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Analogs as a research platform: Systems-based optimization approach to facility selection

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Abstract

NASA's Artemis program and Moon to Mars objectives target development of a sustained human presence on the Moon. This drives the need for understanding what technologies and procedures are critical for long-duration surface habitation, in both a lunar and Martian environment. Earth-based analogs provide the ability to test mission components in comparable environments. However, there are a limited number of analog facilities, each with high-fidelity approximations of different features of the target environment. The limited availability of analog spots and associated high costs of testing make efficient use of analogs as a research platform critical to provide useful data for space exploration. Here, we present a review of analog platforms with a focus on surface analog facilities. We propose a framework to evaluate the merit and need for testing a given experiment in different analog facilities. Multiple criteria decision analysis techniques utilizing analytic hierarchy process calculations are used to evaluate the compatibility of each analog facility's level of feature approximation with a given experiment or mission profile. 24 simulation features such as terrain, isolation, mission control, and available technology are used to evaluate facility approximation and analog needs of researchers. The experimental value, or merit, of a given experiment is quantified according to NASA's targeted knowledge gaps as ranked in the Science Technology Mission Directorate's shortfall list and the Human Research Program risk assessment, and the proposed technology/human readiness level increase resulting from the experiment. This selection methodology framework quantifies the merit of conducting a given experiment in various analog environments. It enables analog selection by researchers to target the best possible facility for their work, and enhances the ability of facilitators to select experiments that utilize the unique capabilities of their analog. The efficient use of analog resources via optimized experiment and facility selection will enable improved and rapid advancements to the technologies deemed most critical to test prior to in-situ integration.

Keywords: analog experiments, space systems, field tests, system optimization, space exploration

Introduction

The field of human space exploration has changed drastically in the last decade. Commercial operation successes, NASA's Artemis missions, and new milestones met by international space agencies all continue to accelerate the advancement of exploration science capabilities [1]. The resulting accelerations in deployment timelines drive a growing need for rapid technology development. Commercial spaceflight alone has seen considerable expansion, with a 157% increase in the number of space companies established between 2011 and 2016 [2]. Each new product or technology requires testing to meet safety standards. In NASA's Technology Readiness Level (TRL) system, this typically requires a technology demonstration in a spaceflight-relevant environment prior to launch [3]. The need for testing extends beyond technology to integrated mission architecture decisions, too; with the development of high-capacity launch vehicles like the SpaceX Starship, larger mission architecture options are becoming feasible [4,5]. These options require additional testing to reach the same mission readiness as historical mission architectures [6].

Mission concepts and technologies are typically tested in analogs prior to implementation as a full exploration mission

[7]. With new mission architecture options becoming not only feasible, but desirable, there is a notable need for testing different mission sizes in analog facilities. Analog missions provide an avenue to test these architectures and technologies in relevant environments and mission scenarios, to enable rapid iteration without the cost and risk levels of spaceflight [8]. There are several different types of analog platforms available for experiments that must be carefully selected based on desired level of fidelity in the experiment. This work will focus on surface field analogs used in the vast majority of analog experiments. There are several analog facilities that provide different levels of fidelity for different mission features. Attempts have been made to quantify the overall fidelity of analog facilities [9]; however, this work is largely unfinished and does not account for differing analog feature requirements in experiments. Additionally, it does not accommodate experiments that may be able to effectively utilize varying degrees of fidelity in analog testing [5].

Research opportunities using analog platforms are constrained by facility availability, with inherent limits on the number of analog missions that can occur at each facility in a given time frame. Analog facilities are used both for space tourism and as a research platform [10], which further constrains the availability of analog research opportunities. With the growing need for rapid space technology development and limited analog testing opportunities, there is a need for a systematic approach to optimize experiment-facility matching for research output.

In this work we review analog platforms, highlighting how surface field analogs fit into the roadmap of technology and procedure implementation for spaceflight. We present a facility and experiment selection framework for analog research using a nested analytic hierarchy process (AHP) model and research priority alignment calculations. AHP is widely used as a multiple criteria decision analysis technique that weighs multiple inputs according to their importance to optimize decision making [11-13]. The nested AHP model takes user inputs on analog feature priorities and compares against a compiled list of analogs and their features, to return a ranked list of facilities that provide the best fit for an experiment's requirements. The research priority alignment calculations consider an experiment's projected TRL or human readiness level (HRL) increase from the proposed analog test, and the importance of the research area as assigned by NASA's Space Technology Mission Directorate (STMD) Shortfall List [14] and Human Research Program (HRP) risks [15]. This outputs a mission or experiment value parameter, which quantifies the value to NASA and other stakeholders of conducting the experiment in analog. This framework is designed for use by two key stakeholders: analog facilities for selection of experiments and missions that will most benefit from the available features, and researchers looking to conduct impactful analog testing. Implementing this framework enables the effective use of analogs as research platforms to support the expansion of the space exploration ecosystem.

Review of analog platforms

NASA's Human Research Program defines 5 major risk categories of human spaceflight. These include exposure to space radiation, altered gravity fields, isolation and confinement, closed or hostile environments, and distance from Earth [16]. There is a need to simulate these categories for experiments and countermeasure development, to address critical knowledge gaps on Earth prior to spaceflight. Different simulation methods achieve different fidelity levels of feature approximation. The fidelity progression and limitations of radiation and reduced gravity simulations are established in the literature [17,18]. Here, we review the analog platforms that are available to address these risk categories. The fidelity progression for the remaining 3 risk categories is less clear, because each facility prioritizes different features. This paper then seeks to establish a systems-based approach to identifying the experiment-specific fidelity progression, as discussed in later sections.

Radiation simulation methods

The radiation environment in spaceflight depends on location relative to radiation sources like the Sun, as well as proximity to planetary bodies that cause fluctuating radiation properties, such as the Earth and its magnetic field [19–21]. Many computational models exist to simulate radiation impacts on materials [22–25]. Experimental Earth-based simulations rely on testing in radiation beams, which have varying particle compositions and energies that simulate the space environment to different levels of fidelity [26,27]. The highest-fidelity platforms are galactic cosmic radiation beams including the NASA Space Radiation Laboratory and the GSI accelerator run in partnership with the ESA [28,29].

Reduced gravity simulation methods

The mechanism, benefits, and drawbacks of each simulation method have been extensively reviewed [30,31]. A summary is provided of each method below.

Cell and tissue models

Clinostats simulate microgravity by rotating a sample around one or more axes. Continuous rotation eliminates unidirectional effects of gravity on a sample by averaging the gravity vector over the direction of the rotation [32]. Cells are forced to move in circular paths during rotation; the diameters of the paths decrease with increasing rotation speed [33,34]. Simulated microgravity occurs when the relative motion of the cell is only around itself, with no movement relative to the Earth gravity vector. There are multiple types of clinostats that are used for different applications. Those that rotate around one axis are called 2-D clinostats, while those with a second rotation axis are 3-D clinostats. A random positioning machine (RPM) is a 3-D clinostat with independently rotating frames that randomly vary the speed and direction of rotation of each axis [35,36]. The rotation rate of a clinostat or RPM determines the fidelity of microgravity simulation for a given experiment, and has been studied across different experiment

types [37]. When known, rotation speeds of a clinostat or RPM should be defined according to the speed of the process sensing gravity in the proposed experiment to isolate effects of microgravity from confounding factors. However, this is often not known and can only be confirmed on investigation in true microgravity, highlighting use of these platforms as research tools to progress towards in-space experimentation [37].

