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An independent assessment of the technical feasibility of the Mars One mission plan – Updated analysis[☆]

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ABSTRACT

In recent years, the Mars One program has gained significant publicity for its plans to colonize the red planet. Beginning in 2025, the program plans to land four people on Mars every 26 months via a series of one-way missions, using exclusively existing technology. This one-way approach has frequently been cited as a key enabler of accelerating the first crewed landing on Mars. While the Mars One program has received considerable attention, little has been published in the technical literature regarding the formulation of its mission architecture. In light of this, we perform an independent analysis of the technical feasibility of the Mars One mission plan, focusing on the architecture of the life support and in-situ resource utilization (ISRU) systems, and their impact on sparing and space logistics. To perform this analysis, we adopt an iterative analysis approach in which we model and simulate the mission architecture, assess its feasibility, implement any applicable modifications while attempting to remain within the constraints set forth by Mars One, and then resimulate and reanalyze the revised version of the mission architecture. Where required information regarding the Mars One mission architecture is not available, we assume numerical values derived from standard spaceflight design handbooks and documents. Through four iterations of this process, our analysis finds that the Mars One mission plan, as publicly described, is not feasible. This conclusion is obtained from analyses based on mission assumptions derived from and constrained by statements made by Mars One, and is the result of the following findings: (1) several technologies including ISRU, life support, and entry, descent, and landing (EDL) are not currently "existing, validated and available" as claimed by Mars One; (2) the crop growth area described by Mars One is insufficient to feed their crew; (3) increasing the crop growth area to provide sufficient food for the crew leads to atmospheric imbalances that requires a prohibitively large ISRU atmospheric processor or a notably different system architecture to manage; and (4) at least 13 Falcon Heavy launches are needed to deliver a portion of the required equipment to the Martian surface, a value that is at least double that planned by Mars One for the same mission phase. Most importantly, we find that the one-way nature of the Mars One mission, coupled with its plans to increase its crew population every 26 months, causes the operating costs of the program to grow continually over time. This is due to the fact that maintaining a growing colony on the Martian surface incurs increasing equipment and spare parts resupply requirements and hence launch costs over time. Based on published launch vehicle and lander estimates, our analysis finds that by the launch of the fifth crew, the cost associated with launching a portion of all required equipment and spares is approximately equal to half of the total NASA FY2015 budget – and this cost will grow when other critical systems outside the

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scope of this analysis are included. To mitigate these costs and bring the plan closer towards feasibility, we recommend a number of mission architecture modifications and technology development efforts be implemented before the initiation of any Mars settlement campaign. These include the further development of EDL, life support, and ISRU technologies, as well as additive manufacturing technology that utilizes ISRU-derived Martian feedstock as a potential means to address the growing cost of resupply.

1. Introduction

In mid-2012, the Mars One program was announced with the aim of building the first human settlement on the surface of Mars. Following a series of precursor missions to demonstrate and deploy key technologies, the first crewed mission would depart Earth in 2024, sending four people on a one-way journey to the surface of Mars. Following this initial mission, additional four-person crews would be sent to Mars at every subsequent launch opportunity to expand the extraterrestrial colony.

While this program has received significant publicity, little has been published in the technical literature on the formulation of this mission architecture. Moreover, common arguments for the mission's feasibility based on its exclusive use of existing technologies [1] conflict with the widely published capabilities and limitations of the current suite of validated human spaceflight technologies.

As the Mars One mission plan represents a departure from the traditional approach of initial sortie missions followed by later long-duration missions, there are many uncertainties in the mission design that need to be addressed prior to its implementation. Long-term colonization efforts on Mars present new logistical challenges, and rely on several technologies that are at a low Technology Readiness Level (TRL) [2,3].

In light of these observations, this paper aims to:

(1) Objectively assess the feasibility of the Mars One mission plan based on statements made by Mars One and the technical information that the organization has made publicly available;
(2) When applicable, provide recommendations for the stated Mars One mission architecture and operational strategy. We note that in some instances, the implementation of a recommendation requires the relaxation of one or more of the constraints imposed by statements and assumptions made by Mars One. When this is the case, recommendations are made with the intent of improving the Mars One mission architecture while minimizing the number of Mars One-specified constraints that are violated; and
(3) Highlight areas in which focused technology development can better enable future Mars settlement efforts in general.

With regards to items (2) and (3) listed above, we emphasize that this analysis does not attempt to design the Mars One mission architecture. Rather, recommendations are suggested and analyzed to extend the scope of this feasibility analysis to less-constrained variants of the Mars One architecture.

We perform this analysis by first compiling statements and assumptions publicly made by Mars One to model and simulate their baseline mission plan. When insufficient data is available from Mars One sources, we use data from standard aerospace handbooks and data sources, such as the NASA Human Integration Design Handbook [4] and the NASA Baseline Values and Assumptions Document (BVAD) [5]. After analyzing the results of the baseline Mars One mission simulation, we assess its feasibility, and if applicable, make recommendations to the mission architecture based on the considerations listed earlier. These recommendations are then implemented into a modified system architecture and the process of simulating, analyzing, providing recommendations based on an intermediate feasibility assessment, and performing an updated analysis with an updated architecture is repeated. We continue to iterate through this analysis cycle until we find that either: (1) the mission requires the development of new technologies whose capabilities are so uncertain that their performance and lifecycle properties cannot yet be confidently predicted; and/or (2) the lifecycle cost of the program does not reach a steady state and is hence unsustainable.

Finally, we note that the first version of this analysis was originally reported in a paper presented at the 65th International Astronautical Congress [6],[1]. This paper presents an update to this original analysis that incorporates:

1. A refined crop growth model that captures crop death due to insufficient CO_2 concentration within the crop growth environment;
2. An updated intermodule atmospheric exchange model;
3. An updated Atmospheric Processor model;
4. A refined Sparing module that accounts for commonality in spare parts across multiple crews;
5. A longer campaign time horizon of ten crews to the surface of Mars, as compared to the five crews considered in the previous analysis; and
6. A first order power and thermal system analysis to compare the system level impacts of different strategies for providing food to the crew.

While these updates have led to some changes in the quantitative results of each of the areas studied, this updated analysis finds that the overall results and conclusions presented in the original paper remain unchanged.

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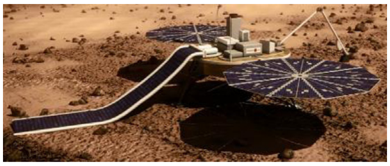
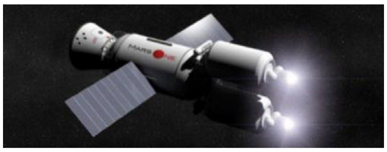
[1] Available at: http://bit.ly/mitM1.

Table 1
The Mars One mission architecture for establishing a settlement on the surface of Mars [7].

Mission phase	Timeframe	Elements deployed	Image
Precursor	2018	Technology demonstration lander on Martian surface and communications satellite deployment in Mars orbit (not shown)	
Pre-deployment	2020	Multipurpose rover used for site prospecting and clearing, habitat set up, crew transportation, and regolith collection for local processing	
Pre-deployment	2022–2023	Crew habitat: this consists of three variants of a core unit based on the SpaceX Dragon [9] module, as well as a 500 m^3 Inflatable Unit. The initial habitat will consist of six modified Dragon modules connected with two inflatable units. Refer to Section 3.1 for additional details. (Image from Business Insider [12])	
First Crew Transit	2024	Mars Transit Vehicle: this consists of a Transit Habitat and a Mars Lander and functions as the means of crew transport from Earth to the Martian surface	
Colony expansion	2025 onwards	Additional crew habitat units are launched during the same launch window as every crew launch. These are integrated into the Mars One habitat, enabling the infrastructure to grow over time	

This paper is structured as follows: Section 2 provides a background on the Mars One architecture, and defines the scope of this analysis. Section 3 describes the process and assumptions used to model and simulate the baseline Mars One mission architecture. Section 4 presents the results of the iterative analysis process that was employed to investigate the feasibility of the Mars One mission architecture, as well as and the corresponding recommendations made. Finally, Section 5 summarizes the conclusions of the study with a focus on system mass and cost drivers and possible avenues for reduction of these quantities.

2. Background

This section provides a summary of the Mars One mission plan and the underlying assumptions made in this analysis. Since no information regarding the Mars One mission was found in the technical literature, mission architecture details are primarily derived from the Mars One website [7], as well as the publicly-released request for proposals and proposal information package for a 2018 Mars Lander [8]. This analysis was performed from April to December 2014 and as such, all data used was taken from the Mars One website at this time. It is possible that at the time at which the reader reviews this paper, the corresponding data described at the Mars One website would have been changed from the dataset used in this analysis. As a result, all website URLs cited in this paper present both the current URL and a URL linking to an archived version of the webpage referenced at the time of this study.

2.1. *Summary of the Mars One Mission Plan*

A distinguishing feature of the Mars One architecture is the philosophy of sending people on a one-way journey to Mars using “existing, validated, and available technology” [1]. The Mars One mission plan consists of a series of unmanned precursor missions to demonstrate and deploy key technologies, followed by one-way crewed missions to Mars at every subsequent launch opportunity (26-month intervals [1]). These missions are accomplished with a set of common mission elements, summarized in Table 1.

The campaign commences with a precursor mission launching in 2018, involving a Mars surface lander based on the design of the NASA Phoenix Lander. The goal of this mission is to demonstrate key technologies required to sustain a human settlement on the Martian surface, including thin-film solar arrays and an oven to extract water from Martian regolith. A Mars orbiting communications satellite will also be launched on this mission to support both the precursor and subsequent missions [7].

Pending the success of this first mission, a follow up mission is planned for launch in 2020, transporting a multi-purpose rover to a predetermined site, likely in the northern hemisphere near 45° latitude [8]. The rover will survey the region for a suitable settlement site and prepare the selected site for the subsequent arrival of the habitation modules.

On the following launch opportunity in 2022, six scaled-up versions of the SpaceX Dragon [9] spacecraft will be launched and upon arrival in 2023, will be connected together using the previously deployed rover to form a contiguous habitat. These habitation units come in three variants:

1. *Living units*, which each contain a 500 m^3 inflatable structure, an airlock for crew extravehicular activity (EVA), and the wet areas of the habitat, such as the waste and hygiene compartment [10]. Within the inflatable units, 50 m^2 of crop growth area is allocated to provide food to sustain three crews of four people [11].
2. *Life support units,* which each contain air revitalization, water processing and waste management technologies and stores. In addition, these units contain an ISRU system, as well as the thin-film solar arrays that will supply power to the habitat. The systems within the Life Support Units "will be very similar to" the ECLS technology currently flying on the International Space Station [13].
3. *Supply units,* which store supplies and spare equipment for the habitat [1].

For the purposes of redundancy, each complete habitat contains two copies of each unit. More detail regarding the Mars One habitat layout is described in Section 3.1. In addition, a separate human lander unit, also based on the Dragon capsule, is used to deliver each crew to the surface from the year 2025 onwards.

After the initial emplacement of the habitation units, the thin-film solar arrays are deployed along with the ISRU system. Over the subsequent 500 day period, the rover delivers regolith to the ISRU oven, where it is baked to extract water. A portion of this water is then electrolyzed to generate oxygen. At the same time, an atmospheric processor extracts and stores nitrogen from the Martian atmosphere. By the time the first crew departs Earth, the ISRU system will have produced 3000 L (3 m^3) of contingency water, 120 kg of contingency oxygen, and sufficient oxygen and nitrogen to generate a breathable atmosphere of 70 kPa within the habitat [14,11].

This first crew will nominally depart Earth in 2024 in a Mars Transit Vehicle (MTV) that will primarily employ an open-loop life support system. Within the same launch window, another six habitation units will be sent to provide the equipment and surface habitation required for the second four-person crew.

After landing in 2025, the first crew will enter the habitat, activate the food production system, and integrate the six habitation units that were launched with them into the initial habitation system. These newly added units will support a second four-person crew, who will depart Earth in 2026, along with another set of equipment to support the subsequent third crew. This cycle of sending four person crews along with the habitation equipment to support follow-on four-person crews continues every 26 months, thereby allowing the settlement to expand over time [7].

2.2. Analysis scope

For the purposes of this study, we bound our analysis to focus exclusively on environmental control and life support (ECLS) and in-situ resource utilization (ISRU) technologies, and their impact on sparing and space logistics strategies for the mission. These systems compose only a subset of the entire architecture. It is important to note that several other areas need to be investigated in detail in order to mature the Mars One mission architecture into an executable plan. These include the Mars entry, descent, and landing strategy, the radiation protection strategy, and the communications architecture, to name a few. These areas each impose their own requirements on the operations and logistics architecture of the mission and must be considered in concert with those analyzed here.

The analysis presented herein concentrates on the habitat pre-deployment and crewed phases of the Mars One mission profile. We treat the period between the pre-deployment of a complete surface habitat (consisting of 6 modified SpaceX Dragon capsules) and 26 months after the crew arrives (one launch cycle) as a repeating unit of resource demands over time. This allows us to quantify the resource demands of the settlement as it expands beyond the arrival of the first four-person crew. The only exception is the spare parts requirement, for which it is assumed that crews can share spare parts for identical items. As discussed later in Section 3.3, this commonality means that each crew can benefit from the spares that were brought by any missions before them and requires an analysis of the full mission campaign.[2]

2.3. Currently "Existing, Validated and Available" technologies

The Mars One mission plan is built upon a philosophy of exploiting existing technology [1]. The claim that currently available technology is capable of supporting the mission has often been used as an argument to justify the mission's feasibility, and is stated clearly on the Mars One website:

> *"No new major developments or inventions are needed to make the mission plan a reality. Each stage of the Mars One mission plan employs existing, validated and available technology"* [1].

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[2] Commonality between crews was not captured in the original analysis [6].

Given the potential for numerous interpretations of this statement, it is important to clearly define our interpretation of this statement in order to provide an unambiguous basis for this analysis. As a result of the lack of available clarifying data, we use the industry-standard Technology Readiness Level (TRL) metric, as specified in the NASA Systems Engineering Handbook [15], to define our interpretation. We note that the following TRL-based interpretations of the above statement are our own, and may not necessarily align with those of Mars One.

The claim that "No new major developments or inventions are needed" implies that all technologies are at TRL 5–6, where they have been demonstrated in a relevant operating environment at either the component or system level [15]. The use of the term "validated" further supports this interpretation, based on the widely accepted definition that a validated technology has been proven to accomplish "the intended purpose in the intended environment… as shown through performance of a test, analysis, inspection, or demonstration" [15].

Finally, an "existing" technology can be considered as one that is at least at TRL 3, where an "analytical and experimental proof-of-concept" has been demonstrated [15]. Anything beneath this readiness level is within its early formulation phase, has not yet been built, and is therefore considered as nonexistent.

Given these definitions, we survey the current state of the art in spaceflight technology and find that in many cases, the technologies required for the Mars One mission plan either do not yet exist, or have not been demonstrated in a relevant operating environment. Some relevant technologies and operational approaches have had significant use in spaceflight but they were not designed for the Martian environment, while other relevant technologies are still in the early stages of development, where they are still being tested at small scales in laboratory or analog environment conditions. This technology survey is presented in Section 4.1.1, where we perform the first iteration of our analysis.

However, given the possibility for successful technology development and validation efforts for all required systems prior to the launch of the first Mars One crew, we make the optimistic assumption that all technologies specified by Mars One will be available when required, and continue our analysis based on the statements made on Mars One's website. It is important to highlight, however, that the development effort required to mature the required technologies to their necessary levels will contribute significantly to the cost of the Mars One program. Due to the high uncertainty in predicting this development cost, we do not capture it within this analysis.

We further note that because of the lack of relevant data and operational experience for many of the technologies included in Mars One's mission plan, we have been forced to make several assumptions. These have been based on extrapolations of the current state of the art (as discussed throughout Section 3), and on the fundamental design philosophies discussed earlier.

In cases where the analysis has necessitated architectural modifications, these have been implemented with the goal of increasing the feasibility of the system architecture while remaining as much as possible within the constraints set forth by statements and assumptions made by Mars One.

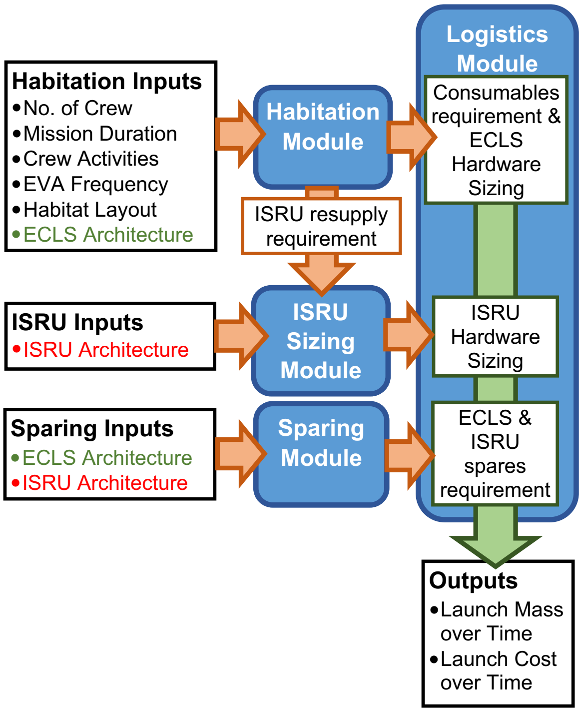

Fig. 1. High level block diagram of the simulation environment.

3. Methodology

To evaluate the feasibility of the Mars One mission plan, we have developed an integrated simulation environment that captures both the functional performance and sizing of selected technologies. Fig. 1 depicts a block diagram of the simulation environment.

As can be seen in Fig. 1, the simulation environment consists of four modules: a Habitation module, an ISRU Sizing module, a Sparing module, and a Space Logistics module. The Habitation module uses key mission parameters to calculate the consumables requirement and the sizing of the ECLS hardware. Additionally, the Habitation module generates a resupply requirement for the ISRU Sizing module, which combines this information with the selected ISRU architecture to predict the mass and volume of the required ISRU hardware. In parallel, the Sparing module takes the master equipment list from the ECLS and ISRU systems and updates it with the number of spares required for each component. Finally, the Space Logistics module receives the master equipment list from the three pre-processing modules to predict the launch mass and launch cost over time. In the following subsections, the implementation and initial results obtained from each of these four modules are described in greater detail.

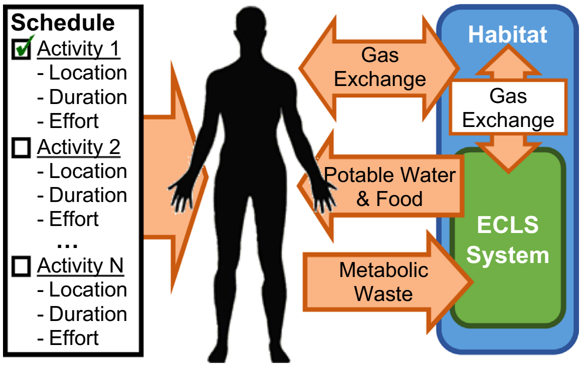

Fig. 2. Data flow within the Habitation module.

3.1. Habitation module

The Habitation module predicts requirements for consumables and identifies failure modes that occur as a result of depleted resources and unanticipated control interactions. Based on the BioSim [16] dynamic ECLS modeling environment developed in the early 2000s at NASA Johnson Space Center, this model propagates the state of resource stores and crew health over time. Fig. 2 depicts a summary of the data flow within the Habitation module.

As shown in Fig. 2, a crew schedule is required to initialize the Habitation module. This consists of a set of activities, each with a location, duration, and effort level. As the simulation propagates forward in time, each crewmember progresses through their own schedule, expending varying levels of effort, which in turn varies their resource consumption and metabolic exchange rates with the habitat. Moreover, activities can be allocated to individual modules within the habitat to affect the spatial distribution of resources. Varying effort levels and activity locations introduces transient behavior into the habitation simulation environment.

