates="1000"
61             maxFlowRates="1000"></airConsumer>
62         <dirtyWaterProducer desiredFlowRates="1000"
63             outputs="Dirty_Water_Store" maxFlowRates="1000" />
64     </Dehumidifier>
65     <Fan moduleName="Maintenance_to_Crew_Fan">
66         <airConsumer inputs="Maintenance" desiredFlowRates="300"
67             maxFlowRates="300" />
68         <powerConsumer inputs="Fan_Battery" desiredFlowRates="50"
69             maxFlowRates="50"></powerConsumer>
70         <airProducer desiredFlowRates="300" outputs="Crew_Quarters"
71             maxFlowRates="300"></airProducer>
72     </Fan>
73     <Fan moduleName="Crew_to_Maintenance_Fan">
74         <airConsumer inputs="Crew_Quarters" desiredFlowRates="300"
75             maxFlowRates="300" />
76         <powerConsumer inputs="General_Power_Store"
77             desiredFlowRates="50" maxFlowRates="50"></powerConsumer>
78         <airProducer desiredFlowRates="300" outputs="Maintenance"
79             maxFlowRates="300"></airProducer>
80     </Fan>
81     <Fan moduleName="Crew_to_Galley_Fan">
82         <airConsumer inputs="Crew_Quarters" desiredFlowRates="300"
83             maxFlowRates="300" />
84         <powerConsumer inputs="General_Power_Store"
85             desiredFlowRates="50" maxFlowRates="50" />
86         <airProducer desiredFlowRates="300" outputs="Galley"
87             maxFlowRates="300" />
88     </Fan>
89     <Fan moduleName="Galley_to_Crew_Fan">
90         <airConsumer inputs="Galley" desiredFlowRates="300"
91             maxFlowRates="300" />
92         <powerConsumer inputs="General_Power_Store"
93             desiredFlowRates="50" maxFlowRates="50" />
94         <airProducer desiredFlowRates="300" outputs="Crew_Quarters"
95             maxFlowRates="300" />
96     </Fan>
97     <Fan moduleName="Galley_to_Labs_Fan">
98         <airConsumer inputs="Galley" desiredFlowRates="1000"
99             maxFlowRates="1000" />
100         <powerConsumer inputs="General_Power_Store"
101             desiredFlowRates="50" maxFlowRates="50" />
102         <airProducer desiredFlowRates="1000" outputs="Labs"
103             maxFlowRates="1000"></airProducer>
104     </Fan>

```

```

105     <Fan moduleName="Labs_to_Galley_Fan">
106         <airConsumer inputs="Labs" desiredFlowRates="1000"
107             maxFlowRates="1000" />
108         <powerConsumer inputs="General_Power_Store"
109             desiredFlowRates="50" maxFlowRates="50" />
110         <airProducer desiredFlowRates="1000" outputs="Galley"
111             maxFlowRates="1000" />
112     </Fan>
113     <Fan moduleName="PlantEnvironment_to_Crew_Fan">
114         <airConsumer inputs="PlantEnvironment" desiredFlowRates="0"
115             maxFlowRates="0" />
116         <powerConsumer inputs="Fan_Battery" desiredFlowRates="0"
117             maxFlowRates="0"></powerConsumer>
118         <airProducer desiredFlowRates="0" outputs="Crew_Quarters"
119             maxFlowRates="0"></airProducer>
120     </Fan>
121     <Fan moduleName="Crew_to_PlantEnvironment_Fan">
122         <airConsumer inputs="Crew_Quarters" desiredFlowRates="0"
123             maxFlowRates="0" />
124         <powerConsumer inputs="General_Power_Store"
125             desiredFlowRates="0" maxFlowRates="0"></powerConsumer>
126         <airProducer desiredFlowRates="0" outputs="PlantEnvironment"
127             maxFlowRates="0"></airProducer>
128     </Fan>
129 </environment>
130 <air>
131     <NitrogenStore capacity="10000" moduleName="Crew_Quarter_Nitrogen_Store"
132         level="10000" logLevel="DEBUG">
133     </NitrogenStore>
134     <NitrogenStore capacity="10000" moduleName="Galley_Nitrogen_Store"
135         level="10000" logLevel="DEBUG">
136     </NitrogenStore>
137     <NitrogenStore capacity="10000" moduleName="Labs_Nitrogen_Store"
138         level="10000" logLevel="DEBUG">
139     </NitrogenStore>
140     <NitrogenStore capacity="10000" moduleName="Maintenance_Nitrogen_Store"
141         level="10000" logLevel="DEBUG">
142     </NitrogenStore>
143     <VCCR moduleName="Main_VCCR">
144         <powerConsumer inputs="General_Power_Store"