Rotating wall vessels (RWV) were developed by NASA as a platform to simulate growth conditions expected in spaceflight by maintaining cells in suspension during culture [38–41]. This is accomplished through use of a cylindrical culture vessel that rotates horizontally, with a coaxial oxygenator [42]. RWVs are designed to maintain laminar flow, avoiding shear stresses associated with turbulent flow. By matching the rotation speeds of the inner and outer cylinders, the radial velocity gradient of the laminar fluid flow is minimized and the associated shear stress can be eliminated. Additionally, the rotation acts to mix the culture medium and avoids the need for stirring mechanisms [43]. The RWV has been widely used in cell culture experiments to investigate microgravity effects [44–46].

Diamagnetic levitation uses a strong, spatially varying magnetic field and the diamagnetic properties of live tissue to counteract the effects of gravity and induce levitation. It has been demonstrated in cell culture as well as live animals, including mice [47–50]. Diamagnetic levitation has been used as a microgravity simulation method due to its ability to create a net force which balances the gravitational force, establishing a "no mechanical support" state similar to that experienced in spaceflight. However, the addition of a strong magnetic field can itself be the dominant factor driving physiological changes in an experiment, rather than the microgravity state [51].

Animal models

Ground-based studies of animals in microgravity are widely used to investigate physiologic changes [52]. Hindlimb unloading typically involves suspension of a rodent model at a head-down tilt using tail traction, surgical pins, or a body harness, such that the head is at an angle of approximately 30 degrees. This analog induces a cephalad fluid shift mimicking that which is experienced by humans in microgravity. Additionally, it provides a high level of microgravity feature approximation for reduced activity levels and load levels on the hind limbs by removing the ground reaction forces [53–55].

Some microgravity simulation methods discussed in other sections can also be used for small animal models. For example, diamagnetic levitation has been demonstrated with several small animals, as mentioned above. Variations of the RWV are also used for amphibian or aquatic animal models. Additionally, clinostats or RPMs can be modified to house small animals for several days of continuous microgravity exposure [56]. Notably, there are no microgravity simulations in use for large animal models, despite the prevalence of swine studies in terrestrial clinical applications.

Human subject models

Microgravity simulation platforms for human subjects rely on changing the effects of the gravity vector on the body. Horizontal bed rest (HBR) and head-down tilt (HDT) accomplish this through removal of the positional changes associated with typical biphasic sleep-wake cycles on Earth. When upright, the body is under a uniform 1g gravitational force along the longitudinal axis, from head to toe. When horizontal such as during sleep, the net gravitational force along that same axis is approximately zero. Spaceflight-induced disruptions to human physiology are at least in part due to the continued absence of a gravitational force along the longitudinal axis. For example, cephalad fluid redistribution in the body is driven by the absence of a 1g directional force, which induces significant physiologic changes [57–60]. HBR is a microgravity analog that reduces the participant's time in 1g upright position, instead placing a participant in a horizontal state. HDT further approximates the cephalad fluid shifts experienced in spaceflight by placing participants at head-down angles of 4º to 15+ º, with most studies using angle of 6º to result in approximately -0.1g [61,62]. These studies range in duration and can persist for several months. HBR and HDT methods typically allow short intervals of partially or completely upright posture for eating or showering, and may include exercise countermeasure experiments with different positional requirements. These periods of partially upright posture, even from changing the head-down tilt angle from use of a pillow, have been shown to affect the fidelity of the analog by reducing the magnitude of cephalad fluid shift [63].

Other human subject analogs for microgravity use the buoyancy of water to counteract the gravitational force. Wet immersion is used for short-duration studies in which the participant is submerged from the neck down in a seated or standing position. This relies on external hydrostatic pressure to counteract the intravascular gradients in hydrostatic pressure typically driven by gravity [61,62,64]. However, the external hydrostatic pressure of the water induces a negative pressure breathing paradigm, limiting its use in certain respiratory experiments [65]. The use of wet immersion is limited to experiments of less than 72 hours, to prevent onset of skin-based clinical symptoms associated with prolonged submersion [66]. Dry immersion relies on similar principles but allows for long-term experiments by submerging participants from the neck down in a waterproof covering, bypassing prolonged contact between the skin and water [67,68].

Additional simulation methods exist to simulate aspects of microgravity for specific experiment types. For example, lower-extremity limb suspension isolates the effects of musculoskeletal deconditioning through single-leg elevation in a crutch and platform shoe setup [69]. NASA's Neutral Buoyancy Laboratory is another analog that uses the buoyancy of water to create a simulated microgravity

environment, in which procedures and operations can be tested [70,71].

Flight test platforms

Flight test platforms include Earth-based analogs, suborbital flight, and orbital flight opportunities. Earth-based analogs, including drop towers and parabolic flight, provide single or repeated intervals of microgravity simulation of up to 30 seconds [72]. Suborbital flights, like those offered commercially by NASA-contracted flight providers including Blue Origin's New Shepherd and Virgin Galactic's VSS Unity, provide approximately 3 minutes of microgravity [73]. Experiments with targeted microgravity exposure exceeding these time frames reach the highest fidelity microgravity conditions via orbital platforms. Orbital flight experiments to the ISS or commercial research platforms provide microgravity exposure ranging from several days to over one year, as determined by the mission timeline [74].

Isolation and confinement, closed environment, and distance from Earth simulation methods

These spaceflight risks are typically represented using isolated and confined environments, including polar research stations and designated Moon or Mars analog facilities. These facilities are the focus of this paper; the available platforms, their features, and the fidelity of those features are discussed in detail in the Facility Feature Approximation Definition section.

Analog research roadmap

Experiment development for analog testing requires careful design to align the goals of the experiment with a test platform's simulation features. There are many available simulation methods; method selection is determined by the aspects of spaceflight that are relevant for a specific experiment, and at what fidelity the test needs to be conducted. Targeted analog features in early-stage analogs must also be carefully selected to make the greatest use of a series of analog experiments, such that the experiment does not require redesign of critical components for testing in higher-fidelity systems as the technology or operation progresses towards in-space implementation. Figure 1 depicts the general fidelity progression of analog platforms.

Materials and methods

We define two models that together describe the merit of testing an experiment in a given analog facility. The nested AHP model, with framework shown in Figure 2, evaluates the "best fit" facilities for an experiment's feature fidelity requirements. The research priority alignment model quantifies the experiment's merit with regards to NASA's published research targets. This framework is shown in Figure 3.