A set of Environmental Control and Life Support (ECLS) technologies modeled within this module act to manage this transient behavior by controlling resource consumption and production to levels appropriate to maintaining crew health. These ECLS technologies are allocated to different modules within the habitat.

Once running, one of two conditions terminates the simulation: (1) One of the pre-specified failure conditions shown in Table 2 is met; or (2) the simulation uneventfully reaches the end of the specified simulation time horizon. Actions taken to rectify the failure for subsequent simulation runs depend on how far into the simulation time horizon the failure occurs. In the case that the failure occurs early in the simulation, an architectural change for the ECLS system is typically required. Conversely, failures that occur later in the simulation time horizon are typically rectified by introducing additional resources. These can come from either an ISRU technology, from a logistics resupply source, or by increasing the initial amount of resource carried.

As stated in Section 2.2, the Habitation module was used to simulate the first Mars One habitat from the arrival of the first crew on the Martian surface to the second crew's arrival. Such a habitation architecture can be used as a common repeating functional unit that is deployed with every expansion mission beyond the arrival of the first crew.

To perform the habitation analysis, several assumptions were made to simulate the Mars One habitat. The majority of these assumptions, detailed in Appendix A, come from the recommendations of the NASA Exploration Atmospheres Working Group (EAWG) [17], NASA's Baseline Values and Assumptions Document (BVAD) [5], and the Human Spaceflight Mission Analysis and Design book [20]. The detailed design of each subsystem within the habitation system is described in the following sections.

3.1.1. Crew composition

The Habitation module uses the model developed by Goudarzi and Ting [21], to determine crew resource demands based on their activity level and their basal metabolic rate, which is driven by their gender, age, and body mass. For the purposes of this analysis, we assume a four person crew consisting of two males and two females, all aged 35 years old. One of the males has a mass of 72 kg while the other has a mass of 75 kg. Both females have a mass of 55 kg. These values are typical of the astronaut population [22].

3.1.2. Crew schedule

The assumed crew schedule is based on the typical schedule of a current ISS crewmember [23]. For each crewmember, 8 h of sleep and 2 h of exercise are budgeted per day. On EVA days, 8 h of EVA are scheduled, with the remainder allocated to Intravehicular Activities (IVA) such as performing science experiments, preparing meals, or harvesting and replanting crops. All activities that are not EVA, sleep, or exercise are classified as IVA, and are assumed to require the same level of crew energy expenditure. As a result, on non-EVA days, crewmembers are assigned with IVA tasks during their non-exercising waking hours. The impact of variations in this schedule on the system architecture is investigated in Section 5.5.

3.1.3. ECLS technologies

Based on the claim that the Mars One life support units will "*be very similar to those units which are fully functional on-board the International Space Station*" [13], we assume that technologies similar to those onboard the International Space Station (ISS) United States Orbital Segment (USOS) will be used. We note that while there are currently ongoing development efforts for European [24] and Japanese [25,26] ECLS capabilities, the performance of these technologies in-flight has yet to be completely evaluated, and the operational data required for a sparing analysis is therefore unavailable (see Section 3.3). Similarly, while there has been substantial operational experience with Russian ECLS systems onboard the ISS, little information is publicly available regarding their mass and reliability properties, thus limiting the extent to which a quantitative analysis can be performed. Additionally, we observe that the current NASA baseline Mars surface habitat ECLS architecture [27] is also based on that of the

Table 2
Failure conditions employed within the Habitation module.

Failure condition	Model implementation
Crew starvation	Crew caloric consumption requirement is greater than calories available within food store
Crew dehydration	Crew water requirement is greater than potable water available within potable water store
Crew hypoxia	Partial pressure of oxygen within crew environment is less than 15.168 kPa [4]
Crew hyperoxia	Molar fraction of oxygen within crew environment exceeds 50% (for a 70.3 kPa atmosphere) [4]
Crew CO_2 poisoning	Partial pressure of CO_2 within crew environment is greater than 0.482 kPa (0.07 psi) [4]
Cabin underpressure condition	Total cabin pressure is less than 20.7 kPa (3 psi) [4]
High Fire Risk	Molar fraction of oxygen within crew environment exceeds 30% [17]
Crop Death[a]	CO_2 concentration within plant growth environment reduces below 150 ppm (ppm) [18,19]

[a] Crop death was not modelled in the original analysis [6].

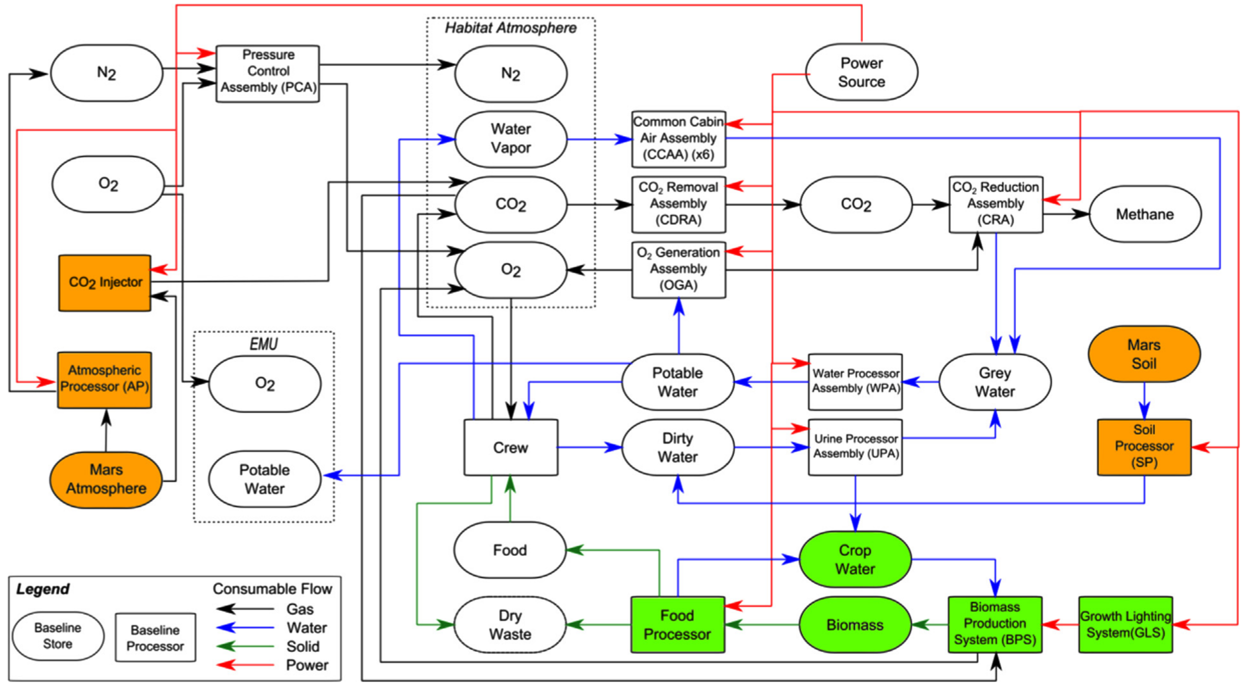

Fig. 3. Baseline Mars One ECLS and ISRU system assumed for this study. Orange elements correspond to ISRU technologies and resources, and green elements represent plant growth technologies. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ISS USOS. This observation provides additional confidence on the suitability of our ECLS technology assumption.

The one modification to our assumed ECLS architecture, however, is the food production system, which according to Mars One, will come predominantly from locally grown crops [11]. We assume this to be accomplished via the Nutrient Film Technique (NFT) described by Wheeler [28] and adopted as the baseline horticultural approach for crop growth within the NASA Kennedy Space Center (KSC) Biomass Production Chamber, due to its flexibility across plant species and its water efficiency [29].

Further, we note that the ECLS technologies onboard the ISS were originally developed specifically for use in microgravity and have not been validated for use on the Martian surface. The introduction of a partial gravity environment will inevitably lead to different ECLS technologies that will likely be less complex than those onboard the ISS, due to the simplification in chemical separations that a gravity environment affords. Thus, in the absence of data for Mars-specific ECLS technologies, the assumption of ISS-based ECLS mass and volume properties for similar-functioning Mars-based ECLS systems can be considered to be conservative. However, in light of Mars One's existing technology constraint, the assumption of similar reliability characteristics between ISS-based and Mars-based ECLS systems can be considered reasonable, as increasing the reliability of flight-rated ECLS systems beyond that of the ISS remains an ongoing challenge within the ECLS community [30].

Moreover, as mentioned in Section 4.1.1, the lack of currently available Mars-based ECLS technologies and the lack of experience in growing food crops on the Martian surface necessitates the adoption of the assumption stated in Section 2.3: that all technologies required by Mars One will be available when needed. These technologies are summarized in Appendix B.

Fig. 3 depicts the baseline ECLS and ISRU system assumed for this analysis. In this figure, white elements with solid edges represent technologies currently on the ISS, green elements represent the BPS, and orange elements represent ISRU technologies. From this figure it is apparent that the baseline Mars One ECLS architecture is a version of the ISS ECLS architecture augmented with BPS and ISRU systems. Because there is currently no flight experience with these two systems, first order engineering estimates on their performance and sizing were performed for this analysis. Details of the BPS sizing process are described in Section 3.1.8, while Section 3.2 discusses the approach taken to size the ISRU system.

3.1.4. *Portable life support system technologies*

For the spacesuit portable life support system, we assume the use of the next generation Portable Life Support System 2.0 (PLSS2.0) [31,32] currently being developed at NASA Johnson Space Center (JSC). For this particular system, we have been forced to adopt a completely new technology as the current spacesuit used on the ISS was designed for use in a microgravity and vacuum environment, and is hence inappropriate for use on the Martian surface [5]. The PLSS2.0 employs a Spacesuit Water Membrane Evaporator (SWME) for heat rejection, and a Rapid Cycle Amine (RCA) Swing Bed for carbon dioxide removal [31]. The SWME is designed to operate in the Martian atmosphere and uses less water with an increased operational life compared to current sublimator technologies used on the ISS PLSS [31].

Furthermore, the RCA has the same CO_2 removal capability as the Metal Oxide (METOX) technology used on the ISS while weighing 75% less [31]. RCA also has the added capability of removing humidity (thus simplifying the PLSS architecture) [32] and continuously regenerating its adsorption beds, enabling longer Extravehicular Activities (EVAs) than the current METOX architecture [32]. These attributes of the RCA over the METOX have been deemed to outweigh the power intensive METOX capability of reintroducing crew-expired CO_2 back into the habitat cabin after EVA for subsequent reduction back into oxygen [31].

3.1.5. *Crew systems and habitat structures*

The crew system and habitat structures considered in this analysis are based on first-order estimates provided in Stilwell et al. [20]. The commodities in this category include a galley and food system, a metabolic waste collection system, personal hygiene equipment, a clothing and laundry system, recreational equipment and personal stowage, housekeeping, operational supplies and crew restraints, photography, sleep accommodations, and crew health care. The mass of the inflatable habitats is calculated using the NASA BVAD estimate of 9.16 kg/m^3 for an unshielded inflatable module on the surface of Mars [5]. The stowed volume of these inflatable modules is calculated by assuming a 15:1 packing ratio based on that of the Expandable Habitat Demonstration System deployed at McMurdo Station in Antarctica in 2008 [33]. A detailed mass and volume breakdown of these systems can be found in Appendix E.

3.1.6. *Solid waste management*

The ISS currently employs a solid waste management strategy of transferring all solid waste into the various single-use logistics vehicles that visit the station for subsequent burn up in the Earth's atmosphere. For a Mars settlement, the increasing storage requirement for solid waste over time makes this approach unsustainable, and necessitates the adoption of alternative solid waste management practices. Past approaches adopted within closed environments have included incineration (as part of NASA's Lunar Mars Life Support Test Project (LMLSTP) [34]), and biological means such as anaerobic digestion (see Section 3.1.8.8.1). Although these approaches have been shown to work within closed environments, several problems were experienced during their operation, and further research and development is needed to increase the reliability of these systems, and to scale their performance to the level required for the Mars One mission. Moreover, a review of publicly available Mars One literature found that no information regarding the solid waste management strategy has been specified, other than the statement that their life support system will be ISS-like.

Given these observations, along with the fact that information related to the expected waste streams is required to specify and size a notional solid waste management system (information that has not been made available), we have chosen to exclude solid waste management considerations from the scope of this analysis.

3.1.7. *ECLS technology location allocation*

An important element of modeling ECLS systems in multi-module habitats is the allocation of technologies to physical locations within the habitat. This introduces a spatial dimension into the simulation environment that captures resource exchanges between the crew and the various modules that they will occupy as they move throughout the habitat. This allows for insight to be gained into the effectiveness of the allocation of a particular ECLS technology to the activities expected to be performed in a given module. For example, carbon dioxide removal systems are generally located near exercise areas to handle local increases in carbon dioxide. A further separation between this system and the exercise areas would require additional intermodule ventilation to limit the total increase in ambient CO_2 concentration across the habitat.

In this analysis, we allocate technologies to locations within the Mars One habitat using a combination of images rendered by Mars One (see Fig. 4), and heuristics derived from the allocation of ECLS technologies onboard the ISS (see Appendix C). Fig. 5 depicts the baseline layout assumed for this analysis. Note here that only half the habitat is shown as it is assumed that the other half is a symmetric copy. This assumption is supported by claims that the combination of one Living Unit and one Life Support Unit is capable of sustaining a four-person crew, with the secondary units acting as redundant backups [35]. While in an emergency (i.e. unrepairable failure in the primary system) the redundant unit could sustain the crew, this dangerous loss-of-redundancy condition is not a nominal operating condition. Therefore, in this model, the redundant units are utilized only

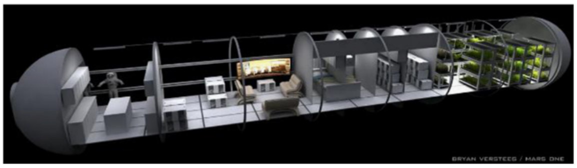

Fig. 4. : Artist's rendering of the Mars One inflatable unit [37].

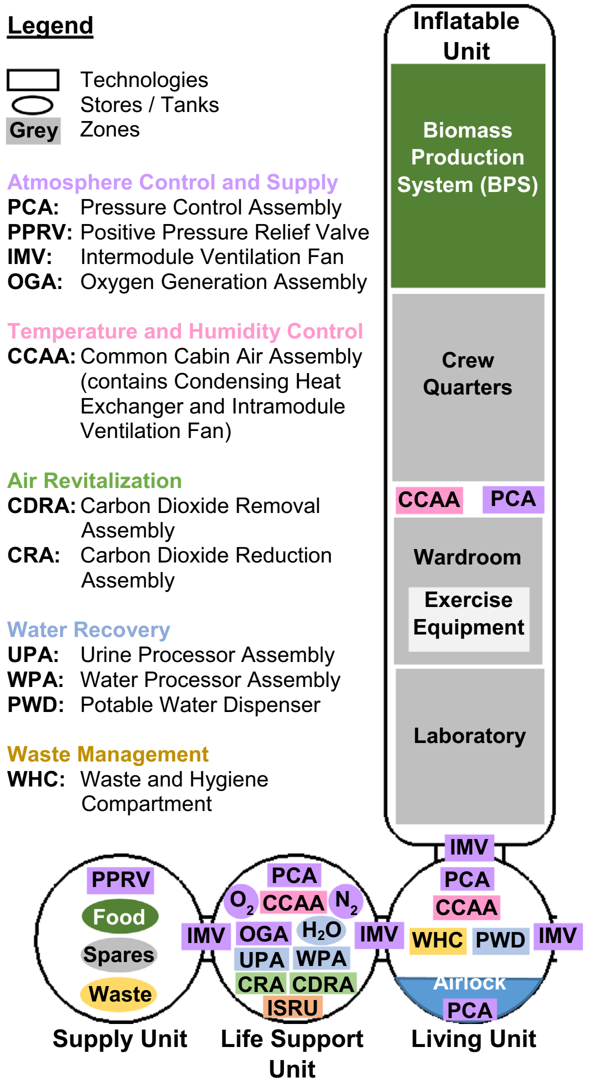

Fig. 5. Assumed ECLS technology location allocation. Note that the BPS shares the same volume and atmosphere as the rest of the Inflatable Unit.

to support the crew temporarily during maintenance operations on the primary unit.

3.1.8. Biomass production system design

3.1.8.1. Biomass production system (BPS) crop selection. The lack of BPS flight experience introduces significant uncertainty to the integrated behavior of the habitat. Such a system can demand significant resources, depending on the number and type of crops grown. The quantity of crops ultimately depends on the proportion of the crew diet sourced from plant growth, as well as the daily caloric demand of the crew, which is in turn driven by each crewmember's gender, age, weight, and activity level.

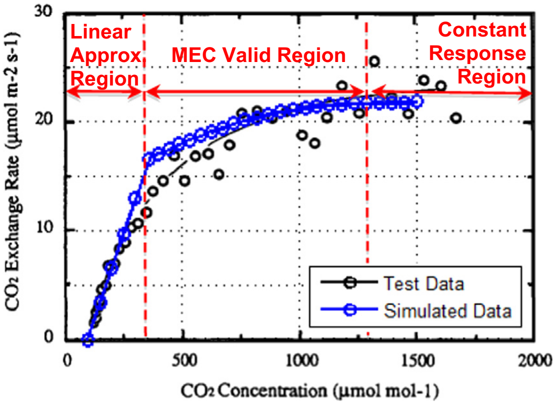

Fig. 6. Comparison between test data from a CO_2 Drawdown Test of 20 m^2 of Wheat under PPF=550 μmol/m^2/s lighting conditions at 36 days of growth (black [39]) and data obtained from the MEC model under the same conditions (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

For the purposes of this analysis, we use the approach described in Jones [36] to determine the crew daily macronutrient demand, and introduce our own optimization scheme to determine the appropriate crop selection to meet this demand. Here, we base all crop growth predictions on the Modified Energy Cascade (MEC) models described in the NASA BVAD [5]. These models predict plant growth, transpiration, and oxygen production rates as a function of atmospheric CO_2 concentration, humidity level and local lighting level, and have been validated with test data published in the literature [38], as shown in Fig. 6.

Crop death, while not captured within the MEC models, is modeled as a response to a local CO_2 atmospheric concentration of less than 150 ppm[3]. This is in line with experimental observations made by Gerhart et al. [18], and Dippery et al. [19] Since the MEC models are only valid between CO_2 concentrations [5] ($[CO_2]$) of 330–1300 ppm, a linear trend has been assumed for crop responses beneath 330 ppm to approximate behavior at low $[CO_2]$ conditions [18,19]. Above $[CO_2]=1300$ ppm, the crop response is enforced to equal to the corresponding value at 1300 ppm. This insensitivity at high $[CO_2]$ values is support by observations made by Wheeler et al. [28,39,40]. These assumptions are depicted in Fig. 6.

The MEC models are limited to a set of nine crops due to the lack of experimental data for other crops. As a consequence, our crop selection is also limited to this same set of MEC-modeled crops. These are: dry bean, lettuce, peanut, rice, soybean, sweet potato, tomato, white potato, and wheat.

The required quantity of crops ultimately depends on the total caloric demand of the crew and the proportion of the crew diet sourced from plant growth. An average

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[3] Crop death was not modelled in the original analysis [6].

Table 3
Optimized growth areas for various objective function weightings.