145             desiredFlowRates="2000" maxFlowRates="2000"></powerConsumer>
146         <airConsumer inputs="Maintenance"
147             desiredFlowRates="10000" maxFlowRates="10000"></airConsumer>
148         <airProducer desiredFlowRates="10000" outputs="Maintenance"
149             maxFlowRates="10000" />
150         <CO2Producer desiredFlowRates="10000" outputs="CO2_Store"
151             maxFlowRates="10000"></CO2Producer>
152     </VCCR>
153     <VCCR moduleName="Backup_VCCR">
154         <powerConsumer inputs="General_Power_Store"
155             desiredFlowRates="0" maxFlowRates="0" />
156         <airConsumer inputs="Labs"
157             desiredFlowRates="0" maxFlowRates="0"></airConsumer>
158         <airProducer
159             desiredFlowRates="0" outputs="Labs" maxFlowRates="0"></
160             airProducer>
161         <CO2Producer
162             desiredFlowRates="0" outputs="CO2_Store" maxFlowRates="0"></
163             CO2Producer>
164     </VCCR>
165     <OGS moduleName="OGS">
166         <powerConsumer inputs="General_Power_Store"
167             desiredFlowRates="0" maxFlowRates="0" />
168         <potableWaterConsumer inputs="Potable_Water_Store"
169             desiredFlowRates="0" maxFlowRates="0" />
170         <O2Producer desiredFlowRates="0" outputs="O2_Store" maxFlowRates=
171             "0"></O2Producer>

```

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169         <H2Producer desiredFlowRates="0" outputs="H2_Store" maxFlowRates=
            "0" />
170     </OGS>
171     <O2Store capacity="100000" moduleName="O2_Store" level="100000" logLevel=
        ="DEBUG">
172 </O2Store>
173 <H2Store capacity="10000" moduleName="H2_Store" level="1000" logLevel="
    DEBUG"></H2Store>
174 <CO2Store capacity="100000" moduleName="CO2_Store" level="100000"
    logLevel="DEBUG"></CO2Store> <!-- EDIT -->
175 <CRS moduleName="CRS">
176     <powerConsumer inputs="General_Power_Store"
177         desiredFlowRates="100" maxFlowRates="100" />
178     <CO2Consumer inputs="CO2_Store" desiredFlowRates="100"
179         maxFlowRates="100" />
180     <H2Consumer inputs="H2_Store" desiredFlowRates="100"
181         maxFlowRates="100" />
182     <potableWaterProducer desiredFlowRates="100"
183         outputs="Potable_Water_Store" maxFlowRates="100" />
184     <methaneProducer desiredFlowRates="100" outputs="Methane_Store"
185         maxFlowRates="100"></methaneProducer>
186 </CRS>
187 <MethaneStore capacity="1000" moduleName="Methane_Store"
188     level="100" logLevel="DEBUG">
189 </MethaneStore>
190 <Pyrolizer moduleName="Pyrolizer">
191     <powerConsumer inputs="General_Power_Store"
192         desiredFlowRates="100" maxFlowRates="100" />
193     <methaneConsumer inputs="Methane_Store"
194         desiredFlowRates="100" maxFlowRates="100" />
195     <H2Producer desiredFlowRates="100" outputs="H2_Store"
196         maxFlowRates="100" />
197     <dryWasteProducer desiredFlowRates="100"
198         outputs="Dry_Waste_Store" maxFlowRates="100" />
199 </Pyrolizer>
200 </air>
201 <framework>
202     <Injector moduleName="Crew_Quarters_Nitrogen_Injector">
203         <nitrogenConsumer inputs="Crew_Quarter_Nitrogen_Store"
204             desiredFlowRates="0" maxFlowRates="100">
205         </nitrogenConsumer>
206         <nitrogenProducer desiredFlowRates="0" outputs="Crew_Quarters"
207             maxFlowRates="100">
208         </nitrogenProducer>
209     </Injector>
210     <Injector moduleName="Galley_Nitrogen_Injector">
211         <nitrogenConsumer inputs="Galley_Nitrogen_Store"
212             desiredFlowRates="0" maxFlowRates="100">
213         </nitrogenConsumer>
214         <nitrogenProducer desiredFlowRates="0" outputs="Galley"
215             maxFlowRates="100">
216         </nitrogenProducer>
217     </Injector>
218     <Injector moduleName="Labs_Nitrogen_Injector">
219         <nitrogenConsumer inputs="Labs_Nitrogen_Store"
220             desiredFlowRates="0" maxFlowRates="100">
221         </nitrogenConsumer>
222         <nitrogenProducer desiredFlowRates="0" outputs="Labs"
223             maxFlowRates="100">
224         </nitrogenProducer>