Nested AHP model

AHP is a widely used optimization method; a detailed description of the underlying theory with sample calculations can be found in [11–13]. This method requires pairwise comparisons to assign a relative importance to a set of decision criteria, which are then applied to the possible outcomes. We apply a nested AHP approach that allows consideration of category- and subcategory-level features with independent assigned weights, and integrates a desired or not desired feature option to indicate the direction of preference of a given feature. Figure 2 summarizes this model.

Facility feature approximation definition

Analog facilities approximate the features of a space exploration mission to varying degrees of fidelity. To evaluate the fit of a given experiment for analog testing, we first define the features and their approximation across facilities.

Analog features are divided into five categories:

- Exploration Conditions, including precipitation, temperature variation, dust, terrain features, and gravity simulation;
- Field Science, including geomorphology, geochemistry, and exobiology;
- Human Science, including population, psychology, and crew size;
- Isolation and Risk, including the distance to and complexity of reaching medical care, and the mission failure consequences;
- Reliance on Technology, including extravehicular activity (EVA) suits and procedures, life support, and mission control.

The categories and lists of analog features are meant to be a general aggregation of common requirements for experiments looking to simulate the conditions of microgravity, the Moon, or Mars. The list includes 24 features and is made intentionally general to suit a wide range of experiments and missions. Additional categories and items may be added to better represent conditions that must be met in analog missions.

Tables 1, 2, 3, 4, and 5 provide a complete list of the facility feature approximation inputs used in the model for the analog facilities considered. These inputs include a mix of quantitative values and qualitative rankings to evaluate a facility's approximation of a given feature for lunar and/or Martian relevance. Quantitative values are calculated for precipitation, temperature, and dust features [75,76]. Qualitative features are assigned a quantitative high, medium, or low value (H/M/L or H/M/L/N corresponding to a score of 3-1 or 4-1, respectively). Note that this is not intended as a comprehensive list of analog facilities; these include some of the most commonly used analogs, considering only analogs with set facility locations because so many of the features are location-dependent. New and other existing facilities can be added to the list and used in this framework in the future.

Quantitative values are used where available. Qualitative rankings are evaluated relative to the feature approximation available at the other analog facilities. For example, control of gravity environment (Table 1) is defined as N for standard 1g operations, L-M for facilities that provide 1 or more alternate gravity environments, and H for the ability to simulate

multiple relevant gravity conditions. It is assumed that experiments with a need for altered gravity environments in an analog facility have operational time frames which exceed those available in parabolic flight, or are otherwise unsuitable for testing in higher-fidelity simulations of altered gravity. Terrain features refer to EVA conditions surrounding the facility, and are classified as N when the analog is indoor-only or does not offer EVA opportunities. Slope variance refers to the amount that the terrain varies within the EVA range of a facility, with a higher ranking indicating more uneven terrain and lower rankings indicating a smooth surface or constant slope. Unknown terrain refers to the degree to which the surrounding area has been mapped; for example, facilities like Asclepios which occur in frequently visited areas score lower than the polar stations, which have access to relatively unexplored regions, mimicking the lack of ground-truth terrain information in space exploration. Limited mobility is ranked highest when considering facilities that have caves or tight passes which restrict ability to maneuver with bulky EVA equipment. Limited comms refers to the frequency with which those on EVA are expected to encounter communication outages or delays, either with each other or with mission control; this can be due to terrain features or intentional simulation. Limited visibility is scored higher in cave-like terrain and lower in flat open areas, to evaluate line of sight between EVA sites. Restricted access refers to ease of accessing EVA sites, and can be scored higher due to the presence of narrow caves, tight passes, or sites that require climbing. Surface diversity indicates the breadth of field conditions which can be represented at the facility. Distance to Medical Care is classified such that L < 25km, M = 25-200km, and H > 200km to the nearest hospital or emergency room. Complexity is defined based on the steps needed to reach the nearest hospital or emergency room; for example, polar stations have complicated procedures for medical evacuations compared to facilities that can be reached by car. EVA Procedures are evaluated based on quantity and fidelity of features including suit functionality, EVA simulations such as habitat egress protocols, and approvals or standard operating procedures.

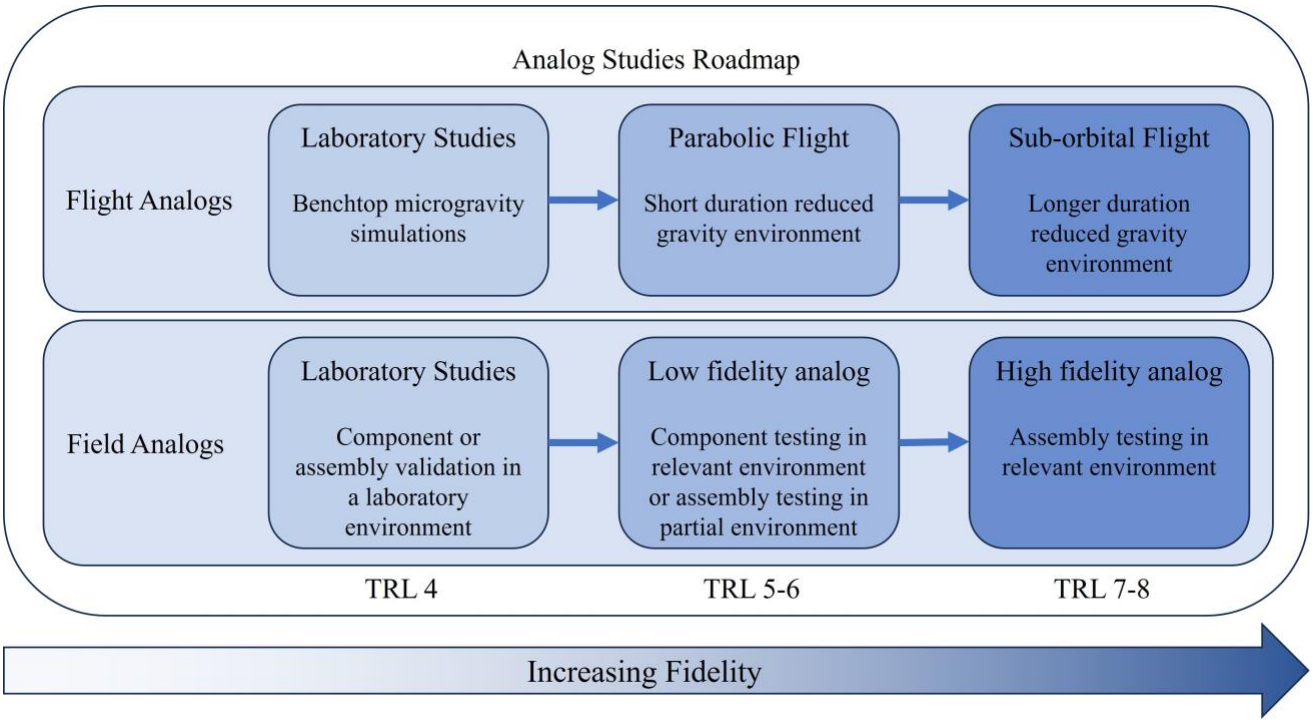

Figure 1. Analog experiment roadmap.