Crop	Option 1 $w_1=1$, $w_2=0$	Option 2 $w_1=0.4$ $w_2=0.6$	Option 3 $w_1=0.3$ $w_2=0.7$	Option 4 $w_1=0.27$ $w_2=0.73$	Option 5 $w_1=0$ $w_2=1$
Dry Bean					52
Lettuce					52
Peanut	98	82	75	73	52
Rice					52
Soybean		23	35	40	52
Sweet Potato			4	10	52
Tomato					52
Wheat	87	85	81	73	52
White Potato				5	52
Total Growth Area	185	190	195	201	468

crewmember caloric demand of 3040 kcal was determined by running the Habitation module with the crew composition and crew schedules described in Sections 3.1.1 and 3.1.2. According to Mars One, 100% of these calories will be provided every day by a biomass production system with a growth area of 50 m^2. This area is claimed to be sufficient to feed three crews of four people [11].

For a typical diet consisting of a caloric macronutrient makeup of 68% carbohydrates, 12% protein, and 20% fat [36], this equates to a biomass production requirement of 2067.2 g of carbohydrates, 364.8 g of protein, and 270.2 g of fat per day per crew of four with a daily caloric demand of 3040 kcal.

Using these values, the required crop growth areas were determined by formulating and solving the following multi-objective optimization problem:

$$\min w_1 \sum_{i=1}^{i=9} x_i + w_2\sigma(\mathbf{x}) \tag{1.1}$$

$$\text{s.t.} \sum_{i=1}^{i=9} c_i r_i x_i \geq 2067.2 \tag{1.2}$$

$$\sum_{i=1}^{i=9} p_i r_i x_i \geq 364.8 \tag{1.3}$$

$$\sum_{i=1}^{i=9} f_i r_i x_i \geq 270.2 \tag{1.4}$$

$$x_i \geq 0 \text{ for } i = 1, \ldots, 9 \tag{1.5}$$

where $\mathbf{x}$ is a nine element vector representing the growth area allocation for each of the nine candidate crops; $\mathbf{c}$, $\mathbf{p}$, and $\mathbf{f}$ correspond to vectors representing carbohydrate, protein, and fat fractions of dry mass of the nine candidate crops; $\mathbf{r}$ corresponds to a vector of static growth rates. These values are listed in Appendix D. Furthermore, σ represents the standard deviation function; and w_1 and w_2 are weighting factors.

Here, the chosen objective function is the weighted sum of the total allocated crop growth area, and the standard deviation of the individual areas of each of the crops. The first component of this objective function is based on the goal of minimizing biomass production system mass and volume, since these parameters typically grow with increasing crop growth area [5]. Conversely, the second component of the objective function corresponds to maximizing the variety of crops grown. Reducing the standard deviation across the set of selected areas effectively drives the optimizer towards introducing more crop species into the solution. Finally, the constraints imposed ensure that the daily crew requirement for carbohydrates, proteins, and fats is met by the BPS. To solve this optimization problem, differing values for the weighting factors w_1 and w_2 were applied to the objective function and a non-linear constrained optimization solver was employed. Table 3 summarizes the results obtained for different weighting value combinations[4].

As we increase the weighting of the second component of the objective function (w_2), we move across Table 3 from left to right, causing the optimizer to gradually introduce more variety into the crew diet, at the cost of increased growth area. Moreover, we observe crops being added in a sequential manner with increasing variety, indicating that there is a priority towards selecting plants that have both a high growth rate and a large nutrient content. Peanut and wheat crops are always included in the crop mix because peanuts have the highest fat content of all the crop options, while wheat has a high carbohydrate content.

From Table 3, we observe a maximum crop growth area of 468 m^2 (Option 5) and a minimum crop growth area requirement of 185 m^2 (Option 1) to support one crew of four. The full range of crop growth areas is significantly greater than the 50 m^2 per three crews of four claimed[5] by Mars One [11].

Having noted that the stated Mars One food production plan is calorically insufficient, we select Option 4 in Table 3 in order to continue our analysis, as it represents a reasonable balance between the two competing objectives. This profile achieves three more crop species over the minimum growth area option for the relatively low cost of an added 16 m^2 of growth area.

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[4] The results presented in Table 3 are an update to the original analysis [6]. The original analysis contained an error in the average growth rate of lettuce, which has since been corrected (see Appendix D)

[5] We note that since this analysis was performed, Mars One has increased their planned crop growth area [11] from 50 m^2 to 80 m^2. Since this value is still significantly lower than the growth areas derived here, this update does not affect the conclusions of our analysis.

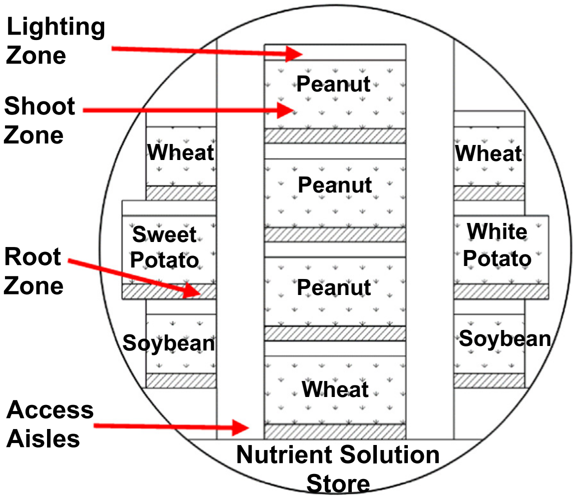

Fig. 7. Potential shelf layout for the selected crop growth areas.

3.1.8.2. Biomass production system (BPS) hardware layout. While the 201 m^2 area required for Option 4 of Table 3 is four times larger than that originally stated by Mars One, a dimensional analysis indicates that it may still be possible to fit this into a portion of the Inflatable Unit if a high density packing and lighting scheme is employed, such as that originally planned for NASA's BIO-Plex [41] - a proposed integrated habitation and BPS test facility that was in development in the late 1990s.

Fig. 7 shows a potential layout for the BPS based on the BIO-Plex [41] architecture, consisting of densely packed plant shelves, each with a dedicated lighting system and hydroponic root zone. The root zones contain a nutrient solution supplied by a tank installed into the floor of the chamber. This particular BPS design requires about 40% of the pressurized volume of a single Inflatable Unit, as compared to the value of 17% volume estimated from renderings of the system as provided by Mars One (Fig. 4). Furthermore, while the BIO-Plex was designed with a dedicated chamber for its BPS, rendered images of the baseline Mars One BPS indicate that it shares space and atmosphere with the crew inside each Inflatable Unit [37] (see Fig. 4). The following subsections further expand on the various technologies required to grow the selected crop mix, while Section 4.1.3 explores the operational implications of including a BPS of this scale on the system-wide behavior of the habitat.

3.1.8.3. BPS lighting. We assume the use of LED lights in the Growth Lighting System (GLS) similar to the Heliospectra LX601 grow light [42], a current state of the art commercially available option. Using the performance data of this lighting system, it was calculated that at least 137 LED units, each weighing 8 kg, would be required to provide full coverage of the 201 m^2 growth area. This calculation was based on comparing the photosynthetic photon flux (PPF) requirements of the various crops selected for the BPS, with the published PPF density values of the selected grow light. This calculation is summarized in Table 4.

3.1.8.4. BPS water management. For the selected crop profile, the MEC models estimate that up to 150 L of water will be consumed per hour, a quantity significantly beyond the capacity of the nominal ISS-derived water recovery and management system described by Mars One [13]. As a result, a dedicated crop water system was implemented, based on that of the NASA KSC Biomass Production Chamber mentioned earlier.

Here, a nutrient solution layer 0.5–1 cm deep is maintained at the crop root zone. This solution flows in a circuit at a rate of 3.2–4.8 L/min/m^2, and is recharged on a daily basis to make up for nutrients lost through crop uptake. To support this flow rate and nutrient recharge frequency, the KSC system maintains a nutrient solution reservoir of 185 L to support the approximately 40 L of solution required for each 5 m^2 of crop growth area [43]. Assuming a linear relationship between nutrient solution buffer capacity and crop growth area, this equates to 9045 L of nutrient solution required to sustain the 201 m^2 of crop growth area required for the Mars One BPS.

Based on Mars One's reliance on ISRU technologies (see Section 2.1), we assume that this solution will be produced by dissolving raw nutrients into ISRU-derived water. Thus, to ensure that sufficient water is available to activate the BPS upon the arrival of the first Mars One crew, the pre-deployed ISRU system is required to generate at least 9045 L of water (see Section 3.2.1 for ISRU system sizing details). This requirement is in addition to the 3000 L of contingency water budgeted by Mars One for the entire habitat [14]. We further make the optimistic assumptions that all water used within the BPS can be completely recycled for reuse by the growing crops and that all nutrients are available when required (as per the assumptions of the MEC models [5]), without needing to be transported from Earth. Previous plant growth experiments at KSC have indicated that daily water makeup requirements can range from 0.7–10 L/m^2/day depending on the type of crop grown, and the level of maturity of the crops [43].

3.1.8.5. Horticultural strategy. We select a continuous growing scheme as recommended by Gitelson et al. [44], where the total growth area of each crop is divided into smaller batches that are staggered in time, such that after the first harvest, a batch of crops reaches maturity on every subsequent day. While increasing the crew time dedicated to horticulture, this growth scheme reduces food storage requirements and ensures that food will be available when required by the crew.

3.1.8.6. CO_2 management. A commonly quoted heuristic in biological life support system analysis is that if approximately 50% of a crew's food requirements are sourced from a biomass production system, this same system can regenerate all of the air required for crew respiration [5]. Since the Mars One plan involves feeding the crew primarily with locally grown crops, this gas exchange will be imbalanced, with the CO_2 expired by the crew being insufficient to sustain the planned level of crop growth.

This phenomenon can be observed in Fig. 8, where a preliminary simulation of the BPS finds that without additional CO_2 sources, crop death occurs after 12 to 19

Table 4
GLS Requirements Calculation.

Crop	Assigned area (m^2)	Ideal PPF density ($\mu mol/s/m^2$)[a]	Equivalent PPF (Area × PPF Density) ($\mu mol/s$)
Peanut	73	313	22849
Soybean	40	325	13000
Sweet Potato	10	325	3250
Wheat	73	1332	97236
White Potato	5	325	1625
Total equivalent PPF			137960
Minimum number of grow lights[b]			137

[a] Calculated from data listed in the NASA BVAD [5].

[b] Based on a PPF density performance value [42] of 1011 μmol/s.

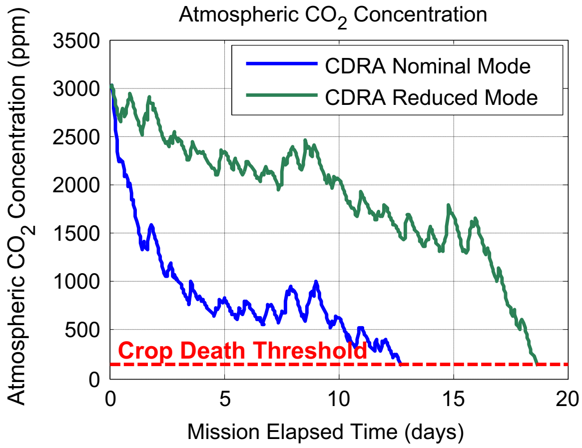

Fig. 8. Atmospheric CO_2 concentration time histories for simulations of the baseline Mars One habitat configuration with the CDRA in both nominal (blue) and reduced (green) operating modes. The reduced mode involves switching the CDRA off as the crops grow and become capable of managing the CO_2 load of the crew. As the crops continue to grow, crew-exhaled CO_2 becomes insufficient for the crops as they demand increasing levels of CO_2, eventually resulting in crop death. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

days into the mission, even when the Carbon Dioxide Removal Assembly (CDRA) is operated in a reduced mode, where it is initially switched on to maintain atmospheric CO_2 to within crew safety levels, and switched off as the crops grow and are capable of managing the CO_2 load of the crew. These values are based on an assumed initial atmospheric CO_2 concentration of 3000 ppm – a value commensurate with levels observed on the ISS [28]. In Fig. 8, the increased CO_2 concentration occurring at every 7–8 day period corresponds to weekend days when all four crew are within the habitat. On every weekday, two crewmembers each perform eight hour EVAs.

In addition, we find that because this time of crop death is well before the time of harvest of the first crop (62 days for the wheat crop in this case), initially employing oxidation techniques such as incineration or aerobic digestion to recover CO_2 from inedible biomass [45] would be ineffective, since this biomass would not yet be available[6].

Mars One plans to address this imbalance by introducing CO_2 from the Martian atmosphere into the Martian cabin [11]. In this analysis, we model this system as an idealized CO_2 injector that selectively separates and compresses CO_2 from the Martian atmosphere. A controller introduces CO_2 into the habitat to maintain a CO_2 concentration level of 1200 parts per million (ppm) – a value within the region of maximum growth for most C3 type plants [28,39,40]. This system is based on the cryocooler-based CO_2 capture concept described by Yu et al. [46] and sized by scaling to the commercially available Sunpower Inc. CT-F flight-rated cryocoolers [47]. A cryocooler-based concept was chosen over one based on mechanical compression due to its approximately 9 times lower mass and 3 times lower power consumption [48].

3.1.8.7. Food processing. To convert raw biomass into edible food and to recover water consumed by mature crops for reuse back into the BPS water management system, a notional food processor is included in the system architecture. Like many of the other technologies previously discussed, no space-rated version of this technology has yet been developed.

Regardless, we can still infer what such a system might contain. To process raw wheat, a mill will likely be required to convert wheat seeds into flour. From this form, multiple additional processing options are available, including an extruder to produce cereals and pasta, a breadmaker to produce bread, or a starch/gluten separator to extract wheat gluten, which can then be used to make seitan [49].

To process soy, a multifunctional processing system has been proposed by NASA JSC to produce soymilk, tofu, okara, and whey from raw soybeans [50]. The soaking, and boiling functions contained within this system are likely sufficient to process the remaining crops chosen for this study.

3.1.8.8. Additional BPS design considerations. In the preceding sections, we sized a BPS based on Mars One's stated objective of developing a life support system that: (1) is based on existing technology [1]; and (2) provides all food using locally-grown crops [11]. As a result, the objective function used in developing the BPS was formulated with the primary goal of providing sufficient and varied calories for the crew. This represents a simplified, first order analysis that omits a number of additional considerations that are introduced as a result of including a BPS within a life support architecture. These can be broadly categorized as additional ECLS options that accompany the inclusion of a BPS, and additional requirements that need to be accommodated to support a BPS. The following sections discuss how these considerations are considered in this analysis.

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[6] This is a new finding within this updated analysis resulting from the introduction of a crop death model.

3.1.8.8.1. Additional ECLS options. The inclusion of a BPS system introduces additional ECLS options beyond those that can be served by physiochemical ECLS systems alone. These include biological options for water processing, urine pretreatment, air revitalization, nutrient recovery, and solid waste processing.

As discussed in Section 3.1.8.4, we assume an independent BPS water management system for this analysis, due to the high water demand of the BPS. This system is assumed to be decoupled from the portion of the ECLS system that provides potable water to the crew, based on Mars One's assumption of ISS-like ECLS systems [13]. While biological options do exist for both urine pretreatment and water processing, these typically come in the form of microorganisms (such as the thermophilic anaerobic bacteria used in the ESA MELiSSA project [51]), or aquatic plants (such as the duckweed, water hyacinth, and aquatic reeds used in the Biosphere 2 experiment [52]) – systems that have not been specified by Mars One and are hence not included within the scope of this study. Food crops on the other hand, are generally not considered for water processing due to concerns related to toxin accumulation and food safety. Rather, a minimal threshold for recycled water quality is required before it can be fed to food crops [53]. As a result, this study assumes physicochemical water and urine processing technologies for all water recycling functions.

Similarly, biological means for processing solid waste and recovering nutrients for plant growth are not considered in this analysis as they also have not been specified by Mars One. Approaches such as those adopted by the Biosphere 2 and MELiSSA projects (see above) are potential candidates, but require further research and development before they can be reliably operated in the Martian environment.

Conversely, the potential for crops to serve air revitalization functions will be explored in this analysis (see Section 4.2.1). Unlike the biological life support functions discussed earlier, air revitalization based on food crops has been previously demonstrated in the laboratory setting at relevant scales. Specific examples include NASA's LMLSTP [34] and the Japanese Closed Ecology Experiment Facilities (CEEF) [54].

3.1.8.8.2. Additional BPS-derived requirements. In addition to providing further options for ECLS, plant growth systems also impose additional requirements that would otherwise not be present. These primarily come in the form of additional power and thermal management requirements that arise from the need for dedicated lighting systems to support plant growth, and storage and processing requirements for inedible biomass produced by the BPS. For this study, we will consider power and thermal system requirements only in the context of comparing the lifecycle resupply requirements of a BPS-based ECLS architecture to one that is dependent on the periodic resupply of Stored Food (SF) (see Section 4.2.3). Power assumptions will be based on Mars One's stated power architecture consisting of flexible thin-film solar arrays and batteries for energy storage [55].

Conversely, inedible biomass storage and processing requirements will not be incorporated within this analysis. We note that these requirements impose mass and volume penalties on the system architecture and should be quantified when performing a detailed design of a flight system.

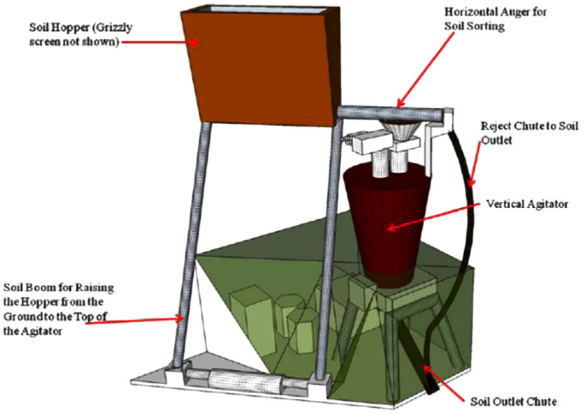

Fig. 9. The soil processing module, derived from Interbartolo et al. [56], which was geometrically scaled to provide mass estimates for the Mars ISRU system.

3.2. In-situ resource utilization sizing module

The Mars One architecture leverages resources from both the Martian soil and atmosphere to support the habitat. To produce water, a soil processor utilizes a specialized oven to evaporate the water ice in the local ground soil. This water will be condensed and a fraction will be electrolyzed to produce oxygen. The second system, an atmospheric processing module, utilizes the local atmosphere to produce nitrogen and argon to resupply the habitat atmosphere. These two technologies represent the lowest-TRL systems in the Mars One Architecture, as neither has spaceflight experience. This section attempts, to the highest degree possible, to derive designs from existing hardware and literature in order to remain true to the Mars One technology plan of utilizing existing technology.

3.2.1. Soil processor module

The soil processor (SP) module is derived from designs developed by Interbartolo et al. [56]. As depicted in Fig. 9, this module contains a hopper to hold regolith excavated by the rover, an auger to transport the regolith from the hopper to the oven, an oven with an internal auger to extract the water ice in the regolith, and various screens and chutes to filter and direct the soil. A geometrically-similar design was scaled to provide the appropriate water production rate derived from the ECLS simulations[7]. That is, the ISRU requirements generated by the ECLS simulations were used to parametrically size the oven such that it could process enough soil to meet that demand.

Once the oven design was determined, a mass estimate was generated using aluminum for most components and titanium for high-temperature applications, including the internal mixing auger. A heater similar to that used by Interbartolo et al. [56] was also included in the design,

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[7] As discussed in Section 4.2.3, we assume that ISRU systems operate only during daylight, since Mars One assumes that all power will be generated from flexible thin-film solar arrays. Consequently, ISRU sizing is based on production rate demands derived from the Habitation module, adjusted such this resource demand can be obtained within the hours of sunlight available per day.

based on "The OMEGALUX Complete Electric Heater Handbook and Encyclopedia" [57]. Although the design from Interbartolo et al. was used as a benchmark, future oven designs will likely incorporate many of the lessons learned from the hardware implementation of the Curiosity Rover's Sample Analysis at Mars instrument suite [58].