225     </Injector>
226     <Injector moduleName="Maintenance_Nitrogen_Injector">
227         <nitrogenConsumer inputs="Maintenance_Nitrogen_Store"
228             desiredFlowRates="0" maxFlowRates="100">
229         </nitrogenConsumer>
230         <nitrogenProducer desiredFlowRates="0" outputs="Maintenance"
231             maxFlowRates="100">
232         </nitrogenProducer>

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233     </Injector>
234     <Injector moduleName="Maintenance_Oxygen_Injector">
235         <O2Consumer inputs="O2_Store" desiredFlowRates="4.2" maxFlowRates="
236             4.2"></O2Consumer>
237         <O2Producer desiredFlowRates="4.2" outputs="Maintenance" maxFlowRates
238             ="4.2"></O2Producer>
239     </Injector>
240     <Injector moduleName="PlantEnvironment_CO2_Injector">
241         <CO2Consumer inputs="CO2_Store" desiredFlowRates="0" maxFlowRates="0"
242             ></CO2Consumer>
243         <CO2Producer desiredFlowRates="0" outputs="PlantEnvironment"
244             maxFlowRates="0"></CO2Producer>
245     </Injector>
246     <Accumulator moduleName="Accumulator">
247         <O2Consumer inputs="PlantEnvironment" desiredFlowRates="0"
248             maxFlowRates="0"/>
249         <O2Producer desiredFlowRates="0" outputs="O2_Store" maxFlowRates="0"/
250             >
251     </Accumulator>
252 </framework>
253 <water>
254     <WaterRS moduleName="Water_Distiller" implementation="LINEAR">
255         <powerConsumer inputs="General_Power_Store"
256             desiredFlowRates="1000" maxFlowRates="1000"></powerConsumer>
257         <dirtyWaterConsumer inputs="Dirty_Water_Store"
258             desiredFlowRates="10" maxFlowRates="10">
259         </dirtyWaterConsumer>
260         <greyWaterConsumer inputs="Grey_Water_Store"
261             desiredFlowRates="10" maxFlowRates="10" />
262         <potableWaterProducer desiredFlowRates="1000"
263             outputs="Potable_Water_Store" maxFlowRates="1000" />
264     </WaterRS>
265     <DirtyWaterStore capacity="500" moduleName="Dirty_Water_Store"
266         level="0" logLevel="DEBUG">
267     </DirtyWaterStore>
268     <GreyWaterStore capacity="50000" moduleName="Grey_Water_Store"
269         level="50000" logLevel="DEBUG">
270     </GreyWaterStore>
271     <PotableWaterStore capacity="100000" moduleName="Potable_Water_Store"
272         level="10000" logLevel="DEBUG">
273     </PotableWaterStore>
274 </water>
275 <power>
276     <PowerStore capacity="100000" moduleName="General_Power_Store"
277         level="100000" logLevel="DEBUG">
278     </PowerStore>
279     <PowerStore capacity="100000" moduleName="Fan_Battery"
280         level="100000" logLevel="DEBUG">
281     </PowerStore>
282     <PowerStore capacity="400000" moduleName="CO2_Removal_Battery"
283         level="400000" logLevel="DEBUG">
284     </PowerStore>
285     <PowerPS moduleName="Fan_Battery_Source" generationType="NUCLEAR">
286         <powerProducer desiredFlowRates="1000" outputs="Fan_Battery"
287             maxFlowRates="1000" />
288     </PowerPS>
289     <PowerPS moduleName="General_Power_Producer" generationType="NUCLEAR">
290         upperPowerGeneration="500000">
291         <powerProducer desiredFlowRates="1000000" outputs="
292             General_Power_Store"
293             maxFlowRates="1000000" />
294     </PowerPS>
295 </power>
296 <food>
297     <FoodStore capacity="10000" level="8000" moduleName="Food_Store" logLevel
298         ="DEBUG">
299     </FoodStore>
300     <BiomassPS moduleName="BiomassPS" autoHarvestAndReplant="true"

```

```

293         logLevel="DEBUG">
294         <shelf cropArea="25" cropType="SOYBEAN" />
295         <powerConsumer maxFlowRates="1000" desiredFlowRates="1000"
296             inputs="General_Power_Store" />
297         <potableWaterConsumer maxFlowRates="1000"
298             desiredFlowRates="1000" inputs="Potable_Water_Store" />
299         <greyWaterConsumer maxFlowRates="1000"
300             desiredFlowRates="1000" inputs="Grey_Water_Store" />
301         <airConsumer maxFlowRates="1000" desiredFlowRates="1000"
302             inputs="PlantEnvironment" />