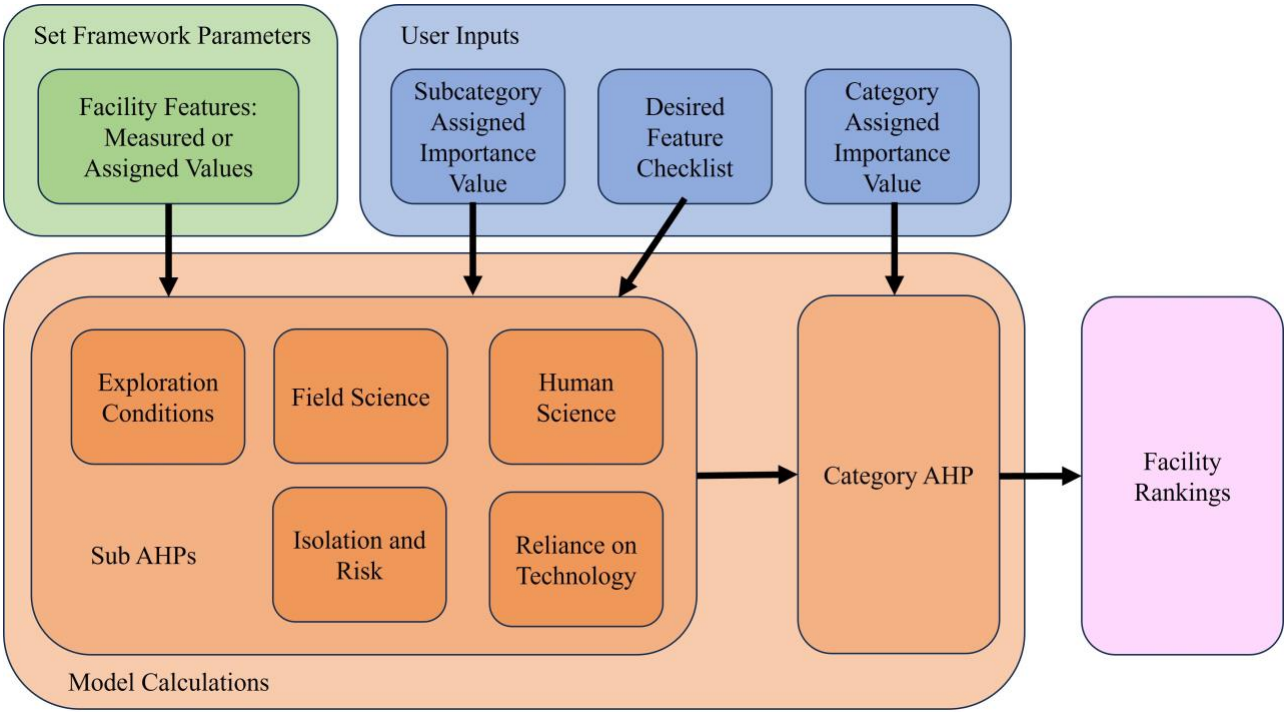

Figure 2. Experiment and facility matching model layout.

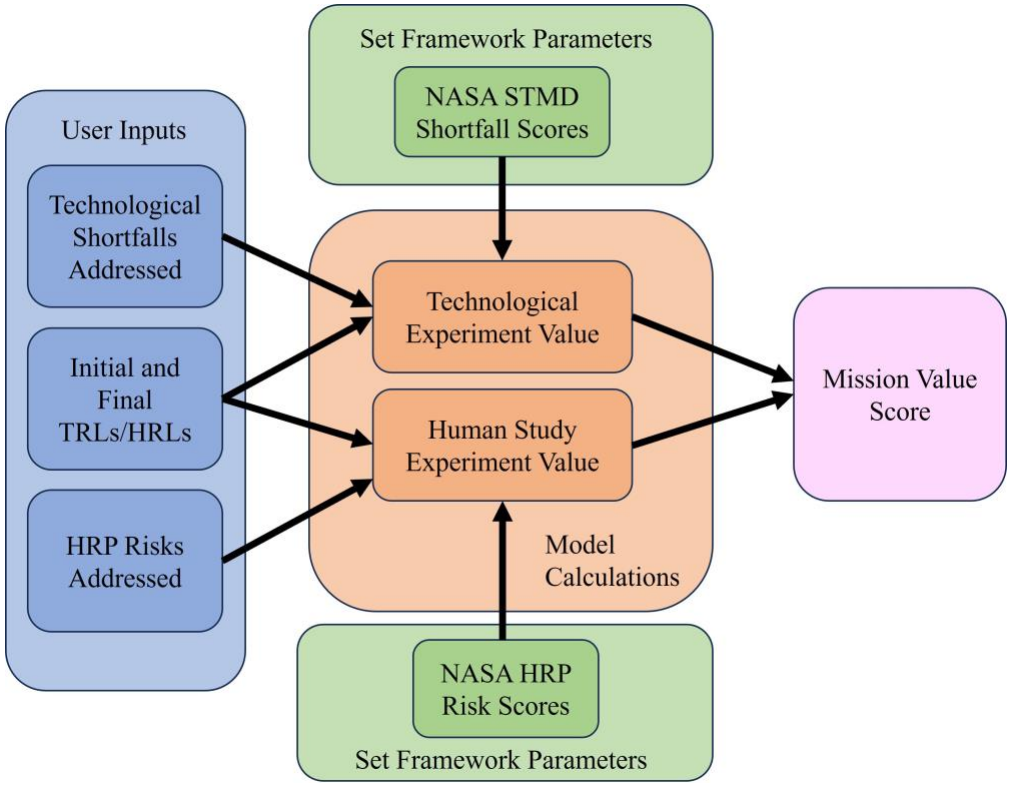

Figure 3. Experiment value score model layout.

Table 1. Exploration conditions.