There are two primary assumptions in the soil processor module. First, the concentration of water in the soil is assumed to be 3% by mass, which has been detected by Curiosity, though higher concentrations on the order of 10% may perhaps be found in localized regions [58,59]. The second assumption is that this water can be readily extracted by heating and stirring the soil with an auger, and that this water will not require further processing to remove contaminants. Although Martian soil-derived water will likely include perchlorates [56], a water cleanup module was left out of the ISRU system design for simplicity.

3.2.2. *Atmospheric processor module*

The atmospheric processor (AP) module design is based more loosely on existing designs than the SP. The majority of Martian atmospheric processing research has focused on obtaining CO_2 for the purpose of producing oxygen [56,60–62], but the Mars One architecture suggests a different use for the Martian atmosphere: the capture of inert gases for the purpose of maintaining the habitat atmosphere against leakage and EVA losses. The design of a gaseous processing system for capturing nitrogen and argon from a CO_2-rich atmosphere is somewhat different from existing techniques developed for CO_2 acquisition from the Martian atmosphere. Thus, the design detailed herein and shown in Fig. 10 is strongly conceptual in nature and will require further development prior to flight.

The atmospheric processor assumes a standard Martian atmosphere (95.3% CO_2, 2.7% N_2, and 1.6% Argon by volume) [56] with a density of 0.02 kg/m^3 and a pressure of approximately 0.6 kPa [61].

The first challenge of Martian atmospheric processing is compressing the low ambient pressure of 0.6 kPa to a nominal value of 101.3 kPa for typical processing technologies. Although vacuum pumps are ideal for such a requirement, they are typically too large for space missions. Regression data from the DVJ family of blowers by Dresser Roots was used to generate the estimated mass, volume, and power of the inlet compressor as a function of flowrate [63]. Future work may analyze the effectiveness of alternative compression techniques.

The compressed gas is then directed through a cylindrical zeolite filter that selectively allows CO_2 to permeate to the atmosphere while retaining nitrogen [64,65]. To determine the required area of the zeolite membrane, a permeation simulation of the membrane was developed to calculate the required membrane area to achieve a certain cut fraction (the fraction of permeated gas flow over initial gas flow). The results from this model, shown in Fig. 11, were used to determine the surface area required to achieve a cut fraction of 0.99. A cut ratio of 0.99 was chosen to eliminate as much CO_2 as possible from the inlet stream while also avoiding too significant of a pressure drop. As the flow pressure approaches the ambient atmospheric pressure, the effectiveness of the membrane filter drops dramatically. From Fig. 11, we can see that even with such a dramatic filtering of the atmosphere, the retained flow still contains approximately 30% CO_2, with nitrogen and argon comprising the rest of the flow.

Once a cut fraction was chosen, the required surface area was used to generate a membrane design with a cylindrical diameter of 5 cm. A zeolite membrane with a density of 2.1 g/cm^3, a void fraction of 0.45 and a CO_2 permeance of 5×10^{-7} was used for this particular design [65]. A thin aluminum supporting frame was designed around the zeolite membrane. This frame was assumed to cover 33% of the zeolite surface area, so the length of the membrane was increased by 50% to achieve the required surface area. After passing through the zeolite membrane filter, the gas is compressed to tank pressure and directed to one of two cryocoolers (operating out of phase in parallel, similar to a pressure-swing system) which freeze the remaining CO_2 out of the flow before venting the remaining nitrogen to the storage tank (see Fig. 10). These cryocoolers were modelled after the 16 W CryoTel GT cryocooler [66].

It should be noted that it was assumed that two cryocoolers would be able to process enough gas, as simulating the performance of the cryocoolers was beyond the scope of this study. All other components in the AP were parametrically sized to produce enough inert gas to supply the average demand predicted by the ECLS simulations. It was also assumed that the zeolite membrane would be sufficient to yield high purity N_2 after utilizing the cryocooler to remove additional CO_2. Additional components may be necessary to ensure that the trace amounts of Carbon Monoxide and Nitric Oxide do not contaminant the product gases, as their melting points are significantly lower than that of CO_2.

ISRU systems corresponding to two distinct mission phases were sized for each case examined in this study. A Pre-Deployed ISRU (PDISRU) was designed to produce enough O_2, N_2, and water to inflate the habitat and fill the reservoir tanks prior to human arrival. After the arrival of the first crew, this system was assumed to continue operations to prepare for the next crew's arrival. The second ISRU system that was sized as a “support” system design to resupply resources to counteract ECLS system inefficiencies, atmospheric leakage, and makeup for EVA losses during the crewed phase of the mission.

To appropriately combine the mass estimates from the ISRU system with those from the ECLS system, both a margin and contingency was added to the ISRU system mass estimate. This is because the mass and volume estimates for the ECLS system are based on ISS hardware data while the ISRU system mass estimate comes from conceptual designs of low-TRL technology. The atmospheric processing module is at a low TRL; all of the technology has undergone a proof-of-concept demonstration, but, to the authors’ knowledge, no integrated test of such a system has been conducted. There has been significant development of technology for capturing and processing CO_2 from the atmosphere [60,67], but no such development has occurred for a system to capture N_2 and Argon [59]. Thus, we estimate the

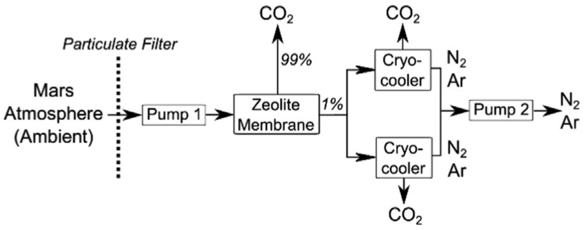

Fig. 10. Block diagram of atmospheric processor.

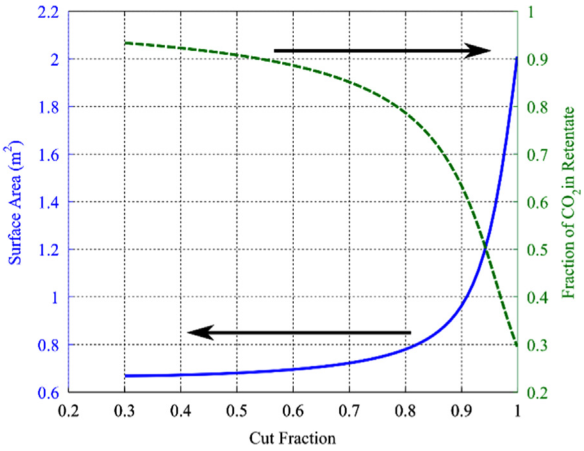

Fig. 11. The design of the atmospheric processor. A larger zeolite membrane surface area results in a larger cut fraction (ratio of retained to permeated gas) and decreases the fraction of CO_2 in the retentate (retained gas). A cut fraction of 0.99 was chosen for the atmospheric processor design.

atmospheric processor to be TRL-3, indicating the need for continued technology development. The soil processing module is at a slightly higher TRL, as oven technology has been demonstrated on Martian soil in a relevant environment [58], but not at the scale of a full ISRU production system. We estimate soil processing technology to be TRL 4–5 [58]. Given the low TRL and conceptual nature of the system design, a mass and volume contingency of 30% along with a margin of 25% was included in the design [68]. A complete listing of mass and volume estimates for the components of the ISRU system is presented in Appendices E.

3.3. *Sparing module*

The emplaced ECLS and ISRU components are only one portion of the mass required to support the crew in the time between resupply missions and the arrival of new crewmembers. A supply of spare parts will also be required to maintain the system as components fail or reach the end of their design lifetime. The continued operation of the ISS is dependent upon regular (and even unplanned) resupply of replacement parts from Earth, and in the event of an unrecoverable system failure, the crew has the option to quickly return to Earth [69]. On Mars, resupply logistics will be much more challenging and there will be no feasible option for the crew to return to Earth in a timely manner. In the case of the Mars One plan, which intentionally excludes the capability to return to Earth from Mars, there is no option for the crew to return to Earth at all in the event of an emergency. The ability of the crew to repair the systems that sustain them – and therefore the availability of spare parts to implement repairs – is critical to mission safety [3]. This section describes the analysis used to determine the number of spares required for each repairable element in the system over the 26-month period between resupply missions. The required number of spares considers both random failures and scheduled repair, where the number of spares associated with the former is based upon the requirement of a probability of at least 0.99 that enough spares are available to repair random failures between resupply.

3.3.1. *Data sources*

The spares analysis was conducted for ECLS, ISRU, and EVA hardware, as they are critical to the survival of the crew. The data used are presented in Appendix E. Primary values of interest for each component are the mean time between failures (MTBF) and life limit (LL). The MTBF for a given component is the inverse of the failure rate, and gives the average time between failures of that component. The LL informs the frequency of scheduled repairs for that component, where the component is replaced every time it reaches its LL. As the Mars One ECLS architecture and technology is considered to be very similar to ISS ECLS technology (see Section 3.1.3), the MTBF and LL for ISS equipment are utilized for the analysis of ECLS spares demands [13,69]. The values listed in Appendix E are based on the NASA BVAD unless otherwise noted [5]. Data are much scarcer for ISRU systems, and therefore reliability data for those systems are determined based on analogy to ECLS equipment wherever possible. If no suitable analogue is present, an MTBF of 500,000 h is assumed – this is considered to be an optimistic value, as it is higher than most of the MTBF values for ECLS components. The primary EVA components considered are the batteries, as they are items that are only useable for a limited number of EVAs. For this analysis, data for the Extravehicular Mobility Unit (EMU) Series 2000 battery are used as an analogy to the batteries that will be used for Mars surface systems [71].

3.3.2. *Component failure model*

Random failure was modelled using an exponential distribution, or constant failure rate model – a commonly used first-order model of component failure behavior. The Probability Density Function (PDF) describing the time to failure of a component is given by Eq. (2) [72].

$$f_{fail}(t) = \frac{1}{MTBF} e^{\frac{-1}{MTBF}t} \tag{2}$$

For LL-related repairs, the number of scheduled repairs is calculated by dividing the mission duration by the LL of the component and rounding down to the nearest integer, as shown in Eq. (3).

$$n_{repair} = \left\lfloor \frac{t_{mission}}{LL} \right\rfloor \tag{3}$$

We assume that the overall number of spares required for a given component is dominated by either scheduled repairs or random failure; thus the number of spares corresponding to scheduled maintenance and random failures are calculated separately, and the larger of the two results is used. For components with no LL, only random failures were considered. Additionally, storage tanks and other buffers are assumed to not fail.

3.3.3. *Maintenance strategy and repair model*

The concept of operations for component replacement is assumed to follow the ISS paradigm of remove-and-replace maintenance. When a component failure occurs, the portion of the system containing that component is shut down and the backup system (in this case, the redundant Life Support Unit) is brought online to support the system during maintenance. The failed component is replaced with an identical spare, and the primary system is brought back online once maintenance is complete [73]. For simplicity, the Mean Time To Repair (MTTR) for any component is assumed to be 12 h (with a standard deviation of 1 h), and repairs are assumed to bring the system back to good-as-new condition. The time required for repairs is modelled using a log-normal distribution, which provides a good representation of a corrective repair process [74,75]. The PDF of the repair time distribution is given by Eq. (4).

$$f_{rep}(t) = \frac{1}{t\sqrt{2\pi}\sigma} e^{\frac{-(\ln(t)-\mu)^2}{2\sigma^2}} \tag{4}$$

For the MTTR and standard deviation values given above, the shape parameter σ and log-scale parameter μ are equal to 0.0832 and 2.4814, respectively.

3.3.4. *Level of sparing and commonality*

The ISS implements sparing using Orbital Replacement Units (ORUs) as the nominal "building block" of systems. These ORUs are designed to minimize the crew time required to implement repairs by encapsulating complex systems in easily replaceable packages. However, implementing spares at a lower level has the potential to reduce the total mass and volume of spares required, though it may increase the required mass of support infrastructure such as tools and diagnostic equipment [3]. This analysis did not utilize only the high-level ORUs implemented on the ISS. Instead, in order to minimize spares mass, this analysis examines spares at the lowest level of component for which data were found. In general, this consists of subassembly-level sparing for ECLS and ISRU technology. It is possible that even lower levels of repair could further reduce the spares mass requirements at the cost of additional diagnostic equipment, tools, and crew time; however, no data were available upon which to base a quantitative assessment of a lower-level sparing case. The potential impact of lower level repair (even down to the point of in-situ manufacturing, the lowest level of repair) is discussed further in Section 5.1.

Commonality is another means to reduce spares demands by allowing a single spare to cover multiple possible failures [69]. For this analysis, it was assumed that the six identical CCAA units could share spare parts. Commonality was only assumed for the CCAAs because they are identical and therefore should already accept common spares. While commonality between different systems with different functions could potentially be implemented, this would require redesign of these systems to accept common spares, which is not considered within the scope of this analysis. Finally, commonality is assumed to exist between different crews – that is, each crew's system is identical to those of the crews already on Mars, and therefore spare parts could be shared among crews[8]. It is important to note, however, that this commonality between different crews would place heavy constraints on Mars One's ability to upgrade systems over time, since any changes to system design would have to ensure that the resulting spares remain common with previous systems in order to maintain the benefits of commonality. If a design change is implemented due to system upgrades, loss of a component supplier, or any other reason, this commonality is eliminated and the spares mass required to sustain the Mars One plan will increase beyond the amount calculated here.

3.3.5. *Redundancy and probability of failure*

The purpose of this analysis is to determine the mass of spares that must be provided at each resupply opportunity in order to maintain the ECLS and ISRU systems. The number of spares manifested in a given resupply mission is the number of spares required to cover all failures for all ECLS and ISRU systems on Mars with a probability greater than 0.99. This analysis does not examine the probability of system failure. Instead, it is assumed that repairs are executed successfully (and return the system to full health) as long as the required spare is available.

The Mars One mission plan incorporates single-fault-tolerance for critical life support functions by including two identical Life Support Units for each crew – one primary and one redundant secondary system [35]. For the purposes of this analysis, it is assumed that when a component failure occurs in the primary system, the redundant system is brought online to provide life support functions until a repair can be implemented. Calculations using the methodology described below found the expected primary system downtime (and therefore redundant system operational time) to be less than 1% of the time between resupply opportunities from Earth for each major subsystem. Therefore, the amount of operational time required for the secondary system is assumed to be negligible for the purposes of this analysis. It is assumed that the secondary unit does not fail while the primary unit is offline, and that the operation of the secondary unit does not significantly increase the total number of spares required by the system.

In addition, the storage tanks and buffers within the system are assumed to be large enough to isolate failures while they are repaired; that is, the failure of a given processor does not cause downstream processors to go offline due to a lack of resource supply. The mass of stored ECLS consumables is given in Appendix A. Since the

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[8] Commonality was not included in the original analysis [6].

objective of this analysis is not to examine the probability of failure but rather to determine the spares logistics demand, the probability that stored consumables will run out before a repair is implemented is not calculated. Rather, the redundant Life Support Unit is assumed to be sufficient to maintain the system during maintenance operations, as mentioned above. In addition, failures of different components are assumed to occur independently. As a result, failure of a particular component only causes downtime for the assembly including that component and requires the replacement of only that component.

All of the above assumptions are considered to be very optimistic, and are used to formulate a lower bound on the number of spares required. The impact of common cause failures, cascading failures, design flaws, manufacturing defects, and operator error are not examined here, though these represent significant risks for the Mars One mission plan given that all Life Support Units are identical and the system does not incorporate dissimilar redundancy for critical functions. This stands in contrast to systems like the ISS, which utilize dissimilar redundant systems with double fault tolerance to accomplish ECLS functions [73]. Since the Mars One mission plan does not provide the capability for crews to return to Earth, crewmembers will have to find a workaround for any systemic issues or design flaws that are discovered after deployment and operation of the habitat on the Martian surface in order to survive for 26 months until the next resupply mission. However, the purpose of this spares analysis is to examine the sparing requirements of the Mars One plan as described, not the overall risk of mission failure. Therefore, the probability of system failure is beyond the scope of this analysis and the only output of the sparing module is a spares demand at each resupply opportunity.

3.3.6. Methodology

The failure and repair behavior of the ECLS and ISRU systems were modelled as Semi-Markov Processes (SMPs), which are described in greater detail by Warr and Collins [76], Owens [77], and Owens et al. [78]. The SMP model structure provides a framework to calculate several values of interest, including state probabilities and the distribution of the number of times a given state will be visited [76]. For this analysis the Markov renewal probabilities for the various states are used to determine the minimum number of spares required for each system element in order to achieve a threshold probability of having enough spares to repair the random failures that will occur over the course of the mission. In addition, the expected time spent in partially failed states gives an estimate of the system downtime and the resulting operational time put on the redundant Life Support Unit, as described above [77,79,80].

A consequence of the assumption that all repairs are completed successfully is that the SMP state network contains no fully failed state, and is hence not used to calculate the probability of system failure. Instead, failure of a component places the system in a partially failed state from which the only exit transition is repair of that component. The assumption of buffers large enough to isolate failures also enables a partitioning of the system and examination of one ECLS/ISRU assembly at a time, thus enabling one-failure-at-a-time analysis (since the failure of a subassembly will take the entire assembly offline until the subassembly is repaired). This simplifies the analysis process, and results in SMP diagrams of the form shown in Fig. 12. Each failure transition is described by an exponential distribution based on the component's MTBF (see Eq. (2)); each repair transition is described by the log-normal repair distribution (see Eq. (4)). For the case in which multiple copies of the same component exist within the same assembly, it does not matter which copy fails, and therefore the identical components are condensed into a single partially failed state. This case is represented by the minimum of a set of simultaneous identical exponentially distributed processes, which has an MTBF equal to the MTBF of an individual process divided by the number of processes [81].

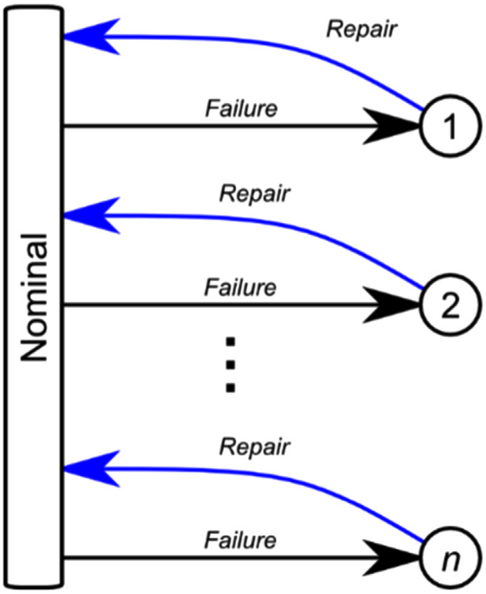

Fig. 12. SMP diagram for a one-failure-at-a-time analysis, showing failure/repair cycles for n components. Once the assembly leaves the nominal state due to failure of one of its subassemblies, the only possible transition is a repair of the failed subassembly.

The overall probability that the system has sufficient spares is the product of the probabilities for each component. For this analysis, the system probability requirement of 0.99 is distributed evenly among the various components of the system. That is, for a system with n repairable components, each component must supply sufficient spares to provide a probability greater than p, as described by Eq. (5):

$$p = 0.99^{\frac{1}{n}} \tag{5}$$

Using the Markov renewal probabilities for each partially failed state, the Cumulative Distribution Function (CDF) describing the number of spares required was calculated for each component. Commonality between different assemblies (in this case, the 6 identical CCAAs) and between different crews is captured in this analysis by convolving the Probability Mass Functions (PMFs) describing demand for the same component[9]. To model commonality between different crews, this CDF was calculated for the cumulative number of spares required from the mission start to the time of each resupply mission (i.e. for 26 months, then 52 months, and so on), taking into account the demand for all crews on the surface, rather than as a discrete set of 26-month periods. Once these PMFs are developed, the number of spares required to achieve a probability higher than the threshold value p is determined. This gives the cumulative number of spares that will need to be delivered to the surface up to that point in order to provide the desired probability of sufficient spares. In order to determine the number of spares that need to be sent on a particular mission, the number of spares that have been sent on all missions beforehand is subtracted from the required cumulative number of spares at that point.