303         <dirtyWaterProducer maxFlowRates="1000"
304             desiredFlowRates="1000" outputs="Dirty_Water_Store" />
305         <biomassProducer maxFlowRates="10000"
306             desiredFlowRates="10000" outputs="BiomassStore" />
307         <airProducer maxFlowRates="1000" desiredFlowRates="1000"
308             outputs="PlantEnvironment" />
309     </BiomassPS>
310     <BiomassStore moduleName="BiomassStore" capacity="100000"
311         level="0" logLevel="DEBUG" />
312 </food>
313 <waste>
314     <DryWasteStore capacity="1000000" moduleName="Dry_Waste_Store"
315         level="0" logLevel="DEBUG">
316     </DryWasteStore>
317 </waste>
318 <crew>
319     <CrewGroup moduleName="Crew_Quarters_Group">
320         <potableWaterConsumer inputs="Potable_Water_Store"
321             desiredFlowRates="3" maxFlowRates="3">
322         </potableWaterConsumer>
323         <airConsumer inputs="Crew_Quarters" desiredFlowRates="0"
324             maxFlowRates="0" />
325         <foodConsumer inputs="Food_Store" desiredFlowRates="5"
326             maxFlowRates="5">
327         </foodConsumer>
328         <!-- might try changing this input -->
329         <dirtyWaterProducer desiredFlowRates="100"
330             outputs="Dirty_Water_Store" maxFlowRates="100">
331         </dirtyWaterProducer>
332         <greyWaterProducer desiredFlowRates="100"
333             outputs="Grey_Water_Store" maxFlowRates="100" />
334         <airProducer desiredFlowRates="0" outputs="Crew_Quarters"
335             maxFlowRates="0" />
336         <dryWasteProducer desiredFlowRates="10"
337             outputs="Dry_Waste_Store" maxFlowRates="10">
338         </dryWasteProducer>
339         <crewPerson age="35" name="Buck Rogers" sex="MALE"
340             weight="75">
341             <schedule>
342                 <activity intensity="2" name="ruminating" length="12" />
343                 <activity intensity="0" name="sleep" length="8" />
344                 <activity intensity="5" name="exercise" length="2" />
345                 <activity intensity="4" name="EVA" length="2"
346                     xsi:type="EVAActivityType" evaCrewGroup="EVA_Crew_Group"
347                     />
348             </schedule>
349         </crewPerson>
350     </CrewGroup>
351     <CrewGroup moduleName="Galley_Group">
352         <potableWaterConsumer inputs="Potable_Water_Store"
353             desiredFlowRates="3" maxFlowRates="3">
354         </potableWaterConsumer>
355         <airConsumer inputs="Galley" desiredFlowRates="0"
356             maxFlowRates="0" />
357         <foodConsumer inputs="Food_Store" desiredFlowRates="5"
358             maxFlowRates="5">
359         </foodConsumer>
360         <dirtyWaterProducer desiredFlowRates="100"

```



```

360         outputs="Dirty_Water_Store" maxFlowRates="100">
361     </dirtyWaterProducer>
362     <greyWaterProducer desiredFlowRates="100"
363         outputs="Grey_Water_Store" maxFlowRates="100" />
364     <airProducer desiredFlowRates="0" outputs="Galley"
365         maxFlowRates="0" />
366     <dryWasteProducer desiredFlowRates="10"
367         outputs="Dry_Waste_Store" maxFlowRates="10">
368     </dryWasteProducer>
369     <crewPerson age="35" name="Wilma Deering" sex="FEMALE"
370         weight="55">
371         <schedule>
372             <activity intensity="2" name="ruminating" length="12" />
373             <activity intensity="0" name="sleep" length="8" />
374             <activity intensity="5" name="exercercise" length="2" />
375             <activity intensity="5" name="exercercise" length="2" />
376             <activity intensity="4" name="EVA" length="2"
377                 xsi:type="EVAActivityType" evaCrewGroup="EVA_Crew_Group"
                 />
378         </schedule>
379     </crewPerson>
380 </CrewGroup>
381 <CrewGroup moduleName="Labs_Group">
382     <potableWaterConsumer inputs="Potable_Water_Store"
383         desiredFlowRates="3" maxFlowRates="3">
384     </potableWaterConsumer>
385     <airConsumer inputs="Labs" desiredFlowRates="0"
386         maxFlowRates="0" />
387     <foodConsumer inputs="Food_Store" desiredFlowRates="5"