Facility	Precipitation (mm/day)	Temperature Variation (°C)		Dust (SDS Annual Index)	Terrain Features (H/M/L/N)							Control of Gravity Environment (H/M/L/N)
		Diurnal	Seasonal		Slope Variance	Unknown Terrain	Limited Mobility	Limited Comms	Limited Visibility	Restricted Access	Surface Diversity	
AATC Habitat 1.0 [77,78]	0.5	0.5	0.5	0.05	N	N	N	N	N	N	N	N
Amundsen–Scott South Pole Station [79,80]	2.36	5.77	10.37	0.05	M	M	L	L	M	L	M	N
Aquarius (NEEMO) [81,82]	0.5	0.5	0.5	0.05	N	N	N	N	N	N	L	M
Asclepios [83,84]	0.5	0.5	0.5	0.05	H	L	M	L	L	M	M	N
CHAPEA [85,86	0.5	0.5	0.5	0.05	N	N	N	N	N	N	N	N
Concordia [87,88]	0.342	11.13	11.31	0.05	M	H	M	M	M	M	M	N
Devon Island: FMARS [89-93]	0.36	6.5	11.65	0.05	M	M	M	L	L	M	M	N
Devon Island: HMP [89-93]	0.36	6.5	11.65	0.05	M	M	M	L	L	M	M	N
CHILL-ICE [94,95]	0.5	0.5	0.5	0.05	L	H	H	M	H	H	L	N
Habitat Marte [96,97]	2.11	9.31	1.22	0.05	M	M	L	M	L	L	L	N
HERA [98,99]	0.5	0.5	0.5	0.05	N	N	N	N	N	N	N	N
HESTIA [100,101]	0.5	0.5	0.5	0.05	N	N	N	N	N	N	N	N
Hi-SEAS [102-105]	6.77	6.56	2.03	0.41	H	H	H	L	H	H	M	N
ILMAH [106,107]	1.36	12.5	11.74	0.28	L	N	N	N	N	N	N	N
LunAres [108,109]	1.51	7.81	6.23	0.08	N	L	N	N	N	N	N	N
MDRS [110-112]	0.58	16.06	7.85	0.73	M	L	M	M	L	L	H	N
McMurdo [113-115]	0.55	7.22	7.11	0.05	M	H	M	M	L	L	M	N
Palmer [116-119]	1.35	4.51	2.31	0.05	M	M	L	L	L	L	M	N
SAM Biosphere 2 [120,121]	1.10	16.19	6.5	0.05	L	L	M	L	N	M	M	H

Table 2. Field science (H/M/L).

Facility	Geomorphology	Geochemistry	Exobiology
AATC Habitat 1.0 [77,78]	L	L	L
Amundsen–Scott South Pole Station [79,80]	H	M	H
Aquarius (NEEMO) [81,82]	M	M	H
Asclepios [83,84]	M	L	M
CHAPEA [85,86]	L	L	L
Concordia [87,88]	H	M	H
Devon Island: FMARS [89-93]	H	H	H
Devon Island: HMP [89-93]	H	H	H
CHILL-ICE [94,95]	H	L	M
Habitat Marte [96,97]	L	M	M
HERA [98,99]	L	L	L
HESTIA [100,101]	L	L	L
Hi-SEAS [102-105]	H	H	H
ILMAH [106,107]	L	L	L
LunAres [108,109]	L	L	L
MDRS [110-112]	H	H	H
McMurdo [113-115]	H	H	H
Palmer [116-119]	H	H	H
SAM Biosphere 2 [120,121]	H	M	L

Table 3. Human science (H/M/L).

Facility	Population	Psychology	Crew Size
AATC Habitat 1.0 [77,78]	L	H	M
Amundsen–Scott South Pole Station [79,80]	H	H	H
Aquarius (NEEMO) [81,82]	H	M	L
Asclepios [83,84]	L	L	M
CHAPEA [85,86]	H	H	L
Concordia [87,88]	H	H	H
Devon Island: FMARS [89-93]	H	M	M
Devon Island: HMP [89-93]	H	L	H
CHILL-ICE [94,95]	L	M	M
Habitat Marte [96,97]	L	L	M
HERA [98,99]	H	H	L
HESTIA [100,101]	H	H	L
Hi-SEAS [102-105]	M	M	M
ILMAH [106,107]	L	M	L
LunAres [108,109]	L	M	M
MDRS [110-112]	M	M	M
McMurdo [113-115]	H	H	H
Palmer [116-119]	H	H	H
SAM Biosphere 2 [120,121]	L	H	M

Table 4. Isolation and risk (H/M/L).

Facility	Distance to Medical Care	Complexity to Reach Care	Risk Consequence
AATC Habitat 1.0 [77,78]	L	L	L
Amundsen–Scott South Pole Station [79,80]	H	H	H
Aquarius (NEEMO) [81,82]	L	H	H
Asclepios [83,84]	M	M	M
CHAPEA [85,86]	L	L	L
Concordia [87,88]	H	H	H
Devon Island: FMARS [89-93]	M	H	H
Devon Island: HMP [89-93]	M	H	H
CHILL-ICE [94,95]	M	M	M
Habitat Marte [96,97]	M	L	M
HERA [98,99]	L	L	L
HESTIA [100,101]	L	L	L
Hi-SEAS [102-105]	M	H	M
ILMAH [106,107]	L	L	L
LunAres [108,109]	L	L	L
MDRS [110-112]	M	M	M
McMurdo [113-115]	H	H	H
Palmer [116-119]	H	H	H
SAM Biosphere 2 [120,121]	M	L	L

Table 5. Reliance on technology (H/M/L).

Facility	EVA Procedures	Mission Control	Life Support
AATC Habitat 1.0 [77,78]	L	H	M
Amundsen–Scott South Pole Station [79,80]	L	L	H
Aquarius (NEEMO) [81,82]	H	M	H
Asclepios [83,84]	M	H	L
CHAPEA [85,86]	H	H	L
Concordia [87,88]	H	L	H
Devon Island: FMARS [89-93]	M	M	L
Devon Island: HMP [89-93]	L	L	M
CHILL-ICE [94,95]	M	M	L
Habitat Marte [96,97]	L	L	L
HERA [98,99]	L	H	H
HESTIA [100,101]	L	H	H
Hi-SEAS [102-105]	M	M	L
ILMAH [106,107]	M	M	L
LunAres [108,109]	M	M	L
MDRS [110-112]	M	M	L
McMurdo [113-115]	L	L	H
Palmer [116-119]	L	L	H
SAM Biosphere 2 [120,121]	H	M	M

Assigned importance value (AIV)

In our model, the user inputs a positive number to assign a relative importance for their planned experiment to each analog feature (subcategory AIV) and each of five categories (category AIV). This assigned prioritization is then input into the following pairwise comparison matrix:

$$\boldsymbol{w_{sub}} = \begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \cdots & \frac{w_2}{w_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & \frac{w_n}{w_n} \end{bmatrix} \quad (1)$$

This lets us calculate a consistent weight scale by finding the principal eigenvector of the matrix w and normalizing the result [122]:

$$\boldsymbol{W} = \begin{bmatrix} W_{1,1} & W_{1,2} & \cdots & W_{1,n} \\ W_{2,1} & W_{2,2} & \cdots & W_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ W_{n,1} & W_{n,2} & \cdots & W_{n,n} \end{bmatrix} \quad (2)$$

where

$$W_{1,1} = \frac{\frac{w_1}{w_1}}{\frac{w_1}{w_1} + \frac{w_2}{w_1} + \cdots + \frac{w_n}{w_1}} \quad (3)$$

The final weight factor σ of each feature is calculated by averaging across each row in matrix W such that:

$$\sigma_1 = \bar{W}_{1,1:n} \quad (4)$$

Using this method, the average of row 1 will give the weight factor to be applied to the feature assigned the importance value w_1. This process is repeated to give calculated weight factors for both the subcategory (σ_{sub}) and category (σ_{cat}) AHPs.