The number of spares calculated via the Markov renewal process accounts for random failures; for parts that have scheduled repair based on a LL, the number of spares used by scheduled repairs is calculated using Eq. (3). Since the SMP analysis process described above only accounts for random failures and not scheduled repairs, these two calculations are performed separately. Then, following the assumption that the overall number of repairs required is dominated by either random failure or scheduled repair, the larger of these two numbers is taken as the required number of spares for that component.

3.4. Logistics module

3.4.1. Assumptions

The logistics of transporting items to the surface of Mars plays a major role in any mission architecture. The Mars One architecture explores a new paradigm of one-way trips to Mars without a return trip to Earth. For such long-term missions, sustainability plays an important role - it is crucial to consider the feasibility of logistics for both the pre-deployment and crewed mission phases. The logistics considerations included in this paper include: (1) an assessment of transportation feasibility for both cargo and crewed missions (2) a heuristics-based launch manifest optimization; and (3) computations of systems integration and launch costs.

The Mars One mission plan anticipates using a SpaceX Falcon Heavy rocket as the main launch vehicle, and a scaled-up version of the Dragon capsule as the primary landing vehicle [70]. In this paper, we assume the following sizing parameters for the Falcon Heavy rockets and the landers. The sizing information for the lander, which has not yet been developed, is acquired from an unofficial source [82], and compares well to scaled up values from the Red Dragon study performed by NASA and SpaceX. The recurring cost ($300 M) is estimated by scaling values used in the Red Dragon analysis [83]. The assumed values are as follows:

Falcon Heavy [84]:

- Payload to Low-Earth orbit: 53,000 kg
- Payload to Trans-Martian orbit: 13,200 kg

Lander (a 5 m-diameter variant of Dragon) [9,83,85]:

- One lander is delivered by one Falcon Heavy launch
- Lander mass: 14,400 kg
- Payload mass: 2,500 kg
- Payload volume: 25 m^3 (pressurized)
- Recurring cost: $300 M per launch vehicle and lander
- Propulsive entry, descent, and landing (EDL)

The Red Dragon study selected propulsive landing as the baseline option for the Dragon Martian EDL [83]. This paper assumes that the same technology will become available; therefore no detailed EDL feasibility analysis is performed.

All cargo except the Inflatable Units is assumed to fit within the pressurized volume of the lander. This exception arises because the predicted mass of 4580 kg for each Inflatable Unit (based on equivalency coefficients provided within the NASA BVAD [5]) is heavier than the stated pressurized payload capacity of the assumed Dragon vehicle. It is important to note that this assumption effectively expands the mass capacity of two of the Dragon landers out of each mission to the value required to deliver the inflatable habitats, creating two specialized landers. Thus, 9160 kg of inflatable habitat is assumed to be delivered to the surface by two vehicles with a nominal combined payload capacity of 5000 kg. This is a very optimistic assumption, but is adopted in recognition of the requirement to deliver the inflatable habitats to the surface in one landing. This requirement arises from Mars One's stated plan to have a completely integrated and functioning habitat prior to the departure of the first crew [14], and the need to avoid autonomous manufacture and integration of inflatable structures on the Martian surface due to significant limitations in current technology.

In addition to launch requirements for lander capsules, a series of launches are required to assemble a Mars Transit Vehicle (MTV), to support their journey to Mars. The MTV and the crew lander are launched with an additional crew on-board to assist with the assembly of the crew lander and MTV. Two propulsion stages for trans-Mars injection are also launched separately. After the integration of the MTV and lander, the Mars crew is launched and the assembly crew returns to the Earth. Therefore, transporting a single crew to Mars requires a total of four Falcon Heavy launches. Before entry into the Martian atmosphere, the crew moves to the lander and the MTV is discarded.

3.4.2. Launch vehicle feasibility analysis

Based on the assumptions made in the Red Dragon study, the lander is delivered to Trans-Martian Orbit using the upper stage of the launch vehicle and directly enters the Martian atmosphere prior to landing on the Martian surface [83]. The predicted Falcon Heavy launch capability is 13,200 kg into Trans-Martian Orbit [84] while the estimated gross lander mass including the payload is 14,400 kg (Living, Life Support, or Supply Units; not including the Crew Lander). Therefore, a single Falcon

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[9] Commonality was not included in the original analysis [6]

Heavy launch cannot deliver a lander module with payload to Trans-Martian Orbit ($\Delta V = 3.8$ km/s). Thus, a design change is required either to the lander or to the Falcon Heavy rocket. To continue with this analysis, we make the optimistic assumption that one cargo lander can be delivered by one Falcon Heavy launch.

3.4.3. Manifest optimization

To determine the minimum number of landers required to land a given list of components and spares, a manifest optimization [86] was performed. In this paper, a geometric optimization is not performed due to the lack of component dimension data. Instead, only mass and volume constraints are considered. The resulting formulation is similar to a classical optimization problem known as a bin packing problem, and is presented as follows:

Objective:

J: number of vehicles used

Variables:

$x_{ij} =$ 1, if item i is accommodated in vehicle j;
0, otherwise
$y_j =$ 1, if vehicle j is used;
0, otherwise

Parameters/Constants:

N: number of items (including packaging)
m_{i}: mass of item i
v_{i}: volume of item i
M: mass of vehicle
V: volume of vehicle

Bin Packing Problem Formulation:

$$\min J = \sum_{j=1}^{N} y_i \tag{6.1}$$

$$\text{s.t.} \sum_{j=1}^{N} m_i x_{ij} \le M y_i \quad \forall \mathrm{i} \in \{1, \ldots, N\} \tag{6.2}$$

$$\sum_{j=1}^{N} v_i x_{ij} \le V y_i \quad \forall \mathrm{i} \in \{1, \ldots, N\} \tag{6.3}$$

$$\sum_{i=1}^{N} x_{ij} = 1 \quad \forall \mathrm{j} \in \{1, \ldots, N\} \tag{6.4}$$

$$x_{ij}, y_i \in \{0, 1\} \quad \forall \mathrm{i} \in \{1, \ldots, N\}, \forall \mathrm{j} \in \{1, \ldots, N\} \tag{6.5}$$

Although the above classical bin packing problem assumes all commodities to be discrete, we make an exception for food storage, as well as power and thermal system mass. These masses are assumed to be continuous for the purposes of the bin packing problem, able to fill any remaining mass capacity of already packaged landers. Any remaining food, power, or thermal system mass that cannot be fit into landers that have already been packaged with the discrete bin packing problem is allocated to however many additional landers are required to transport that mass to the surface of Mars. In addition, as described earlier, the inflatable habitats are assumed to each take up a single lander even though their individual mass is larger than the lander capacity.

This optimization problem was solved using the commercial software IBM ILOG CPLEX, yielding the optimal number of launches and logistical cost results presented in Section 4.2.5.

4. Results

This section presents the results of our analysis of the feasibility of the Mars One mission plan using the modelling methodology described above. We apply the iterative analysis process described in Section 1, wherein we first assess the baseline mission plan under the assumptions and constraints stated by Mars One. This assessment then informs whether or not modifications to the architecture and subsequent analysis iterations are required. We reiterate that any modifications implemented to the baseline Mars One architecture throughout this process are made with the goal of achieving a feasible architecture while conforming as much as possible to Mars One's statements and assumptions. When exploring alternative architectures, it was found that typically one or more of Mars One's assumptions was, by necessity, violated in order to move the architecture towards feasibility. This usually comes in the form of new technology development or the relaxation of a payload mass limit on a transportation stage.

The feasibility assessments performed here can be broadly categorized as either architectural or programmatic feasibility assessments. Assessments of architectural feasibility evaluate whether or not a system can sustain the Mars One crew for the 26 month period between resupply missions within the landed mass limits imposed by Mars One. Contrastingly, assessments of programmatic feasibility evaluate the lifecycle cost of the entire program. Architectures that lead to programs that exhibit resupply costs that grow indefinitely over time are deemed to be programmatically infeasible.

In order for the mission plan to be deemed feasible, it must be both architecturally and programmatically feasible. That is, it must not only sustain every crew for the 26-month period between resupply missions, but it must also have a sustainable resupply requirement that can be met for the rest of the crew's lives.

In total, four analysis iterations were performed. These yielded two architecturally feasible architectures that are capable of sustaining the crew over the 26 month period between resupply. Further analysis of these architectures, however, found them to be programmatically infeasible due to a significant rise in cost as the settlement grows over time. Potential solutions to this programmatic infeasibility are discussed in Section 5, but the immense technology development effort required to reach a point where the Mars One mission plan is programmatically feasible make it difficult to quantitatively examine how these solutions would be implemented. As a result, we qualitatively describe technology that could potentially be used and note that an architecturally and programmatically feasible mission plan would by necessity differ significantly from the stated plan of Mars One. The procession of analysis iterations is presented below.

4.1. Assessment of architectural feasibility

4.1.1. Iteration 1: Mars One baseline

In Section 2.3, unambiguous definitions used in the Technology Readiness Level (TRL) metric were adopted and defined as the basis for our interpretation of the Mars One assertion that their mission plan can be accomplished exclusively with existing technology [1]. As a first step in our feasibility assessment, we test this claim by surveying the current state of the art in spaceflight technology. Through this, we observe that in many cases, the technologies required for the Mars One mission plan either do not yet exist, or have not yet been validated. Specific examples relevant to the scope of this analysis include:

- ISRU technologies which, as discussed in Section 3.2, are currently at a low TRL, with most of their past operational experience coming from lunar-focused field analog tests conducted by NASA between 2008 and 2012 [56].
- Unofficial sources have stated that the Mars One habitat will be based on a 5 m diameter, 25 m^3 variant of the SpaceX Dragon capsule [82]. The current Dragon [87] capsule has a diameter of 3.6 m and a pressurized volume of 11 m^3 and as of this writing, there has been no announcement from SpaceX regarding the development of a scaled-up version. Furthermore, the proposed Falcon Heavy launch vehicle does not appear to be capable of putting the lander module with payload on a transfer orbit to Mars, as discussed in Section 3.4.2.
- Plant growth for space applications is still in the early stages of development. Only a handful of small-scale plant experiments have been flown in space [88]. As a result, there is much uncertainty in the performance and reliability of flight-rated crop growth systems. Moreover, as discussed in Section 3.1.8, systems required to compactly support plant growth and efficiently process raw biomass into edible food at the scales required are still very much in development.
- As discussed in Section 3.3, the current operational paradigm for the International Space Station (ISS) relies on regular resupply from the ground. This has in turn affected its system design and operations, especially from the perspective of consumables use. No operational experience has been gained for long-duration human spaceflight missions beyond low Earth orbit [3,69]. Such missions will require crew and life support systems that have lower consumables and spare parts resupply requirements [30]. Thus, dedicated technology development is required to better mature these technologies
- Approaches for mitigating the adverse impacts of long-duration exposure of humans and crops to galactic cosmic radiation and solar particle events while in space and on the Martian surface are still very much in development. In fact, this challenge was highlighted in a 2012 National Research Council report as being one of the most important technology areas to address in order to enable sustained human spaceflight beyond Earth orbit [2].
- Manufacturing spare parts in space and on the Martian surface using additive manufacturing, or "3D printing," has been frequently proposed. While additive manufacturing is an exciting new development with the potential to reduce resupply mass [80], the technology is still very young. Limitations in materials selection as well as the quality, precision, reliability, and reproducibility of parts produced using 3D printing, as well as limited understanding of the impact of a partial gravity environment on the thermal and fluid processes involved in 3D printing mean that significant technology development and validation efforts are required before 3D printing can be deployed in support of critical functions on Mars [89].

Thus, based on the observations made in this first analysis iteration, we conclude that because the baseline Mars One architecture requires extensive use of technologies that are not "existing, validated, and available," the capability to sustain the Mars One crew for the 26 month period between resupply periods is not currently available. Therefore *the baseline Mars One mission plan, as publicly presented, is architecturally infeasible.*

4.1.2. Iteration 2: ISRU, lander, and plant growth technology development

The second analysis iteration addresses the conclusion of the first analysis iteration by making the optimistic assumption that all required ISRU, lander, and plant growth technologies will be developed in time for the mission. The cost of this development effort is expected to be significant, but the estimation of that cost is outside the scope of this study so we simply assume that the required technology exists and proceed with the analysis.

Here, we revisit the analysis performed in Section 3.1.8.1, where Mars One's claim that 50 m^2 of crop growth area will provide "sufficient plant production capacity to feed about three crews of four" [11] [10] was investigated. It was found from this analysis that at least 185 m^2 was required to sustain a single crew of four. A sensitivity analysis of this result found that increasing this area to 201 m^2 would allow for the introduction of more variety to the crew's diet, for the relatively low additional crop growth area of 16 m^2. We note however, that this analysis is based on idealized crop growth rates under optimal lighting and nutrient conditions. A higher fidelity analysis under conditions more similar to that experienced on the surface of Mars will likely result in a substantially larger crop growth area requirement. As a reference, Cassidy et al. [90] estimated that it currently takes on average 1667 m^2 of plant growth area to feed a single person on Earth on a typical diet, accounting for the inefficiencies of feed-to-animal product conversion. If all crops currently grown on Earth were fed directly to people, this value would reduce to 1000 m^2 per person[11]. This leads us to conclude that *despite the assumption of technology availability resulting from the first design iteration, the Mars One architecture is still architecturally infeasible* due to the

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[10] We note that since this analysis was performed, Mars One has increased their planned crop growth area [11] from 50 m^2 to 80 m^2. Since this value is still significantly lower than the growth areas derived in Section 3.1.8.1, this update does not affect the conclusions of our analysis

[11] These plant-growth-area-per-person values were calculated from the number-of-people-fed-per-hectare values listed in Cassidy et al. [90]

insufficiency of their planned 50 m^2 crop growth area to sustain their stated crew population.

4.1.3. Iteration 3: Increased crop growth area

In the third analysis iteration, we increase the plant growth area to 201 m^2 based on the analysis performed in Section 3.1.8.1. This is intended to enable Mars One's plan to provide all food from locally-grown crops [11]. With this adjustment, we run an end-to-end simulation of this modified Mars One architecture.

As described in Section 3, the first step of this analysis is to run the Habitation module to determine requirements for the ISRU Sizing module (Section 3.2). This is accomplished by simulating the habitat with the baseline crew schedule and ECLS architecture, but without the periodic introduction of ISRU-derived consumables. Since the Mars One mission plan relies on all consumables resupply requirements being served by ISRU [1], the resulting rate of consumables depletion is set as the ISRU resupply requirement. This value is then fed to the ISRU Sizing module, where the mass and volume of the corresponding ISRU system is calculated and sent to the Logistics module (Section 3.4).

This first simulation revealed that increasing the crop growth area to sustain the caloric intake of the crew, while growing crops within the same atmospheric environment as that of the crew (see Fig. 4), would introduce atmospheric imbalances that would lead to a nitrogen-depletion rate that would require a prohibitively large atmospheric processor system.

Specifically, this imbalance arises from a mismatch between the respiration rate of the crew and the combined photosynthetic rate of the crops, and is related to the initial simulations performed in Section 3.1.8.6 where the need for a CO_2 injector was discussed. As the various crop batches (see Section 3.1.8.5) of the BPS are planted and grown, the rate of crop photosynthesis enabled by injected CO_2 quickly outpaces the rate of crew respiration. This causes the continual buildup of O_2 within the cabin over time, resulting in the fire safety threshold of 30% O_2 concentration (see Table 2) being exceeded on mission day 36 (see Fig. 13). To address this issue, an ISS-based approach is adopted, based on Mars One's specification that their system will "be very similar to those units which are fully functional on-board the International Space Station" [13]. This involves using Pressure Control Assemblies (PCAs) to vent a portion of the habitat atmosphere before introducing N_2 to dilute the O_2 concentration within the atmosphere, reducing it to below fire safety limits.

Within this simulation, this process occurs between mission days 36 and 49, reducing the O_2 concentration and maintaining it at the set value of 0.265 (see Fig. 13) and rapidly consuming N_2 (see Fig. 14) until day 49, when N_2 tank is depleted.

Once the N_2 tank is depleted, the ISS-based O_2 concentration control strategy is no longer viable, since there is no more N_2 to dilute the atmosphere. Without introducing further N_2 into the system, the O_2 molar fraction rises rapidly after day 49, as shown in Fig. 13. The fire safety threshold – O_2 concentration in excess of 30% [17] – is quickly violated on day 57, triggering one of the mission failure conditions described in Table 2. If this failure condition is ignored, the O_2 concentration continues to increase beyond the hyperoxia threshold of 50% on day 108, as shown in Fig. 13 [12].

As discussed earlier, these initial simulations were run to determine requirements for the ISRU system. Here, it was found that the assumed ISS-based O_2 concentration control scheme consumed N_2 at a rate of approximately 795 mol per day at its peak. To sustain this demand, the ISRU Sizing module found that an Atmospheric Processor (AP) system with a mass of approximately 31,105 kg is required. Table 5 presents a breakdown of this mass estimate[13]. Here, we observe that the total mass of the required atmospheric processor is dominated by the mass of the pumps. This is due to a combination of: (1) the low pressure of the Martian atmosphere (600 Pa); (2) the low nitrogen content of the Martian atmosphere (2.7% by volume); (3) the fact that the system is solar powered and hence can only operate during daylight (thereby increasing the required production rate during operation to compensate for its downtime during the night); (4) losses in flow through the zeolite membrane filter used to separate N_2 from the incoming flow (the cut-fraction described in Section 3.2.2); and (5) pressure losses downstream of the zeolite membrane filter. This combination of factors results in a requirement for 11.9 m^3/s of Martian atmosphere to flow through the system, which in turn leads to the requirement for a large pump mass and support structure mass.

The estimated 31,105 kg mass of the required Atmospheric Processor far exceeds the 2500 kg payload mass of the SpaceX Dragon-derived Life Support Unit (described in Section 3.4), and is therefore considered to be prohibitively large. We thus conclude from this third iteration that *the assumed baseline Mars One architecture augmented with a 201 m^2 BPS remains architecturally infeasible* due to inherent atmospheric imbalances that under Mars One's constraints, can only be managed with a prohibitively large ISRU system that exceeds their specified landed mass capabilities.

4.2. Iteration 4: Assessment of architectural and programmatically feasibility for two habitation cases

In light of the observations made in the third analysis iteration, we further relax Mars One's constraints and develop and compare two alternative habitat options. The first of these options attempts to develop an architecturally feasible solution based on Mars One's plan to

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[12] We note that the phenomenon of excess crop-generated O_2 violating the cabin fire safety threshold was also observed in the original analysis [6]. However, the behavior of the system after exceeding this threshold was found to be different in this analysis. This is due to the implementation of an updated intermodule atmospheric exchange model in this analysis, which results in improved pressure balancing and thus pressure control across the various modules of the habitat

[13] The results presented in Table 5 are an update to the original analysis [6]. The original AP analysis erroneously used the N_2 requirement generated by the Habitation Module as the input flow rate to the AP, rather than the output flow rate required by the AP. This meant that the output produced by the originally modelled AP was much lower than what was required to support the crew. This issue has since been corrected, yielding the values presented in Table 5.

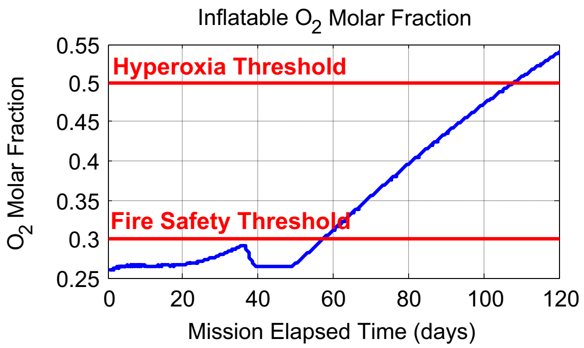

Fig. 13. : O_2 Molar fraction within the habitat atmosphere.