388         maxFlowRates="5">
389     </foodConsumer>
390     <dirtyWaterProducer desiredFlowRates="100"
391         outputs="Dirty_Water_Store" maxFlowRates="100">
392     </dirtyWaterProducer>
393     <greyWaterProducer desiredFlowRates="100"
394         outputs="Grey_Water_Store" maxFlowRates="100" />
395     <airProducer desiredFlowRates="0" outputs="Labs"
396         maxFlowRates="0" />
397     <dryWasteProducer desiredFlowRates="10"
398         outputs="Dry_Waste_Store" maxFlowRates="10">
399     </dryWasteProducer>
400     <crewPerson age="35" name="Tim O'Connor" sex="MALE"
401         weight="72">
402         <schedule>
403             <activity intensity="2" name="ruminating" length="12" />
404             <activity intensity="0" name="sleep" length="8" />
405             <activity intensity="5" name="exercercise" length="2" />
406         </schedule>
407     </crewPerson>
408 </CrewGroup>
409 <CrewGroup moduleName="Maintenance_Group">
410     <potableWaterConsumer inputs="Potable_Water_Store"
411         desiredFlowRates="3" maxFlowRates="3">
412     </potableWaterConsumer>
413     <airConsumer inputs="Maintenance" desiredFlowRates="0"
414         maxFlowRates="0" />
415     <foodConsumer inputs="Food_Store" desiredFlowRates="5"
416         maxFlowRates="5">
417     </foodConsumer>
418     <dirtyWaterProducer desiredFlowRates="100"
419         outputs="Dirty_Water_Store" maxFlowRates="100">
420     </dirtyWaterProducer>
421     <greyWaterProducer desiredFlowRates="100"
422         outputs="Grey_Water_Store" maxFlowRates="100" />
423     <airProducer desiredFlowRates="0" outputs="Maintenance"
424         maxFlowRates="0" />
425     <dryWasteProducer desiredFlowRates="10"
426         outputs="Dry_Waste_Store" maxFlowRates="10">

```

```

427         </dryWasteProducer>
428         <crewPerson age="35" name="Kane" sex="MALE" weight="77">
429             <schedule>
430                 <activity intensity="2" name="ruminating" length="12" />
431                 <activity intensity="0" name="sleep" length="8" />
432                 <activity intensity="5" name="exercise" length="2" />
433             </schedule>
434         </crewPerson>
435     </CrewGroup>
436     <CrewGroup moduleName="EVA_Crew_Group">
437         <potableWaterConsumer inputs="Potable_Water_Store"
438             desiredFlowRates="3" maxFlowRates="3">
439         </potableWaterConsumer>
440         <airConsumer inputs="EVA_Environment" desiredFlowRates="0"
441             maxFlowRates="0" />
442         <foodConsumer inputs="Food_Store" desiredFlowRates="5"
443             maxFlowRates="5">
444         </foodConsumer>
445         <dirtyWaterProducer desiredFlowRates="100"
446             outputs="Dirty_Water_Store" maxFlowRates="100">
447         </dirtyWaterProducer>
448         <greyWaterProducer desiredFlowRates="100"
449             outputs="Grey_Water_Store" maxFlowRates="100" />
450         <airProducer desiredFlowRates="0" outputs="EVA_Environment"
451             maxFlowRates="0" />
452         <dryWasteProducer desiredFlowRates="10"
453             outputs="Dry_Waste_Store" maxFlowRates="10">
454         </dryWasteProducer>
455     </CrewGroup>
456 </crew>
457 </SimBioModules>
458 <Sensors>
459     <power>
460         <PowerInFlowRateSensor input="Main_VCCR"
461             moduleName="MainVccrPowerSensor" index="0" logLevel="INFO"
462             isBionetEnabled="false">
463         </PowerInFlowRateSensor>
464         <PowerInFlowRateSensor input="Backup_VCCR"
465             moduleName="BackupVccrPowerSensor" index="0" logLevel="INFO"
466             isBionetEnabled="false">
467         </PowerInFlowRateSensor>
468     </power>
469     <air>
470         <CO2OutFlowRateSensor input="Main_VCCR"
471             moduleName="MainVccrCo2OutSensor" index="0" isBionetEnabled="false" /
472         >
473     </air>
474     <environment>
475         <AirInFlowRateSensor input="Main_VCCR"
476             moduleName="MainVccrAirInSensor" index="0" isBionetEnabled="false"></
477             AirInFlowRateSensor>
478         <AirOutFlowRateSensor input="Main_VCCR"