Nested AHP design

Values for each feature are compiled as described in the Facility Feature Approximation section. This results in a matrix $\boldsymbol{A_{sub}}$ following the form described by Equation 1 where feature values are used in place of assigned importance values. The facility's unweighted score for a given feature, a, then follows Equation 4 such that the average across the row is taken, giving:

$$\alpha_1 = \bar{A}_{1,1:n} \quad (5)$$

The weighted score S_n is then calculated for each feature by multiplying the resultant $\boldsymbol{a}$ vector by the scalar σ_n:

$$S_n = \boldsymbol{\alpha} \cdot \sigma_n = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_n \end{bmatrix} \cdot \sigma_n \quad (6)$$

where each row in $\boldsymbol{a}$ represents a different facility. This process is repeated across each feature, producing a matrix **S** of weighted scores for all features (columns) and facilities (rows). The final ranking is calculated by summing across each row, giving a numerical score of facility fit for a given experiment's subcategory feature needs.

Our model uses a hierarchical, or nested, AHP approach in which the category and subcategory AIVs are considered independent [123]. Facility features are broken into five subcategories: Exploration Conditions, Field Science, Human Science, Isolation and Risk, and Reliance on Technology. The weight scale and AHP process is applied within the subcategory, producing five **S** matrices. These subcategory AHP results from the start values for the final, category AHP calculations, where values of S are used in establishing the pairwise matrix $\boldsymbol{A_{cat}}$. User inputs for category AIVs form the weight pairwise matrix $\boldsymbol{w_{cat}}$. The final facility rank R is given by repeating the AHP calculation following Equations 1-6 with the corresponding Category AHP inputs in Table 6, such that:

$$R = \boldsymbol{A_{cat}} \cdot \boldsymbol{\sigma_{cat}} \quad (7)$$

The final ranking produces a numerical score of each facility's fit for a given experiment.

As each subcategory contains different numbers of features, there is the potential for one set of features to outweigh the others in a final ranking. The nested structure intends to reduce this effect. Specifically, the Exploration Conditions subcategory (Table 1) contains 12 features, while other subcategories each contain 3 features. Reducing the number of features in the Exploration Conditions subcategory is one option to mitigate this disparity; however, the model is intended to be broad and adaptable to possible needs of a range of missions, which benefit from a variety of different Exploration Conditions. If all 24 features were directly compared in a single AHP, the effects of prioritizing an individual feature like crew size would be much smaller than in the nested AHP structure, because it would be evaluated as 1/24th of the final ranking as opposed to 1/15th (1/3rd of the ranking in the subcategory AHP, then 1/5th in the category AHP). With the nested AHP, user input (the category AIV) determines the weighting of category. This allows tailored adjustments to the model's sensitivity to represent different mission needs through the nested AHP design.

AHP also assumes that the criteria included in the analysis are independent. Some of the criteria in the subcategory AHPs are linked; for example, a location's terrain will dictate multiple of the exploration conditions. This is mitigated by the nested AHP structure, such that each of the subcategory AHPs are independent of each other.

Desired feature selection

A feature can be considered good or bad for a given experiment, depending on the experiment's goals, or the level of fidelity required. For example, the Restricted Access field condition would be desired for an analog investigating lava tube or cave exploration, but not for one studying surface

mobility with large vehicles. By including the option to designate a feature as "Desired" or "Not Desired", we enable flexibility and fine-tuning to a range of possible analog experiments. This turns the unweighted score a of a facility's feature into a vector $\boldsymbol{a}$, with the "Not Desired" features assigned a negative sign for that facility's strength of approximation of the feature.

A condition of the pairwise comparison method is that the inputs must be positive and nonzero for calculation of matrix A (following the form of Equation 1); as such, the negative is not applied to the feature's value until the individual elements are used in the calculation of a (Equation 5). This ensures that the sum taken for the calculation of $\boldsymbol{a}$ includes whether the preference is for or against a given feature.

While the assigned importance value enables a user to set the intensity with which a feature is needed, desired feature selection defines that feature's utility according to the way that the facility approximation table was initially set up. Several features do not have the option to designate as "Not Desired", including the Field Science features, Psychology, Distance to Medical Facility, and Complexity to Reach Healthcare. This is intentional because if an experiment does not rely on one of these features, the assigned importance value can simply be set to 1; the success of an analog experiment is not likely to depend on finding a facility that is specifically a poor geomorphology analog to Mars, for example.

Research priority alignment

While it is important to ensure that the experiment and facility are complementary to ensure optimal scientific output, it is also critical to determine the value of conducting the experiment. This will allow facilities and researchers to select projects with the greatest impact. The value of a given experiment can be determined by the importance of the technology or operational concept being tested, and the degree to which the experiment develops the technology or operational concept itself. The model layout for determining the value of an experiment is shown in Figure 3.

Experiments completed in analog facilities can be broadly categorized as either technological demonstrations or human studies. The value of addressing specific technological developments can be quantified using the NASA Space Technology Mission Directorate (STMD) Shortfall List [14]. This report is a collection of technological shortfalls and scores that assign an importance value (I) to each shortfall being addressed. The scoring is an average of the assigned IVs based on input from NASA and external stakeholders from government, industry, academia, etc. on a scale of 0 to 9. The value of conducting human studies can be quantified using the values assigned to risk levels to humans in space based on their likelihood and consequence using NASA's Space Operations Mission Directorate (SOMD) Human Research Program (HRP) risk data, ranging from 1 to 25 [15]. Table 7 demonstrates the risk scores given a likelihood and consequence of a risk occurring. The value of addressing a specific risk will be assigned by the starting value of the risk score measured by likelihood and consequence, denoted L_xC. The calculated I for human studies using the risk score, denoted I_H, (max. 25) is then linearly scaled down to match the 0 to 9 STMD short-fall scale using Equation 8 such that they can be justly compared when determining merit of experiments.

$$I_H = LxC_{scaled} = \frac{(LxC - 1) \times 9}{24} \tag{8}$$

As space technologies develop, the broader holistic gaps identified in the STMD shortfall and HRP risk assessments will need to be continually refined. New research priorities and gaps will be identified with more narrower specifications to target specific mission objectives. This has been demonstrated in early 2025 through a working group involving more NASA mission directorates including STMD, SOMD, The Science Mission Directorate (SMD), and The Exploration Systems Development Mission Directorate (EDSMD). This group identified a need to continually update the needs and gave explicit examples for Moon to Mars objectives. The group demonstrated an example related to specific Moon to Mars objectives related to the broader category of foundational exploration and its key functions [125]. The group began to identify metrics for evaluating the merit of technology and procedural developments through performance and capability improvements. As these more specified evaluations are finalized and publicized, these can be added to the research priority model to identify the most up

Table 6. Nested AHP terminology.