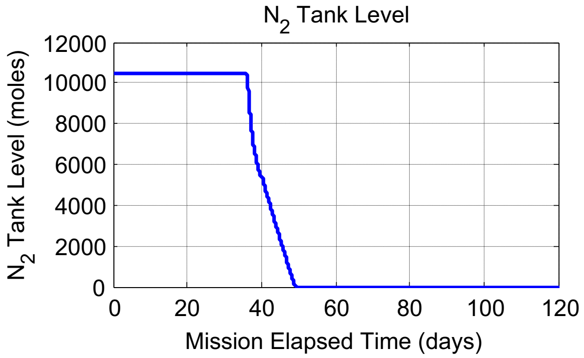

Fig. 14. : N_2 Tank level for the nominal Mars One habitat.

Table 5
Estimated mass breakdown for the atmospheric processor as predicted by the ISRU sizing module.

AP component	Estimated mass (kg)
Zeolite bed	824
Pump 1	12,462
Pump 2	12,462
Cryocooler 1	5
Cryocooler 2	5
Support structure	5,347
Total	**31,105**

produce all food locally with a BPS. Here, a BPS is retained, and an architecture that supports and takes advantage of the presence of this BPS is developed such that it can sustain the four person Mars One crew for 26 months. Subsequent expansion missions are assumed to repeat this architecture.

Contrastingly, the second habitat option is based on removing the BPS from the architecture altogether, and sustaining the crew's caloric needs entirely with prepackaged and stored food that is delivered from Earth. This architecture aims to eliminate the atmospheric imbalances observed in Analysis Iteration 3 by completely modifying Mars One's food system design. These two options, from here on referred to as the “Biomass Production System (BPS) Case” and the “Stored Food (SF) Case”, can be considered as representative of the extremes of the range of food supply options. The following subsections describe these two architectures in greater detail, and present the results of their architectural and programmatic feasibility assessments.

4.2.1. The Biomass Production System (BPS) habitation case

This habitation option attempts to transform the baseline architecture explored in Iteration 3 into one that is architecturally feasible. This is accomplished by relaxing Mars One's constraint of using only technologies that are both “existing, validated, and available” [1] and “very similar to” those used on the ISS [13], to address the issues with atmospheric imbalances observed in Analysis Iteration 3. Specifically, we introduce a notional “Oxygen Removal Assembly (ORA)” that selectively removes O_2 from the atmosphere, and transports it to an O_2 tank for later use by the crew, thereby mitigating the possibility of the cabin O_2 concentration exceeding the fire safety threshold. This ORA system will likely consist of a combination of a CDRA, an adsorption-based nitrogen scrubber, and a photocatalytic ethylene scrubber [91] to separate CO_2, water vapor, nitrogen, ethylene, and other volatile organic compounds from a stream of BPS gas, such that a highly concentrated O_2 mixture remains.

In addition, we move the BPS to a dedicated plant growth chamber to decouple the effects of plant photosynthesis and transpiration from the atmospheric requirements of the crew. This modification enables the separate control of atmospheres for the crew and crops to levels that best suit their respective respiration rates. Implementing this requires dedicating one of the Inflatable Units entirely to plant growth, which in turn removes the dual redundancy originally envisioned by Mars One (see Section 3.1.8).

Finally, we attempt to minimize system mass and complexity by taking advantage of the excess O_2 provided by the BPS. As discussed in Section 3.1.8.8.1 and depicted by the dashed lines in Fig. 15, we rearrange the ECLS system such that the BPS provides both food producing and air revitalization functions[14]. Specifically, we redirect the outlet of the CDRA so that it delivers CO_2 directly to the dedicated BPS chamber. Within this chamber, this CO_2 is supplemented with additional CO_2 introduced by the CO_2 injector to support crop photosynthesis[15]. The resulting O_2 is removed from the BPS chamber by the ORA, and delivered to the habitat's O_2 tanks, where it is used to support crew respiration and EVA.

Preliminary simulations of this modified architecture revealed that O_2 generated by the ORA is sufficient to support all crew respiration and EVA needs without the need for supplementary O_2. Under nominal operating conditions, this means that the O_2 Generation Assembly

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[14] Note that as discussed in Section 3.1.8.8.1, we do not consider using the BPS for potable water recovery functions due to food safety concerns and the high water demand of the BPS

[15] We note that in the later phases of the mission, as the rate of biomass production reaches a steady state, oxidation techniques such as incineration and aerobic digestion can be used to recover CO_2 from inedible biomass, thereby reducing the dependency on CO_2 introduced from the Martian atmosphere. Assessing the impact of this approach on the system architecture is beyond the scope of this analysis, and is left for future work. It should be noted however, that these techniques are inadequate during the start-up phase of the BPS due to the early lack of available inedible biomass (see Section 3.1.8.6). Thus, the approach adopted here for the BPS case is appropriate for supporting the start-up of the BPS.

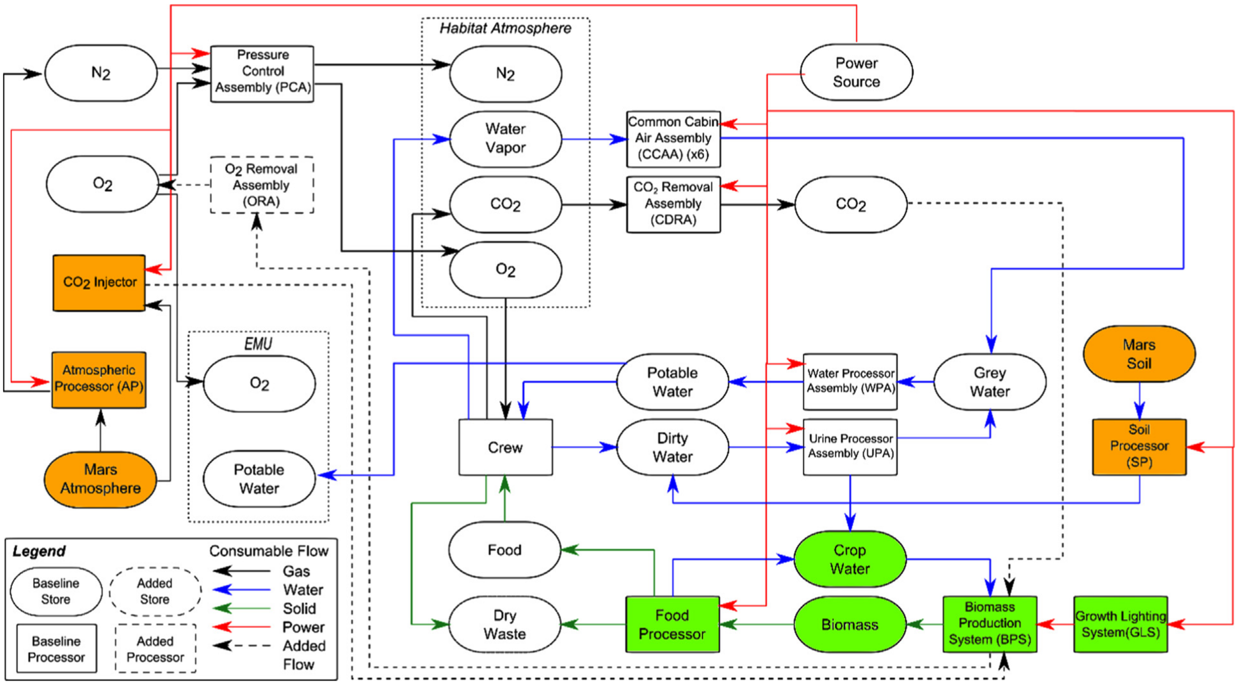

Fig. 15. The biomass production system (BPS) habitation case.

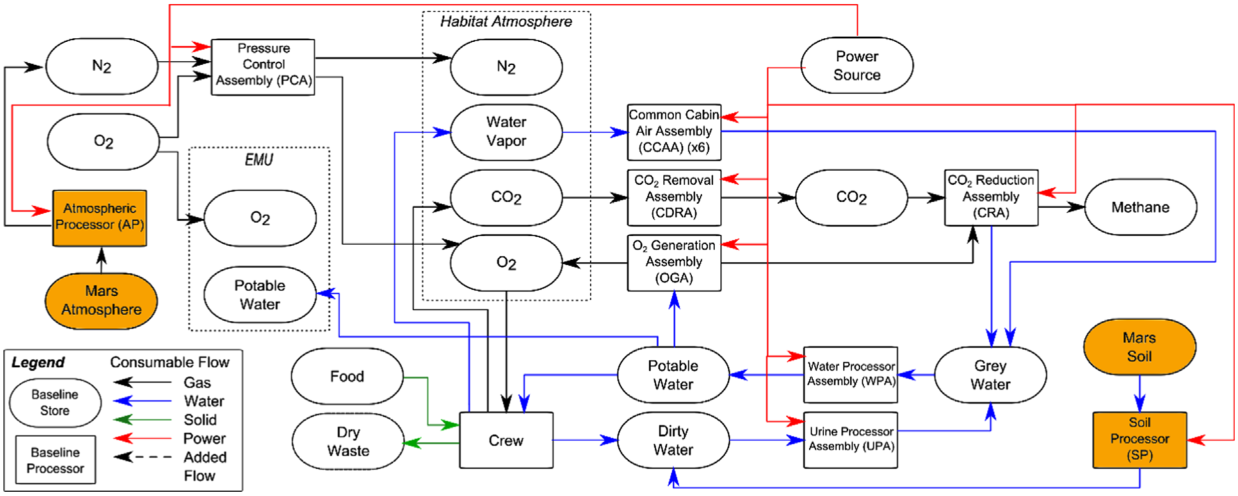

Fig. 16. The Stored Food (SF) habitation case.

(OGA) and CO_2 Reduction System (CRS) are never operated and can hence be removed from the ECLS system of this habitation case for the purposes of assessing architectural and programmatic feasibility. We note, however, that during the predeployment phase of the BPS case, an OGA is still required to generate O_2 for initial inflation of the Inflatable Units, as per the Mars One plan (see Section 3.2). Thus, in the BPS case, the OGA is moved from the ECLS system to the ISRU system.

4.2.2. *The Stored Food (SF) habitation case*

Contrasting to the BPS case, the Stored Food (SF) architecture attempts to address the atmospheric imbalance issues described in Section 4.1 by removing the BPS altogether and using stored food to meet the crew's nutritional needs. This results in a much less complex system, shown in Fig. 16. Without crops creating excess O_2, the notional ORA described in the BPS case is no longer needed. This system does, however, require regular

Table 6
Power demands for systems that differentiate the BPS and SF habitation cases.

BPS architecture		**SF architecture**	
Differentiating system	**Power demand (W)**	**Differentiating system**	**Power demand (W)**
Predeployment phase soil processor module[a]	22,500	Predeployment phase soil processor module[a]	5400
Total for predeployment phase	**22,500**	**Total for predeployment phase**	**5400**
Crewed phase soil processor module[b]	4500	Crewed phase soil processor module[b]	5900
BPS lighting[c]	86,310	OGA[d]	1720
ORA[e]	860	CRS[f]	686
CO_2 injector[g]	1300		
Total for crewed phase	**92,970**	**Total for crewed phase**	**8306**

[a] Although both architectures contain a predeployment phase soil processor module, their requirements are significantly different due to the high water demand of the BPS (which requires 25 L/day as compared to the 6 L/day required by the SF case-see Section 4.2.4 and Table 8). This results in vastly differently power requirements. These power estimates are based on the energy required to heat 3% water content (by mass) Martian regolith from an ambient temperature [113] of 192 K to oven operating temperatures of 603 K (330 °C), as per the ISRU oven operational strategy described by Sanders [114] and Interbartolo et al. [56]

[b] For the crewed phase, supplemental O_2 is required for the SF Case but not the BPS Case (see Section 4.2.4 and Table 8). In addition, ISRU-derived water is required in both cases. Since O_2 is derived from electrolyzed water, which is in turn obtained from the soil processor, this leads to different power demands for the same system when operated in the two different cases. The crew requirement for O_2 listed in Table 8 is equivalent a requirement of approximately 1.5 L of additional water required to be processed by the soil processor per day.

[c] Based on peak power demand for all 137 lighting units (the minimum number of lights required) operating simultaneously at 630 W (based on the Heliospectra LX601 – see Section 3.1.8.3).

[d] Based on the ISS OGA operating at half its maximum O_2 production capacity (determined from O_2 production rates obtained from simulation). This specific power demand is computed from data provided by Bagdigian et al. [106]

[e] Power demand is assumed to be equivalent to the CDRA. This is a lower bound since an ORA will likely be composed of a CDRA, sorbent-based N_2 scrubber, and photocatalytic ethylene scrubber (see Section 4.2.1). Here, we have only budgeted for the power demand of one component of this system.

[f] Based on the combined power demands of the ISS CRS reactor heater, CO_2 compressor and separator listed by Jeng and Lin [112] and Murdoch et al. [115].

[g] Power demand based on estimates made by scaling CO_2 extraction rates to the performance of the commercially available Sunpower Inc. CT-F flight-rated cryocooler [47].

resupply of food, which violates the Mars One plan to grow all food on site. For this architecture, it was calculated that each crew would require 5152 kg of food (including food packaging) to sustain them over the 26-month period between resupply. This value is based on NASA estimates for a Mars transit food system and assumes primarily thermostabilized food supplemented with a lower proportion of natural form and freeze-dried food [49]. This distribution of food type is driven by the shelf-life properties of the various forms of packaging [49].

4.2.3. *Comparative power and thermal system analysis*

In order to ensure a fair comparison between the lifecycle costs of the BPS and SF architectures, an analysis of the required power and thermal management systems is performed. This is particularly important because these two architectures have avenues for mass savings and mass penalties – both of which have significant implications on lifecycle cost. The BPS case for instance, provides additional ECLS functions that remove the total number of technologies needed over the baseline, while requiring additional supporting systems, such as lighting and crop water management. Moreover, a survey of previous studies of bioregenerative life support systems found that power, cooling, and volumetric requirements typically account for 70% of the equivalent system mass [92].

Contrastingly, the SF case leads to a significantly less complex architecture at the cost of needing to deliver an additional 5152 kg of food mass for each crew on the surface of Mars. As the crew population grows, the requirement to deliver food grows accordingly.

Rather than performing a full power and thermal system estimate for all systems in both habitation cases, we examine the power and thermal demands of only the systems that differentiate these two habitation cases. That is, the power and thermal demands of systems that are common to both the BPS and SF habitation cases, such as CDRA and the PCAs, are not considered. Adopting this approach allows us to instead focus our analysis on comparing the lifecycle impacts of both architectures.

Table 6 lists the key systems that differentiate the BPS and SF cases, along with their power demands. Systems listed under each habitation case are present within that particular architecture, but not in the other.

To determine the power and thermal system requirements of these differentiating systems, the following assumptions were made:

- All power will be generated using flexible thin-film solar arrays, as specified by Mars One [13]. For this analysis, we assume the performance characteristics of the MiaSole thin-film array [93] – the highest efficiency commercially available flexible thin-film solar array [94]. This particular model [95] has an efficiency of 15.5% and an areal mass density of 2.7 kg/m^2
- Power storage will be provided by batteries, as per statements made by Mars One [55]. For this analysis, we assume next generation Lithium-Solid Polymer Electrolyte batteries listed in the NASA BVAD [96] with a listed cell specific energy of 200 W h/kg (assumed to be at 100% depth of discharge). These batteries are sized to store energy throughout the longest expected night

Table 7
Power and thermal system contributions of the systems that differentiate the BPS and SF architectures.

	BPS Case	SF Case
Predeployment phase power system contribution		
Power requirement for solar array during daylight (W)	22,500	5400
Solar array area (m^2)	247	60
Solar array mass (kg)	666	160
Battery mass (kg)	1856	446
Total mass contribution (kg)	**2522**	**606**
Crewed phase power system contribution		
Power requirement for solar array during daylight (W)	274,705	13,208
Solar array area (m^2)	3011	139
Solar array mass (kg)	8130	374
Battery mass (kg)	7340	199
Total mass contribution (kg)	**15,470**	**573**
Crewed phase thermal system contribution		
Thermal load (W)	88,970	2406
Internal thermal control system mass (kg)	2225	61
External thermal control system mass (kg)	10,765	292
Total mass contribution (kg)	**12,990**	**352**

(16.5 h during the winter solstice[16] at mid-Northern latitudes, based on Mars One's stated landing location [8])

- No losses occur in the transmission of electricity through the various pathways within the power system
- In order to minimize power storage requirements, ISRU systems are assumed to only operate during daylight [13]
- The solar array area is sized to support the operation of all differentiating systems (Table 6) during daylight on the shortest expected day (winter solstice) and to charge batteries for continued operation of the non-ISRU systems listed in Table 6 during the night. In this analysis, the following equation is used to determine the power requirement for the solar arrays during daylight (P_{SA}):

$$P_{SA} = \frac{P_D T_D + P_E T_E}{T_D} \tag{7}$$

where P_D and P_E are the power demands during daylight and nighttime (eclipse) respectively, and T_D and T_E are the durations spent in daylight and nighttime respectively. For winter solstice, T_D is taken to be 8.1 h, and T_E is taken to be 16.5 h.

- An insolation value of 588.6 W/m^2 is assumed. This corresponds to the mean solar irradiance in Martian orbit [97]. The effects of atmospheric attenuation, non-zero incidence angles, attenuation due to dust storms, and solar array degradation are ignored in this analysis. The estimated solar array area can therefore be considered to be an optimistic lower bound.
- Thermal management systems are sized only for non-ISRU systems listed in Table 6. These systems correspond to those that are contained within the habitable volume.
- Thermal loads for each system assessed are assumed to equal their corresponding power requirements
- The internal thermal control system is assumed to consist of a combination of a flow loop and cold plates. A mass factor of 25 kg/kW is assumed, based on the values listed in the NASA BVAD [96].
- The external thermal control system is assumed to be lightweight, flow-through radiators with a mass efficiency of 121 kg/kW, based on values listed in the NASA BVAD [96].

Table 7 summarizes the mass of the power and thermal system contributions of the BPS and SF architectures over the predeployment and crewed phases of their missions.

From Table 7, it can be observed that the BPS architecture has a significantly larger power and thermal system mass requirement than the SF. This is driven by a combination of the high power demand of the predeployment phase soil processor, which is driven by the high water demand required to sustain the BPS; and the high power demand of the lighting system required to sustain crop photosynthesis.

Finally, we note that Mars One plans to power their surface habitat with a 3000 m^2 array of thin-film solar panels [1]. Based on the results presented in Table 7, this planned value appears to be insufficient to sustain the combined power demand of the differentiating systems for the BPS case during its crewed phase, even under the optimistic conditions assumed for this analysis.

When accounting for less-than-optimal real-world operating conditions, the required solar array area will increase further beyond the power generation capacity budgeted by Mars One. This suggests that either more power generation capacity is required, and/or changes to the food system architecture are required.

4.2.4. *Comparative assessment of architectural feasibility*

In this section, we present the results of our assessments of the architectural and programmatic feasibility of the two habitation cases described in Sections 4.2.1 and 4.2.2. These assessments were performed by cycling through the simulation environment depicted in Fig. 1 and described throughout Section 3. First, the Habitation and ISRU Sizing modules were used to simulate both architectures and to size their required ISRU systems. From this analysis, it was found that both the BPS and SF habitation cases are architecturally feasible, as they are capable of sustaining a four person crew for the 26-month period between resupply with ISRU systems that are within range of the assumed payload mass limits of the lander vehicles.