479             moduleName="MainVccrAirOutSensor" index="0" isBionetEnabled="false"><
480             /AirOutFlowRateSensor>
481
482         <TotalMolesSensor input="Crew_Quarters" moduleName="Crew_Quarters_Moles"
483             logLevel="INFO"></TotalMolesSensor>
484         <TotalMolesSensor input="Labs" moduleName="Labs_Moles"
485             logLevel="INFO"></TotalMolesSensor>
486         <TotalMolesSensor input="Galley" moduleName="Galley_Moles"
487             logLevel="INFO"></TotalMolesSensor>
488         <TotalMolesSensor input="Maintenance" moduleName="Maintenance_Moles"
489             logLevel="INFO"></TotalMolesSensor>
490
491         <AirInFlowRateSensor input="Maintenance_to_Crew_Fan"
492             moduleName="Maintenance_to_Crew_Fan-InSensor" index="0" logLevel="
493             INFO"></AirInFlowRateSensor>
494         <AirOutFlowRateSensor input="Maintenance_to_Crew_Fan"

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491         moduleName="Maintenance_to_Crew_Fan-OutSensor" index="0" logLevel="
492             INFO"></AirOutFlowRateSensor>
493     <AirInFlowRateSensor input="Crew_to_Maintenance_Fan"
494         moduleName="Crew_to_Maintenance_Fan-InSensor" index="0" logLevel="
495             INFO"></AirInFlowRateSensor>
496     <AirOutFlowRateSensor input="Crew_to_Maintenance_Fan"
497         moduleName="Crew_to_Maintenance_Fan-OutSensor" index="0" logLevel="
498             INFO"></AirOutFlowRateSensor>
499     <AirInFlowRateSensor input="Crew_to_Galley_Fan"
500         moduleName="Crew_to_Galley_Fan-InSensor" index="0" logLevel="INFO"></
501         AirInFlowRateSensor>
502     <AirOutFlowRateSensor input="Crew_to_Galley_Fan"
503         moduleName="Crew_to_Galley_Fan-OutSensor" index="0" logLevel="INFO"><
504         /AirOutFlowRateSensor>
505     <AirInFlowRateSensor input="Galley_to_Crew_Fan"
506         moduleName="Galley_to_Crew_Fan-InSensor" index="0" logLevel="INFO"></
507         AirInFlowRateSensor>
508     <AirOutFlowRateSensor input="Galley_to_Crew_Fan"
509         moduleName="Galley_to_Crew_Fan-OutSensor" index="0" logLevel="INFO"><
510         /AirOutFlowRateSensor>
511     <AirInFlowRateSensor input="Galley_to_Labs_Fan"
512         moduleName="Labs_to_Galley_Fan-InSensor" index="0" logLevel="INFO"></
513         AirInFlowRateSensor>
514     <AirOutFlowRateSensor input="Labs_to_Galley_Fan"
515         moduleName="Labs_to_Galley_Fan-OutSensor" index="0" logLevel="INFO"><
516         /AirOutFlowRateSensor>
517     <AirInFlowRateSensor input="PlantEnvironment_to_Crew_Fan"
518         moduleName="PlantEnvironment_to_Crew_Fan-InSensor" index="0" logLevel
519             ="INFO"></AirInFlowRateSensor>
520     <AirOutFlowRateSensor input="PlantEnvironment_to_Crew_Fan"
521         moduleName="PlantEnvironment_to_Crew_Fan-OutSensor" index="0"
522             logLevel="INFO"></AirOutFlowRateSensor>
523     <AirInFlowRateSensor input="Crew_to_PlantEnvironment_Fan"
524         moduleName="Crew_to_PlantEnvironment_Fan-InSensor" index="0" logLevel
525             ="INFO"></AirInFlowRateSensor>
526     <AirOutFlowRateSensor input="Crew_to_PlantEnvironment_Fan"
527         moduleName="Crew_to_PlantEnvironment_Fan-OutSensor" index="0"
528             logLevel="INFO"></AirOutFlowRateSensor>
529     </environment>
530 </Sensors>
531 <Actuators>
532     <power>
533         <PowerInFlowRateActuator output="Main_VCCR"
534             moduleName="MainVccrPower" index="0" logLevel="INFO"
535             isBionetEnabled="false">
536         </PowerInFlowRateActuator>
537         <PowerInFlowRateActuator output="Backup_VCCR"
538             moduleName="BackupVccrPower" index="0" logLevel="INFO"
539             isBionetEnabled="false">
540         </PowerInFlowRateActuator>
541     </power>
542 </Actuators>
543 </biosim>

```


Appendix B

Figures

```
1 %% Postprocessing function
2 % Saves specified values output by Biosim as they change over time
3
4 % Margaret Shaw
5 % Date of first creation: 11/11/2013
6 % Date of last edit:      05/21/2014
7
8 function [y5, y6, y7] = postprocessing()
9
10 % do you want to populate y6 (atmosphere stores)? 1=YES; 0=NO.