Subcategory AHPs		Category AHP	
$\boldsymbol{w_{sub}}$	Pairwise matrix: subcategory AIV	$\boldsymbol{w_{cat}}$	Pairwise matrix: category AIV
$\boldsymbol{\sigma_{sub}}$	Weight factor matrix	$\boldsymbol{\sigma_{cat}}$	Weight factor matrix
$\boldsymbol{A_{sub}}$	Pairwise matrix: unweighted feature values	$\boldsymbol{A_{cat}}$	Pairwise matrix: subcategory AHP results
$\boldsymbol{S}$	Subcategory AHP results	$\boldsymbol{R}$	Final "best fit" ranking

Table 7. HRP risk scores [124].

Likelihood						
	5	10	16	20	23	25
	4	7	13	18	22	24
	3	4	9	15	19	21
	2	2	6	11	14	17
	1	1	3	5	8	12
		1	2	3	4	5
		Consequence				

Table 8. Development scoring values.

TRL/HRL Start	TRL/HRL End	Development score
3	4	1
4	5	2
3	5	3
5	6	4
4	6	6
3	6	7

to date research gaps. This group also notably identified gaps in technologies that would have the highest impact on progressing science goals that were previously undervalued or ignored for future space development.

The degree to which the experiment addresses a technology or operational concept can be quantified by the TRL increase achieved with the analog study. For human-centered studies, the analogous HRL increase is used [126]. This TRL or HRL increase will be referred to as the development score (D). Analog studies focus on readiness levels in the range of 3-6 which will be evaluated for this framework. The assigned development scores for increasing the readiness level from 3 to 4, 4 to 5, and 5 to 6, are 1, 2, and 4, respectively. These values were assigned to obtain a relative scale of the value of achieving increased readiness levels. These values are set such that prototype system demonstration in a relevant environment is 2 times as important as component testing in a relevant environment which is 2 times as important as component testing in the laboratory environments. This leads to prototype testing in analogs to be 4 times as important as lab-based studies. This is more reasonable than the 9 times it would be had an individual readiness level increase led to 3 times more importance. There is currently a gap in the field in terms of accurate quantification of merit between TRLs. The method used in this framework can be updated as required to better fit field standards. If multiple readiness levels are covered under the experiment, the sum of the assigned scores for each readiness level increase is the total development score. The development score assigned to each readiness level improvement is shown in Table 8. The total score for an experiment value (E) is the product of the importance and technological development scores, shown in Equation 9.

$$E = I * D \tag{9}$$

A single shortfall or risk should be selected that best suits the experiment, even though one experiment may address multiple risks. It is expected that mission plans will consist of several experiments. In this case, the total score of the mission value (M) is the sum of products of the importance values (I) and development scores (D), across human experiments defined using risk likelihood and consequence and technological experiments that address shortfall gaps defined by the STMD shortfall list. As the value for the human and technological experiments are derived from two different quantitative metrics, scaling them to be of equal magnitude allows for the summation of value. This summation of value for human centered and technologically centered experiments is shown in Equation 10.

$$M = \sum E_{Human} + \sum E_{Tech} \tag{10}$$

Results

The model has distinct two outputs. The first is a relative ranking of the suitability of each facility for a given experiment. The final output value for each facility from the AHP calculation has no absolute meaning, and is not the score of a facility's value. It is a relative comparison to rank the options, in this case facilities, against each other for a specific set of inputs, in this case an experimental design. The higher scoring facilities are therefore better fits for the experiment given the user inputs for required experimental conditions.

It is important to note that there are other factors that exist in selecting an analog facility including cost, availability, etc. that will affect the final decision for where to conduct the experiment. The top ranked facility is not necessarily the one that should always be selected, even if it is the best experimental fit.

The second model output is an experimental value score based on quantified needs in the field and the prospective development of the technology or operational concept. This is directly tied to the value of the experiment itself and its proposed outcomes. The output for experimental value will range between 0-63, where values close to 0 are not experiments of merit and values closer to 63 indicate experiments of exceptional merit and quality.

The utility of the facility selection model is not limited to a specific type of experiment. A wide range of facilities and features were included in the creation of this framework. Some general examples of the types of experiment-facility pairs for which our model matches well with the expected result include:

- Experiments involving students (particularly minors) may prioritize a low-risk environment that does not require an astronaut-like population. Best fit facilities include AATC, Habitat Marte, ILMAH, and Asclepios.
- Missions solely targeting in-habitat operations with no EVA will best match with NASA isolated and confined environment facilities, and AATC.
- Tests that care about field operations in altered gravity conditions result in high rankings for SAM Biosphere 2 or NEEMO.
- Experiments that prioritize field testing and require specific environmental features will match with the facilities that best demonstrate those features, as shown in the two case studies.

There is consistently good agreement between the expectations based on knowledge of the facilities and the model output. Therefore the model can be used in cases where the optimal facility is not as clear, as shown previously in balancing psychosocial and field science inputs.

Case study: Emergency medical procedures analog experiment

The following case study is set to demonstrate the capabilities and sensitivities of the model. In this case study we consider a test where it is desired to evaluate the emergency medical evacuation and treatment procedures of new medical technologies to be used on EVA for lunar and Martian exploration. Analog testing will allow new technologist to be tested in more realistic situations than those of a laboratory or company workspace. These analog testing facilities may also provide some of the supporting infrastructure needed for specific tests that may not be developed by the researcher themselves. The hypothetical medical procedure that is considered here is a medical evacuation of an incapacitated astronaut on EVA including transport to the habitat, and treatment of their injuries. For this hypothetical experiment it is desired that the facility selected possesses certain specific features that will be most critical to accurately represent in order to accurately and reliably test new technologies.

In terms of the categories identified in the model it will be most critical for the exploration conditions, human science aspects, and facility technological support to accurately simulate the conditions that will be present on the Moon or Mars. For emergency evacuation scenarios it is desired that the outdoor environmental conditions, represented by the exploration conditions category, are accurately simulated to ensure the difficulties associated with evacuations are tested. Features within this category that are rated with higher importance are rough terrain, limited communications and mobility, and the ability to conduct tests in reduced gravity environments. These will provide a more realistic experience for the analog astronauts testing novel rescue equipment. Considering human science aspects, it is highly desired that an astronaut-like population of varying crew sizes will be testing this equipment. Medical evacuation and treatment can include complex procedures that may not be accurately tested with analog astronauts that do not represent the typical astronaut-like population that will be using the tested technology in the future. Larger crew sizes are desired to be tested as specified medical technologies may be more common in later missions to the Moon and Mars where crew sizes could increase. Lastly, the technical support provided by the analog facility will be important for accurately testing new medical procedures. The ability to test new equipment with EVA suits in a realistic habitat environment with mission control support infrastructure will largely affect the ability to represent medical procedures. The categories and features described above are ranked highest in the user inputs section of the model as shown in Figure 4.