Table 8 summarizes the ISRU resource requirements derived by the Habitation module, and the corresponding ISRU system masses determined by the ISRU Sizing module. From this table, we observe that the atmospheric processors required by the BPS and SF cases during the crewed phase are significantly lower in mass than that required by the baseline Mars One architecture analysed in Section 4.1.3. This is because the atmospheric imbalances observed within the baseline architecture are no longer present within the BPS and SF cases.

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[16] Based on dates listed by the Planetary Society [116] and simulated in the Mars 24 Sunclock program developed by the NASA Goddard Institute of Space Studies [117].

Table 8
Summary of ISRU resource requirements and corresponding ISRU system mass for the baseline Mars One habitat and two alternative architectural cases investigated in Section 4.2. BPS: Biomass Production System Architecture and SF: Stored Food Architecture. See Table 5 for a mass breakdown of the Baseline Mars One Atmospheric Processor, and Appendix E for mass breakdowns of the ISRU systems sized for the BPS and SF Cases.

		Baseline Mars One		BPS Case		SF Case	
		Pre-Deploy	Crewed	Pre-Deploy	Crewed	Pre-Deploy	Crewed
ISRU resource requirement	**H_2O [L/d]**	25	5	25	5	6	5
	O_2 [mol/d]	25	27	25	0	25	39
	N_2 [mol/d]	69	795	69	12	69	12
ISRU System Mass [kg]	**Soil processor**	822	292	822	263	326	305
	Atmosphere processor	2,709	31,105	2,709	481	2,709	481

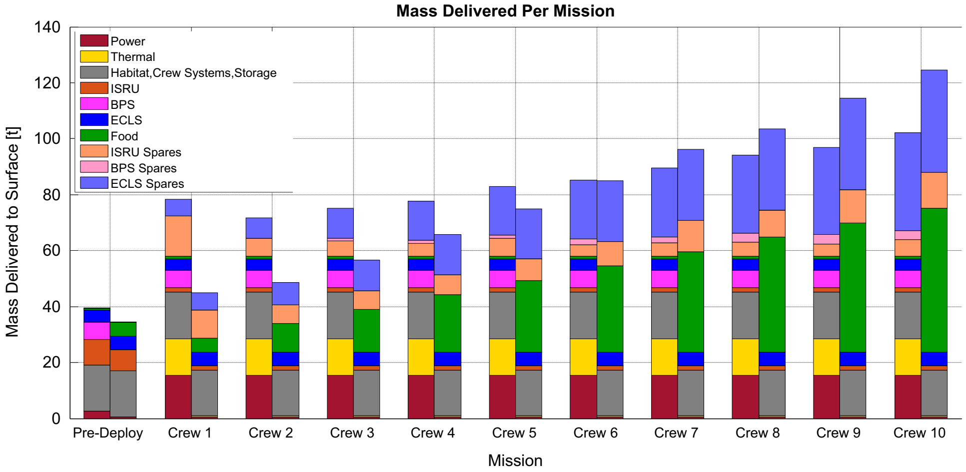

Fig. 17. Mass breakdown of the cargo mass required for the pre-deploy and first 10 crewed missions. The left column of each cluster corresponds to the BPS case, while the right column corresponds to the SF case. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Furthermore, we observe that the BPS case requires a significantly larger soil processor than the SF case during the predeployment phase, due to its need to produce a significantly greater amount of initial water to support crop growth. During the crewed phase however, the BPS architecture has a lower ISRU requirement than the SF case, primarily due to the fact that the O_2 captured by the ORA is sufficient to sustain the crew, thereby eliminating the need for ISRU-generated O_2.

With these results established, the master equipment list (MEL) for the ECLS and ISRU systems for both habitation cases was updated with the required number of spares determined by the Sparing module (see Section 3.3). These results were combined with the power and thermal system mass estimates computed in Section 4.2.3 (see Table 7) and input into the Logistics module (see Section 3.4) to determine the total number of landers and launches required over the lifecycle of each architecture, thus allowing for an assessment of their programmatic feasibility to be performed. The MEL for the BPS and SF cases are presented in Appendix E.

4.2.5. *Comparative assessment of programmatic feasibility*

Fig. 17 shows the distribution of total mass (for the systems described in this paper) that must be delivered to the surface of Mars for the BPS and SF architectures over the first 11 missions, including the predeployment mission. This chart shows the breakdown of mass between the Habitation, Crew and Storage Systems, ECLS, ISRU, and Food systems, as well as the spares required for those systems and the power and thermal systems required to support the differentiating systems between these architectures; thus giving insight into the mass cost of the various elements of the habitat. In this graph, the left bar in each cluster corresponds to the delivered mass requirements of the BPS case, while the right bar of each cluster corresponds to the delivery requirements of the SF case. As discussed in Section 2.2, the mass shown in this figure only includes the mass of components related to ISRU and habitation systems, including the BPS. Therefore, the actual mass requirements will be higher than the amount shown here when all subsystems necessary for a complete mission are included in the analysis.

It is important to note that Fig. 17 is not a plot of cumulative mass, but rather, a plot of mass required per mission. This figure indicates that in both habitation cases, the required mass increases significantly over time as the colony grows.

For the BPS case, the largest driver of this increase in mass over time is the demand for ECLS and ISRU spare parts, calculated using the method described in Section 3.3. Here, we find that the first crew has a larger spares mass requirement than the other crews, since it must initialize the spares stockpile. When the second crew

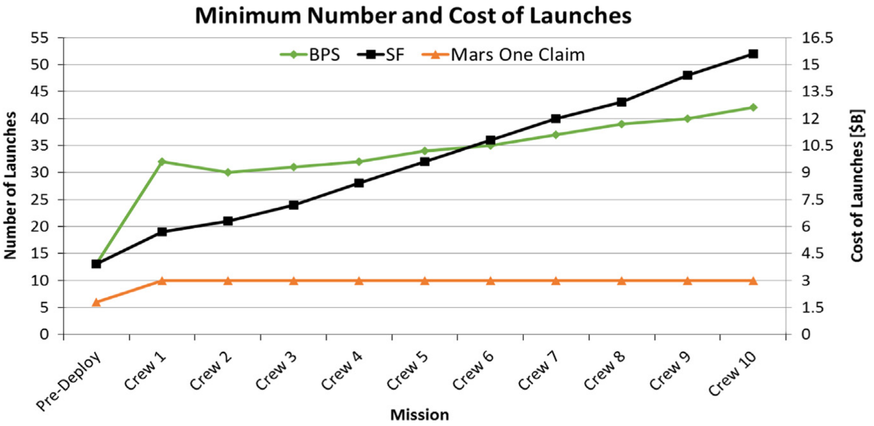

Fig. 18. Minimum number and cost of launches required for the BPS and SF cases, compared to the number of launches estimated for Mars One.

arrives, it must bring enough spares to replenish the stockpile to that same level of confidence for two crews. The third crew must replenish it to the level required for three crews, and so on. As more crews arrive, more Life Support Units are required to sustain them, and therefore more spare parts are required to maintain those Life Support Units. The mass of spares required for the second crew is lower than the mass of spares required for the first due to the large stockpile that was brought by the first crew and the use of commonality between different crews. However, starting with the third crew the effect of increasing demand for spares overwhelms the benefits of commonality between crews. From this point on, the mass of spares required at each resupply opportunity increases over time. By the tenth crewed mission, 44 t of spares are required to support the settlement, compared to the 14 t of spares required at the second crewed mission.

Conversely, for the SF case, we find that the resupply mass growth is driven by a combination of an increasing requirement for food and spare parts. Since no BPS is included, the only food available to the colony is food shipped from Earth. As such, each crew must bring not only enough food to sustain themselves until the next resupply, but also a resupply of food for each crew that is already on the surface. The food resupply requirement grows linearly with the number of crews on the surface.

Contributing to this mass growth is the growing demand for ECLS and ISRU spares at each resupply opportunity, for the same reasons observed in the BPS case. Once again, starting with the third crew, each resupply mission must carry more spares than the mission before it. As a result of the combination of these two growth factors, the resupply mass growth is more rapid in the SF case than in the BPS case.

The fact that both architectural cases experience increasing resupply requirements over time means that the number of required launches grows over time, and hence the operational cost grows over time. This cost growth is particularly evident in Fig. 18, which shows the number and cost of launches required to deliver the manifests predicted for the BPS and SF cases to the Martian surface, as calculated by the Logistics module. In both habitation cases, regardless of their significant differences in food growth strategy, ECLS architecture, and ISRU demands, this cost growth arises from the two defining characteristics of the Mars One plan:

(1) The one-way nature of the Mars One plan means that based on existing capabilities, system reliability, and spaceflight experience, a continual supply of spare parts is required to indefinitely sustain crews on the surface

(2) Mars One's plan to continually increase their Mars surface crew size leads to corresponding increases in resupply requirements. This growth in resupply requirements and hence launch and operations costs will continue as long as the surface crew size grows.

These two characteristics - one-way trips and a continuous buildup of surface infrastructure - are inherent to the Mars One goal and strategy to develop a settlement on Mars while minimizing the development of new technologies. However, this analysis has illuminated the fact that the resupply costs associated with a growing colony on Mars will continue to increase as long as that colony relies on resupply from Earth to maintain critical functions. This continuous growth in cost is programmatically infeasible. Since this cost growth is dominated by the high cost of interplanetary transportation, an appropriate strategy to mitigate this programmatic infeasibility will likely be a balance between aggressive logistics mass reduction strategies and in-situ manufacturing capability. Both of these options will likely require a very significant technology development effort. As a result, we find that the constraints specified by Mars One - specifically, the concept of one-way missions to grow a settlement and the use of only existing technology - do not result in a feasible mission plan. A very significant technology development effort is required to enable the Mars One plan to be architecturally feasible, and an even more significant technology development effort is required to enable programmatic feasibility. *We therefore conclude that the Mars One mission plan is not feasible under the constraints that have been stated publicly and specified by Mars One.*

5. Discussion

In this section, we further explore the architectural and technology development implications of the results derived in Section 4. These are summarized in the following sections.

5.1. Mass growth

A key finding of this analysis is that the amount of mass that must be sent to Mars at each resupply opportunity increases with the number of crews on the surface. As described in Section 4.2.5, this is largely due to the increasing demand for spare parts (see Fig. 17), which cannot be produced on Mars without very significant technology development. Thus, as more and more Life Support Units are put into operation on the surface of Mars, more and more spare parts are required to sustain them. The first crew must bring enough spares to sustain themselves for 26 months. The second crew must bring enough for themselves and the first crew, the third crew must bring enough for themselves, the second crew, and the first crew, and so on. The only system for which spares do not need to be replenished in this way is the pre-deployed ISRU system, which is assumed to be reused every time. In the SF case, the growing mass is exacerbated by the need to resupply food as well.

The use of commonality between crews helps to simplify the system and reduce the number of spares required, since crews can share spare parts. However, to achieve this level of spares requirement, the design of the habitation systems for each crew must be fixed for each crew – the spare parts must remain common. Any equipment updates for future crews that results in non-common spare parts would increase the spares requirement above this baseline. To avoid this, either the new system would need to be designed so that an old system could still accept the new spare parts, or all old habitats on Mars would need to be replaced with new ones in order to maintain commonality. Otherwise the growth in resupply requirements would increase significantly due to a loss of commonality between crews.

The spares mass numbers presented here are an estimate of mass requirements based on the need to provide the same level of assurance to each crew, and could potentially be somewhat reduced by informing spares manifesting based on the performance of the surface systems up until the resupply mission launch date. Due to the long flight times between Earth and Mars, however, it is impossible to manifest resupply missions to only account for failures that have already occurred; resupply requirements will always be a stochastic value and that uncertainty will always drive up the number of spares that need to be manifested to provide confidence in the system.

As more systems are deployed and operated on the surface of Mars, more spares will be required to maintain them. This is true regardless of what level sparing is implemented at – whether at the ORU level utilized on the ISS or the component/subassembly level implemented in this study. The Mars One website notes this challenge, stating that "for a long time, the supply requests from the outpost will be for complex spare parts, which cannot be readily reproduced with the limited technology on Mars" [1]. Without an advanced resource mining, processing, and manufacturing capability on Mars – which would involve both significant technology development efforts as well as (most likely) a very large initial mass transported to Mars from Earth – this demand for spare parts can only be met with supplies from Earth, and indicates that the mass required to resupply the Mars One colony will increase significantly and unsustainably as the colony grows.

3D printing technology, while promising, still requires significant technology development before it can be implemented in a Mars settlement [89]. However, even if 3D printers could be used to manufacture every component in the system the resupply mass would still grow over time due to the need for feedstock material. With significant technology development, this material could be obtained through ISRU processing of Martian soil, or perhaps old parts could be recycled into material for new parts. However, both of these options require significant technology development and validation efforts. Until the entire spare parts supply chain is located on Mars and uses Mars-derived resources – a capability that does not currently exist – the cost of maintaining a growing colony on Mars will continue to increase over time, thereby reaffirming the conclusions made in Section 4.2.5.

5.2. Lifecycle launch requirements

Fig. 18 shows the number of launches estimated by Mars One compared to the required number of launches for the BPS and SF architectures. The Mars One mission plan calls for 6 launches to transport the pre-deployment system to Mars in the first mission, then 10 launches (6 for cargo and 4 for crew transport) at each subsequent launch opportunity [98]. This analysis finds that – even when only considering the mass of the habitation and ISRU systems – Mars One significantly underestimates the number and cost of launches that will be required to place and sustain a colony on Mars.

This is true even for the predeployment missions, where the landed mass requirement for the predeployment mission requires at least 13 launches in both habitation cases - more than double the 6 launches estimated by Mars One. The cost of the 13 pre-deployment launches (estimated at \$300 million per capsule and launch vehicle without adjusting for inflation for future launches - see Section 3.4.1) is approximately \$3.9 billion. As the settlement grows, the mass growth discussed in Section 5.1 causes an increase in the number of launches required at each resupply opportunity. Our analysis finds that for both architecture cases examined, the launch costs associated with the fifth crewed mission are approximately equal to half of the entire NASA FY2015 budget [99] (see Fig. 18). By the tenth mission, the launch cost in the BPS case is approximately \$12.6 billion, and the cumulative cost of launches to grow and sustain the colony is approximately \$109.5 billion. For the SF case, the cost of the tenth mission is approximately \$15.6 billion, and the cumulative launch cost is approximately \$106.8 billion. It is important to emphasize that these estimates account only for the launch costs associated with transporting hardware required for the habitation and

ISRU systems from Earth to Mars. They do not include development costs, nor do they include the costs associated with launching other systems such as communications and surface transportation. The actual number of launches required, and therefore the actual launch costs of the Mars One plan, is higher than the numbers shown here.

5.3. Biomass Production System vs. Stored Food

This analysis examined two options for an architecturally feasible system: one using a Biomass Production System (BPS) for all food production (Section 4.2.1) and one using Stored Food (SF) (Section 4.2.2).

Fig. 19 shows the cumulative mass delivered to the surface of Mars between these two options. Based on these results, it appears that employing a BPS for food production does not to pay off in terms of system mass over the time horizon chosen for this analysis.

The use of a BPS increases the initial mass of the system with the goal of reducing resupply requirements by producing food locally. The power and thermal requirements resulting from the increased infrastructure (GLS, ORA, CO_2 Injector) required to support the BPS, as well as changes in the size of the ISRU systems, results in an increase in the total landed mass requirement when a BPS is used to grow food. In fact, as shown in Fig. 19, the mass of equipment required to support the BPS case remains higher than the mass of spares required for the stored food case, and the gap between the two grows over the first six crewed missions. However, the mass of food required by the growing colony grows at a faster rate, and after the sixth crewed mission, this gap begins to decrease again. Based on the trends observed in Fig. 19, it is expected that a crossover point will occur during the 11th or 12th missions, where the BPS case becomes the lower-mass option.

This result suggests that at least for the first ten crewed missions, it may be more efficient to carry food along rather than grow it in-situ. This finding agrees with those made by other researchers [92].

Further, we note that these two cases represent the two extremes of the food supply spectrum, where either all of the food is produced on-site or none of it is. It is possible that a more optimal architecture could be developed, balancing between food shipped from Earth and food grown on Mars. For example, early crews could supplement their diet with stored food while gradually building up plant growth capability. In addition, a balance could be found that enables the use of plants to grow food without requiring a notional ORA and CO_2 injector system to manage the resulting atmospheric imbalance. The elimination of spares mass for these two technologies may also somewhat reduce the overall resupply requirements.

5.4. Sensitivity to component reliability

The MTBF values used in this analysis are based, to the largest extent possible, on current state of the art ECLS technology with flight heritage on the ISS [5]. It is reasonable to expect, however, that the reliability of these components may increase before the start of the Mars One surface campaign. In order to investigate the potential benefits of more reliable components, the sparing analysis was repeated for an additional case where the MTBF of each individual component was doubled from the baseline value. The results are shown in Fig. 20.

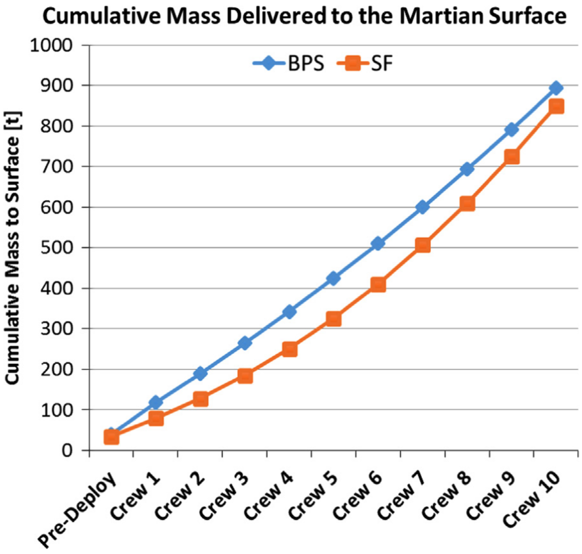

Fig. 19. Cumulative mass of ECLS, ISRU, and their supporting systems delivered to the Martian Surface for the first 10 crews for both the BPS and SF cases.

As expected, increased component reliability reduces the mass of spares required for both architectures. For the BPS case, doubling the MTBF reduces the total mass of spares required for the first crew by 3.7 t. For the SF case, the reduction in spares mass is approximately 2.5 t. The cumulative mass saved over the first 10 crewed missions is 27.5 t for the BPS case and 41.9 t for the stored food case, or about 3.1% and 4.9% from the baseline, respectively. The reduction in mass is slightly higher for the BPS case since the resupply mass is nearly all spare parts. Conversely, in the SF case, there is a fixed resupply mass of food that cannot be reduced through increased reliability.

In both cases, several of the repairable components in the system, particularly filters, have spares demands dominated by scheduled rather than random repairs. Increased component reliability has little impact on the number of spares required for these components.

Thus, while increasing the reliability of individual components can have an impact on the number of spares required, it is a relatively small one. In addition, even at double the current component reliability levels, the resupply requirements still increase with the number of crews on the surface. Consequently, the mass that must be delivered in order to sustain the colony after the first few crews becomes unreasonably high.