11 y6_option = 1;
12
13 %% File Parser
14 %Extract lines of interest from all files in /raw_data folder
15 home = pwd;
16 tic
17 cd trunk/bin/raw_data/
18
19 WD = cd;
20 WD = strcat({' ',''},{WD});
21 files = dir('*.txt');
22
23 % NOTE: This function assumes there is only ONE file to be processed. In
24 % the future if it would save time, this could be altered to do batch
25 % postprocessing if time would be saved.
26
27 % File Parser 1 extracts lines with the "currentLevel" phrase to cut down
28 % the search space
29
30 interest_list = {' '\<currentLevel\>' ' '};
31
32 for i = 1:length(files)
33     for j = 1:length(interest_list)
34         disp(strcat('Parsing run #',num2str(i),' for value of interest #',...
35             num2str(j)))
36         interest = interest_list{j};
37         % save the filename without the .txt
38         fname = files(i).name(1:end-4);
39         full_fname = strcat(WD,'/',fname);
40         raw_data_loc = strcat(' ',full_fname,'.txt ');
41         parsed_data_loc = strcat(WD,'/processing1/',fname,'_parsed',...
42             num2str(j,'%02d'),'*.txt');
43         s = strcat('grep ',interest,raw_data_loc,' > ',parsed_data_loc);
44         system(s{1});
45     end
46 end
47
48 interest_list = {' 'sick' ' '};
```

```

49         ' 'crops have died' ' ';
50         ' 'killed' '};
51 sick = 1;
52 crops_died = 1;
53 crew_died = 1;
54 for i = 1:length(files)
55     disp(strcat('Checking run #',num2str(i),' for crop/crew deaths'))
56     for j = 1:length(interest_list)
57         interest = interest_list{j};
58         % save the filename without the .txt
59         fname = files(i).name(1:end-4);
60         full_fname = strcat(WD, '/', fname);
61         raw_data_loc = strcat(' ', full_fname, '.txt ');
62         parsed_data_loc = 'temp.txt';
63         s = strcat('grep ', interest, raw_data_loc, ' > ', parsed_data_loc);
64         system(s{1});
65
66         % check to see if crops/crew died
67         fid = fopen('temp.txt');
68         if fseek(fid, 1, 'bof') == -1 %empty file
69             if j == 1
70                 sick = 0; % TODO: count number of timesteps that crew is sick
71             elseif j == 2
72                 crops_died = 0;
73             elseif j == 3
74                 crew_died = 0;
75             end
76         end
77         delete('temp.txt')
78     end
79 end
80
81 % Print out binary values indicating crew sickness and death and crop
82 % death.
83 disp(strcat('Crew sick ', ' ', num2str(sick)))
84 disp(strcat('Crops died ', ' ', num2str(crops_died)))
85 disp(strcat('Crew died ', ' ', num2str(crew_died)))
86
87 % File Parser 2 extracts lines with the parameters of interest and puts
88 % them in individual text files.
89
90 cd processing1/
91
92 WD = cd;
93 WD = strcat({' '},{WD});
94 files = dir('*.txt');
95
96 interest_list = { ...
97     ' '\<Crew_Quarter_Nitrogen_Store] - currentLevel\>' ' ';
98     ' '\<Galley_Nitrogen_Store] - currentLevel\>' ' ';
99     ' '\<Labs_Nitrogen_Store] - currentLevel\>' ' ';
100    ' '\<Maintenance_Nitrogen_Store] - currentLevel\>' ' ';
101    ' '\<O2_Store] - currentLevel\>' ' ';
102    ' '\<H2_Store] - currentLevel\>' ' ';
103    ' '\<CO2_Store] - currentLevel\>' ' ';
104    ' '\<Methane_Store] - currentLevel\>' ' ';
105    ' '\<Dirty_Water_Store] - currentLevel\>' ' ';
106    ' '\<Grey_Water_Store] - currentLevel\>' ' ';
107    ' '\<Potable_Water_Store] - currentLevel\>' ' ';
108    ' '\<General_Power_Store] - currentLevel\>' ' ';
109    ' '\<Fan_Battery] - currentLevel\>' ' ';
110    ' '\<CO2_Removal_Battery] - currentLevel\>' ' ';
111    ' '\<Food_Store] - currentLevel\>' ' ';
112    ' '\<BiomassStore] - currentLevel\>' ' ';
113    ' '\<Dry_Waste_Store] - currentLevel\>' ' ';
114    ' '\<PlantEnvironmentO2] - currentLevel\>' ' ';
115    ' '\<PlantEnvironmentCO2] - currentLevel\>' ' ';
116    ' '\<PlantEnvironmentNitrogen] - currentLevel\>' ' ';

```

```

117         '\<PlantEnvironmentOther] - currentLevel\>' ' ';
118         '\<PlantEnvironmentVapor] - currentLevel\>' ' ';
119         '\<Crew_Quarters02] - currentLevel\>' ' ';
120         '\<Crew_QuartersCO2] - currentLevel\>' ' ';
121         '\<Crew_QuartersNitrogen] - currentLevel\>' ' ';
122         '\<Crew_QuartersOther] - currentLevel\>' ' ';
123         '\<Crew_QuartersVapor] - currentLevel\>' ' ';
124         '\<Maintenance02] - currentLevel\>' ' ';
125         '\<MaintenanceCO2] - currentLevel\>' ' ';
126         '\<MaintenanceNitrogen] - currentLevel\>' ' ';
127         '\<MaintenanceOther] - currentLevel\>' ' ';
128         '\<MaintenanceVapor] - currentLevel\>' ' ';
129
130 % which of these are redundantly listed?