5.5. Sensitivity to crew schedule

This analysis assumed an intensive crew schedule that involved each crewmember exercising for two hours a day in addition to the planned EVA schedule of five EVAs per week, each consisting of two crewmembers and lasting 8 h (see Section 3.1.2). Given the increase in ECLS resource demands,

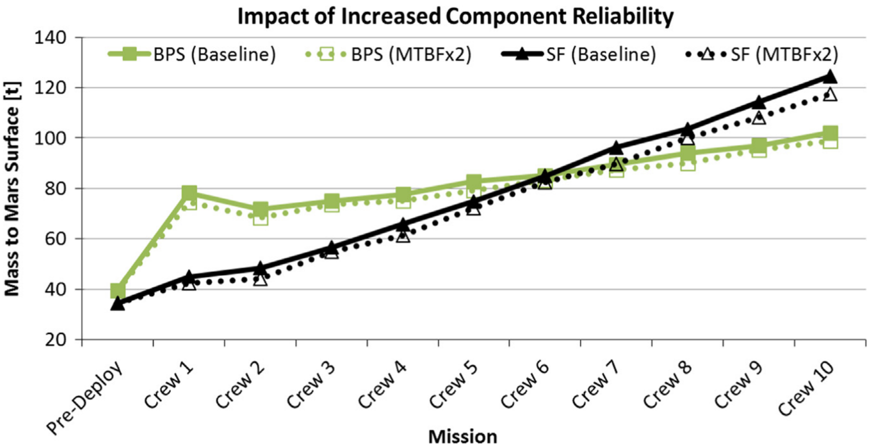

Fig. 20. Impact of increased component MTBF on the mass required for the first 10 crewed missions. The total ECLS/ ISRU/crew systems mass (including spares and resupplied food) is shown for both the BPS and SF case, where the reliability of each individual component is either at the baseline MTBF value (solid line) or double that value (dotted line).

and the energy expenditure required for exercise activities, it may be possible to reduce total system performance and landed mass demands by removing exercise entirely from the crew schedule. To gain insight into the impacts of crew activities on system demands, we first quantify the reduction in caloric demands obtained when the crew maintains their EVA schedule but does not perform any exercise, and investigate the effect of this caloric saving on the SF and BPS architectures. Here, we maintain the existing aggressive EVA schedule in order to support Mars One's objectives of rapid expansion of their surface base through the frequent integration of new systems and modules to their surface habitat [7].

A simulation of this modified crew schedule found that without exercise, the average caloric requirement reduces from 3040 to 2940 kcal per crewperson per day, equating to a reduction of 3.3% - a value that is within the variation between individual dietary needs and day to day caloric intake. This indicates that the caloric requirements of the crew are dominated by the large energy expenditure needed to support the heavy EVA schedule. As a result, changes in the crew exercise schedule are not expected to have a major impact on the total landed-mass requirements.

To further explore this, we propagate this caloric difference into the system designs for the SF and BPS cases. For the SF architecture, we expect that this 100 kcal per person per day difference can easily be accommodated by sending more calorically dense food. Moreover, since the ECLS systems are based on ISS technologies that are sized for more than four people, we expect minimal changes to the mass of the systems delivered. The major mass saving resulting from the removal of exercise from the crew's schedule for the SF case is expected to come from the exercise equipment itself. The total mass of all exercise equipment assumed to be delivered with every crewed mission is estimated to be 1343 kg, based on the mass of current ISS hardware (see Appendix E). This value is approximately equivalent to half the payload mass of a Mars One lander, and equates to a mass saving of 3.9% for the first predeployment mission. Over time, as the demand for resupply increases with the increasing crew, this mass saving has a diminishing effect. By the tenth crew, the removal of crew exercise from the SF case results in a mass saving of only 1.1% from the total delivered mass.

For the BPS case, caloric savings can lead to reductions in BPS requirements, which can result in greater mass savings in supporting systems. Using the same weighting values as Option 4 in Table 3, the plant growth area optimizer (see Section 3.1.8.1) found that a 2940 kcal diet could be supported by 193 m^2 of crops – 8 m^2 less than the 201 m^2. This equates to a reduction in predeployment water demand of 360 L[17] which leads to a predeployment soil processor system and power mass saving of 270 kg[18]. Moreover, the reduction in plant growth area leads to a reduction in lighting demands to 132 grow lights[19], which equates to a combined lighting, power, and thermal mass saving of 1,244 kg[20]. This relatively large mass saving is the result of significant mass factors that arise from the large power storage and thermal control mass required to manage each watt of solar power generated on the surface of Mars. Table 9 summarizes the total mass savings obtained for the BPS case.

Aside from the exercise equipment itself, no other systems are expected to be significantly affected by removing exercise activities from the BPS case. This is because during the crewed phase, N_2 demand (and hence the size of the atmospheric processor) is driven by the leakage rate of the habitat, and the ISRU demand for O_2 is zero, due to the presence of the ORA. Moreover, as was discussed with the SF case, the ISS-based ECLS technologies adopted here are oversized for sustaining a four person crew, and are hence not expected to be affected by minor reductions in crew activity.

Thus, the combined mass savings obtained from eliminating exercise from the BPS case are expected to be approximately 2590 kg during the crewed phase – a value that is a little greater than the payload capacity of a single lander. For the first crewed mission, this equates to a mass

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[17] See Section 3.1.8.4 for calculation assumptions.

[18] As predicted by the ISRU Sizing module

[19] Based on the analysis approach described in Section 3.1.8.3.

[20] See Section 4.2.3 for calculation assumptions.

Table 9
System level impacts of removing exercise from the crew schedule for the BPS architecture.

System	Mass for baseline schedule (kg)	Mass for exercise-free schedule (kg)	Mass saving (kg)
Predeployment phase			
Predeployment soil processor	822	719	102
Predeployment soil processor solar array	666	622	44
Predeployment soil processor batteries	1857	1733	124
Crewed phase			
Grow lights[a]	1096	1056	40
Grow light solar array[a]	8130	7790	340
Grow light batteries[a]	7340	7029	311
Grow light internal thermal control[a]	2225	2130	95
Grow light external thermal control[a]	10,766	10,308	458
Exercise equipment	1343	0	1343

[a] Includes power and thermal demands of all non-ISRU systems listed in Table 6

Table 10
Summary of findings from the analysis iterations performed in Section 4, resulting recommendations, and key sections in this paper describing these results in greater detail.

Analysis Iteration	Finding	Recommendation	Section
1	Mars One claims that their plan utilizes only "existing, validated, and available technology," [1] but many of the technologies described in the mission plan are either nonexistent or at very low levels of technology readiness.	Eliminate the assumption that the Mars One plan can be executed with existing technology, carry out technology development and validation efforts required to produce the technology described in the mission plan, and update mission cost and schedule estimates to account for this technology development and validation effort.	4.1.1, 2.3
2	The 50 m^2 crop growth area described in the Mars One mission plan[a] is too small to provide sufficient food for a single crew of four, much less three crews of four as described by Mars One [11]	Increase the crop growth area to the 201 m^2 required to provide enough food to support a crew of four, or use stored food to supply crew nutritional needs.	4.1.2, 3.1.8.1, 5.3
3	If the crop growth area is increased to the level required to provide enough food for the crew, atmospheric processing imbalances result in a buildup of excess oxygen in the atmosphere, leading to a fire risk state that requires a peak N_2 rate of approximately 795 moles per day to manage. To generate this level of N_2 under Mars One's ISRU strategy, a prohibitively large atmospheric processor system weighing an estimated 31,105 kg is required	Modify the system architecture. Potential solutions include: (1) moving the BPS into its own atmospheric chamber to enable the separate control of atmospheres for the crew and crops to their preferred respiration rates, and developing and validating technology that selectively removes oxygen from the atmosphere; or (2) using stored food to supply crew nutritional needs.	4.1.3, 4.2.4
4	Even when only considering the mass of habitation and ISRU equipment, the number (and therefore cost) of launches required to land the required systems on the Martian surface is significantly higher than that estimated in the Mars One plan [100].	Increase the estimated number of launches to a value that is capable of transporting all required equipment to Mars and update mission cost estimates to reflect this increase.	4.2.5, 5.2
	The amount of spare parts required to sustain a growing colony increases as more and more crews are landed on Mars. By the launch of the fifth crew, the cost of the required launches of a portion of all equipment and spares needed is estimated to be approximately equal to half of the entire NASA FY2015 budget [99]. Without the capability to implement a full supply chain on Mars – a capability that does not currently exist – the cost of resupply missions grows unsustainably over time.	Develop and validate technology to mine, process, and refine raw manufacturing materials from Martian sources, develop and validate 3D printing technology to the level required to produce all spare parts and components from local resources in order to support the growing colony with an entirely Martian supply chain, improve reliability and life limits of mission hardware, and update mission cost and schedule estimates to account for this technology development and validation effort.	4.2.5, 5.1, 5.2

[a] We note that since this analysis was performed, Mars One has increased their planned crop growth area [11] from 50 m^2 to 80 m^2. Since this value is still significantly lower than the growth areas derived here, this update does not affect the conclusions of our analysis.

saving of 6.5%, and by the tenth mission, the effect of this saving reduces to 2.5% due to the increasing demand for spare parts resupply.

Therefore, we find that while removing exercise from the crew schedule can lead to reductions in resupply mass by values up to 2590 kg, these savings are minor compared to the total mass of equipment needed to be delivered to the Martian surface at each launch opportunity.

5.6. *Other systems*

It is important to reiterate that the mass breakdown presented in this analysis includes only the habitation and ISRU systems. Several key systems, including the ground transportation and communications systems, were beyond the scope of this analysis and would need to be investigated to provide a holistic estimate for the cost of the Mars One program. As a result, the anticipated mass of a

Martian settlement is expected to be larger than the estimates presented here. Therefore, the number of launches as well as the cost of those launches will also be higher than the numbers shown here.

6. Conclusions

In this paper, we investigate the technical feasibility of the Mars One mission plan, focusing primarily on aspects related to ECLS and ISRU systems, their spare parts requirements, a portion of their power and thermal management demands, and the logistics supply chain required to deliver and deploy these on the Martian surface. We perform this investigation using an iterative analysis approach in which we model and simulate the Mars One mission plan to assess its architectural and programmatic feasibility, implement any necessary corrective changes to the architecture, and restart the iterative design process with the updated architecture.

On several occasions throughout this analysis process, we find that the Mars One mission plan, as described on the Mars One website and in other sources, is infeasible. This conclusion primarily arises from the claim that “each stage of the Mars One mission plan employs existing, validated and available technology” [1], and the fact that Mars One plans to establish a growing colony on Mars – one that will incur a corresponding growing resupply requirement.

These conclusions are drawn from Section 4, where a series of analysis iterations were performed to assess the feasibility of the Mars One mission plan under various architectural assumptions. In each case, either architectural and/or programmatic infeasibilities were found, and corresponding recommendations were made. Table 10 summarizes these results.

While the problems described in Table 10 are by no means insurmountable, their solution requires a change in the assumptions behind the Mars One plan – specifically, the acceptance of the need for significant technology development, and the corresponding change in timeline and funding requirements for the project.

This analysis identifies specific areas in which technology development could have a significant positive impact on the mission in order to inform investment and guide technology development efforts.

In addition, the spare parts analysis revealed that the mass of spare parts that must be resupplied at each interval increases as the colony grows – after ten crews arrive at Mars, spare parts comprise almost half of the mass transported to the Martian surface in the BPS case.

This finding indicates that the development of technology to enable spare parts manufacturing on Mars, such as 3D printing, has the potential to provide massive benefits. These benefits increase dramatically if local Martian resources, such as aluminum and silicon, can be used to manufacture spare parts on the surface of Mars.

Moreover, we reiterate the fact that this analysis focused primarily on the habitation, life support, ISRU, sparing, and space logistics aspects of the Mars One mission plan. These comprise only a subset of all of the subsystems required for a complete systems analysis. Thus, while our findings reveal a number of areas of infeasibility in the Mars One mission plan, there are several other areas unexplored in this analysis that should be investigated.

In conclusion, this analysis finds that the assumptions made by Mars One do not lead to a feasible mission plan. We suggest modifications to those assumptions that would move the mission plan closer to feasibility. The largest of these is the need for technology development, which will have to focus on improving the reliability of ECLS systems, the TRL of ISRU systems, the capability of Mars in-situ manufacturing, and launch costs. Improving these factors will help to dramatically reduce the mass and cost of Mars mission architectures, thus bringing closer the goal of one day sustainably settling the red planet.

Acknowledgements

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Appendix

See Table A1–D1.

Table A1
Habitation module assumptions.

Parameter	Value	Reference/comments
Time horizon (mission duration)	26 months (19,000 h)	This corresponds to the period between launch windows to Mars from Earth – that is, the period between resource and hardware resupply opportunities. This is the minimum continuous period over which the habitat must be self-sufficient.
Number of crew	4	Specified by Mars One [1]
Habitat atmosphere	70.3 kPa, 26.5% O_2 Diluent gas: N_2	Mars One states that the habitat atmosphere will be 0.7 bar [14]. The equivalent atmosphere studied by the NASA Exploration

Table A1 (*continued*)

Parameter	Value	Reference/comments
		Atmospheres Working Group (EAWG) is a 26.5% O_2 mixture. This corresponds to the Space Shuttle atmosphere employed prior to and during extravehicular activity (EVA) operations [17]
Habitat volume	6x scaled up Dragon capsules (each 25 m^3) and 2x Inflatable modules (each 500 m^3)	See Section 3.4 for a discussion on the assumed SpaceX Dragon modules volume. The inflatable module is specified on the Mars One website [101]
Habitat leakage rate	0.05% lost by mass per day	Value taken from Table 4.1.1 of BVAD [5]
ECLS architecture	Based on that of the International Space Station	Explicit claim made by Mars One regarding the life support unit: *"This system will be very similar to those units which are fully functional on-board the International Space Station."* [13]
Food system	Entirely locally grown	The Mars One foundation plans for 50 m^2 dedicated to plant growth. Moreover, they claim that this: *“will be sufficient plant production capacity to feed about three crews of four”* [11]
EVA frequency	5 EVAs/week, 2 crewmembers per EVA, 8 h per EVA	Although not explicitly specified, the description on the Mars One website [102] implies that EVAs will occur frequently. The NASA Baseline Values and Assumptions (BVAD) document [5] suggests a nominal EVA duration of 8 hours and a maximum EVA frequency of 5 two-person EVAs per week [5]
Spacesuit pressure	29.6 kPa (4.3 psi), at 100% O_2	EAWG recommended suit pressure for EVAs requiring dexterous tasks. This suit pressure also limits the O_2 in-suit prebreathe time from the 70.3 kPa habitat atmosphere to about 40 minutes [17]
Spacesuit Portable Life Support System (PLSS)	NASA PLSS2.0 Architecture	Currently in development, the PLSS2.0 architecture is the current the state of the art in spacesuit life support systems [32]. Unlike the spacesuits currently used on the International Space Station, the PLSS2.0 is capable of supporting a crewmember on the Martian surface.
Spacesuit Urine Management	Urine Collection and Transfer Assembly (UCTA)	Astronauts currently performing EVA from the ISS wear Maximum Absorbency Garments (MAGs) to collect their urine. These are then discarded at the end of the EVA. The large number of EVAs anticipated for Mars One means that choosing to discard urine expelled during EVA can become a major source of water loss to the system over time. To overcome this, we have assumed an Apollo like system, where urine is collected in a bag attached to the astronaut’s thigh [103]. The collected urine can then be emptied back into the habitat’s urine processor for water recovery.
Airlock cycle losses	Equivalent to 13.8 kPa within an assumed 3.7 m^3 airlock	The discussion in Ref. [35] implies that airlocks will be used rather than other means of habitat entry (such as suitports). Here we assume an airlock volume of 3.7 m^3, which corresponds to the minimum volume that can accommodate 2 crewmembers at a time [5]. The equivalent gas loss at 13.8 kPa corresponds to the minimum pressure that the current ISS Quest Airlock depressurization pump can be operated down to [104]
Potable water tanks	2 × 1500 L capacity tanks	Mars One states that 3000 L of water will be produced and stored locally prior to the arrival of the first crew [14]. This water will act as contingency water to sustain the crew in the event that the ISRU system goes offline. Water usage is budgeted for 50 L per person per day [11]
Oxygen tanks	120 kg capacity	Mars One states that 120 kg of oxygen will be produced and stored locally prior to the arrival of the first crew [14]
Nitrogen tanks	292 kg capacity	Corresponds to the amount of nitrogen required to mix with 120 kg of O_2 to produce a 26.5% O_2 (molar percentage) atmosphere

Table B1
Assumed ECLS Technologies employed within the Mars One habitat.

ECLS function	ECLS Technology	Corresponding ISS USOS Technology	Location of technology on ISS
Gas storage	High pressure tanks	High pressure N_2 and O_2 tanks	Installed on the exterior of the Quest airlock [73]
O_2 generation	Solid polymer water electrolysis	Oxygen Generation Assembly (OGA)	Installed in the Oxygen Generation System (OGS) rack in Node 3 [105]
CO_2 removal	Molecular sieve (Zeolite5A)	Carbon Dioxide Removal Assembly (CDRA)	One is installed in the Air Revitalization (AR) rack within Node 3, and another is installed in the AR rack in the Destiny Laboratory [106]
CO_2 reduction	Sabatier reactor	CO_2 Reduction Assembly (CRA)	

Table B1 (*continued*)

			Installed in the Oxygen Generation System (OGS) rack in Node 3 [106]
Humidity control	Condensing heat exchanger	Common Cabin Air Assembly (CCAA)	Located in all USOS modules except for Node 1 and the PMM [107]
Water storage	Bellows Tanks and Soft Containers	WPA Product Water Tank and Contingency Water Containers (CWCs)	Located throughout the ISS [108]
Water processing	Vapor compression distillation and multifiltration	Urine Processor Assembly (UPA) and Water Processor Assembly (WPA)	Installed in the Water Recovery System (WRS) Racks 1 and 2 in Node 3 [106]
Waste processing	Water recovered from urine via VCD. Faeces and brine disposed in logistics resupply vehicles	Advanced Recycle Filter Tank Assembly (ARFTA) collects brine and sends it to Rodnik tanks on the Progress vehicle, or one of the water tanks on ATV. Faeces is collected in a waste canister and disposed of in one of the resupply vehicles	One of the several logistics resupply vehicles that visit the ISS [109]

Table C1
Heuristics used for ECLS Technology location allocation.

Mars One Habitation module	Life support functions supported by habitation module	Analogous ISS module	Comments
Inflatable	Main living area of the habitat. Supports recreation and houses food production units (See Fig. 5) [37]	Node 3 and Destiny Laboratory	The exercise equipment on the ISS USOS is distributed across the Destiny Laboratory and Node 3
Living unit	Contains airlock and habitat "'wet areas', such as the shower and kitchen" [10]	Quest Airlock and Node 3	Node 3 contains the Waste and Hygiene Compartment [110], while the Quest airlock serves all airlock functions on the U.S. Segment
Life support unit	Contains ECLS and ISRU technologies, as well as solar arrays [13]	Node 3	The majority of ECLSS technologies are located within Node 3 [110]
Cargo/supply unit	Storage volume for hardware, spare parts and consumables [70]	Permanent Multipurpose Module (PMM)	The PMM was added to the ISS primarily to increase on-orbit storage volume [111]

Table D1
Crop static parameters.

Crop	Carbohydrate fraction of dry mass (c)[a]	Protein fraction of dry mass (p)i	Fat fraction of dry mass (f)i	Average growth rate (g/m^2/day) (r)[b]	Time to crop maturity (days)[c]	Mature plant height (m)[c]
Dry (kidney) bean	0.711	0.279	0.010	9.064	63	0.5
Lettuce	0.655	0.311	0.034	7.433	30	0.25
Peanut	0.173	0.286	0.542	4.131	110	0.65
Rice	0.919	0.075	0.006	11.86	88	0.8
Soybean	0.348	0.421	0.230	6.867	86	0.55
Sweet Potato	0.925	0.072	0.002	18.29	120	0.65
Tomato	0.783	0.177	0.040	6.609	80	0.4
Wheat	0.866	0.112	0.023	26.74	62	0.5
White Potato	0.898	0.096	0.006	16.82	138	0.65

[a] Data obtained from the United States Department of Agriculture National Nutrient Database for Standard Reference – Release 27. Available at: http://ndb.nal.usda.gov/ndb/, Accessed: August 30th 2014.

[b] Determined through simulation of the Modified Energy Cascade crop models under nominal conditions.

[c] Data obtained from the NASA Baseline Values and Assumptions Document NASA CR-2004-208941.

Appendix E. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.actaastro.2015.11.025.

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