131 redundant_lines = [zeros(1,17) ones(1,15)];
132
133 if y6_option == 0
134     last_interest = 17;
135 else
136     last_interest = 32;
137 end
138
139 for i = 1:length(files)
140     disp(strcat('Parsing run #',num2str(i),' for values of interest'))
141     for j = 1:last_interest
142         interest = interest_list{j};
143         % save the filename without the .txt
144         fname = files(i).name(1:end-4);
145         full_fname = strcat(WD, '/', fname);
146         raw_data_loc = strcat(' ', full_fname, '.txt ');
147         parsed_data_loc = strcat(WD, '/processing/', fname, '_parsed01', ...
148             num2str(j, '%02d'), '.txt');
149
150         if redundant_lines(j) == 0
151             s = strcat('grep ', interest, raw_data_loc, ' > ', parsed_data_loc);
152             system(s{1});
153         elseif redundant_lines(j) == 1
154             s = strcat('grep ', interest, raw_data_loc, ' > temp.txt');
155             system(s{1});
156             s2 = strcat('awk 'NR % 2 == 0' temp.txt > ', parsed_data_loc);
157             system(s2{1});
158             delete('temp.txt')
159         end
160     end
161 end
162
163 toc
164 %% Data extractor
165 %Extract values of interest and put them in values
166
167 cd processing/
168 d = dir('*.txt');
169
170 % values will store the values for each input file
171 % values will be a n_timesteps x length(interest_list) array
172 % length(interest_list) = n_files
173 values = [];
174
175 disp('Extracting values')
176 for i = 1:length(d)
177     vec = [];
178
179     % print out the name of the current file
180     disp(strcat('Extracting values from ', d(i).name))
181
182     fid = fopen(d(i).name);
183     vec = textscan(fid, '%s%f', 'delimiter', '=');
184     vecInt = vec{2};

```

```

185
186     values(:,i) = vecInt;
187     fclose(fid);
188 end
189 toc
190
191 %% y7
192 %Retrieve end_time (time at which simulation was terminated) for each run
193 end_time = zeros(1,length(files));
194 for i = 1:length(files)
195     end_time(i) = length(values(:,1,i));
196 end
197
198 %% y6 atm_composition
199 % This is moles of gas in the atmospheres of each of the environ. modules
200 if y6_option == 1
201     atm_composition(:,1) = values(:,18:22); % plant air comp
202     atm_composition(:,2) = values(:,23:27); % crew air comp
203     atm_composition(:,3) = values(:,28:32); % maintenance air comp
204 else
205     atm_composition = 0;
206 end
207 %% y5 store_levels
208 % This is the kg in each consumable store. Size: n_timesteps x 17 (there
209 % are 17 consumable stores)
210 %store_levels = values(:,16:end);
211 store_levels = values(:,1:17);
212
213 %% Outputs
214 % y7: end_time is a 1xn_files array. (initially a 1x1)
215 y7 = end_time;
216
217 % y6: atm_composition is a n_timesteps x 5 x 3 3D matrix.
218 % (There are 5 components of air; for now, just store three environment
219 % modules: crew, plant, and maintenance)
220 y6 = atm_composition;
221
222 % y5: store_levels is a n_timesteps x 17 array.
223 y5 = store_levels;
224
225 cd(home)
226
227 %% delete files
228 delete('./trunk/bin/raw_data/processing1/processing/*.txt')
229 delete('./trunk/bin/raw_data/processing1/*.txt')
230 delete('./trunk/bin/raw_data/*.txt')
231
232 end

```


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