A category of secondary importance is isolation and risk. In general for this case study it would be beneficial to balance the need to conduct tests in a more representative isolated environment, which is typically associated with higher risk, with the desire to test novel medical procedures and technologies, which is also risky and will require access to emergency services in case of experimental complications. This level of risk will also dictate some psychological effects of those involved in the experiment. This will be especially important for tests with an astronaut-like population that is typically accustomed to higher levels of risk.

The field science category and its subsequent features are not highly rated as field science procedures and supporting technologies are not a focus of this proposed study.

Based on the used inputs the relative fit scores are calculated for each facility. The output of the facility selection optimization model indicates the best fit facilities for the described experiment as seen in Figure 5. It is calculated that the best fit facilities are the polar research stations and SAM Biosphere 2. Intuitively this resembles what users would typically expect. These facilities possess several supporting resources for analog experiments in high fidelity

Category	Assigned Importance Value
Exploration Conditions	5
Field Science	1
Human Science	5
Isolation and Risk	3
Reliance on Technology	5

Category	Feature	Desired Feature ?	Assigned Importance Value	Adjusted Importance Value
Exploration Conditions	Precipitation	☐	1	-1
	Diurnal Temperature Variation	☑	2	2
	Seasonal Temperature Variation	☐	1	-1
	Dust	☐	1	-1
	Terrain Slope Variation	☑	2	2
	Unknown Terrain	☑	2	2
	Limited Mobility	☑	3	3
	Limited Comms	☑	3	3
	Limited Visibility	☑	1	1
	Restricted Access	☑	2	2
	Geologic Diversity	☑	1	1
	Gravity	☑	3	3
Field Science	Geomorphology	N/A	1	1
	Geochemistry	N/A	1	1
	Exobiology	N/A	1	1
Human Science	Astronaut-Like Population	☑	5	5
	Psychology	N/A	1	1
	Large Crew Size	☑	3	3
Isolation and Risk	Distance to Medical Facility	N/A	3	3
	Complexity to Reach Healthcare	N/A	2	2
	Risk Environment	☑	2	2
Reliance on Technology	EVA Suits / Procedure	☑	5	5
	Mission Control	☑	4	4
	Life Support	☑	5	5

Figure 4. Medical experiment case study inputs.

environments. These facilities have the capabilities to allow highly qualified personnel the opportunity to test novel medical procedures and technologies in a representative environment.

A brief qualitative sensitivity assessment of the model demonstrates the changes to the output results based on user inputs. If a very similar model is considered with the only change being the desire to have students, a non-astronaut-like population, testing medical equipment and procedures in a low risk environment a change in optimal facilities can be seen. The input parameters that are changed in this case are the desire to have an astronaut population and a high-risk environment. The categorical inputs and other feature inputs remain the same. It can be calculated that the polar research facilities fall out of favor compared to facilities that are typically used by students including Habitat Marte, Chill Ice, and Asclepios. Concordia and SAM Biosphere 2 are the two facilities that appear in each output case evaluated here. This indicates that regardless of the population, these facilities would be well suited for medical analogs that rely heavily on a representative environment and support structure for the experiment. This analysis also demonstrates that if certain components of an experiment are not known in advance, for example the personnel that will be conducting the experiment, facilities can be identified that will cover the needs of an experiment in the event of future decisions. This can help researchers to create resilient research plans that are flexible to change. Appendix A demonstrates the inputs and outputs of the model using this example.

Facility	Score
AATC Habitat 1.0	0.79
Amundsen–Scott South Pole Station	1.29
Aquarius (NEEMO)	1.24
Asclepios	1.05
CHAPEA	1.00
Concordia	1.64
Devon Island: FMARS	1.30
Devon Island: HMP	1.21
CHILL-ICE	1.13
Habitat Marte	1.00
HERA	0.98
HESTIA	0.98
Hi-SEAS	1.17
ILMAH	0.78
LunAres	0.80
MDRS	1.27
McMurdo	1.47
Palmer	1.38
SAM Biosphere 2	1.48

Figure 5. Medical experiment case study outputs.

The experimental value of the proposed case study would depend on the exact technology or health concern addressed in the experiment. For a technology development case, consider the testing of a new device that will be used to transport an injured astronaut out on EVA back to the habitat to begin treatment. This would address the 30th most important STMD shortfall gap "Crew Medical Care for Mars and Sustained Lunar Advanced Habitation" which has an importance score of 6.56924, as evaluated by the space technology community. Assuming that this technology had not been previously tested, the TRL would go from a 3 to a 6 upon successful completion. This would result in an experimental value of 45.99.

If we instead consider a human risk experiment that involves the development of a novel procedure being tested to reduce human risk in the field on EVA, an alternative experimental score can be calculated. This experiment would address the HRP risk "Risk of Injury and Compromised Performance Due to EVA Operations" which is quantified as a 5x4 (likelihood x consequence) risk for Lunar and Martian planetary operations. If the HRL of this methodology is assumed to be a 3 prior to analog testing, successful completion of this experiment would result in an HRL of 6 and an overall experimental score of 57.75. These scores can be used to identify exactly which experiments should be conducted over the course of the analog campaign depending on available resources, with higher experimental scores indicating greater impact.

Discussion and conclusions

This paper presents a framework to optimize the scientific output of analog experiments, in a model which identifies optimal analog facilities for a specific experiment given a weighted selection of required analog features to achieve the proposed scientific goals [127]. The facility rankings are completed using nested analytic hierarchy process calculations to quantify the relative compatibility of experiments and facilities. The second model quantifies the value of a given experiment based on NASA's STMD shortfall or HRP data and the proposed TRL or HRL advancement resulting from the analog. The types of expected outcomes from the model are discussed for a range of general experiments and highlighted with a case study. This model can be used by researchers proposing experiments to identify the optimal location for their study, and by facilitators that are looking to maximize the scientific outcome of their resources. Utilizing the limited time and resources of high-fidelity analogs more efficiently will be critical for developing technologies and operations for future space exploration. This model provides a systematic approach to optimizing test facility utilization for scientific output across analog fidelity levels, filling a gap in space analog mission design [9,10].

The facility selection framework relies on AHP to quantify the best-fit test platform. AHP is a widely implemented decision optimization tool with some known limitations that require consideration here [128-132]. There is potential for subjective bias or inconsistency in the user-assigned weights that can impact reliability; this is mitigated by use of importance values rather than direct pairwise comparison. When pairwise comparison is used, each feature would need to be ranked in comparison to every other feature, requiring a large number of rankings. With the importance value strategy, each feature is only evaluated once and the pairwise matrix is constructed based on that ranking. This limits decision fatigue and bias in judgment that contribute to inconsistency. Rank reversal, where adding or removing facilities can change the rank order of other facilities, is another known limitation of the method. This is often attributed to inconsistency in assigning weights and is therefore also mitigated by use of importance values [133,134]. Many of the alternative multiple criteria decision analysis techniques face the same limitations [135]. AHP remains as the best option due to its simplicity to implement for a wide range of users.

There are several opportunities for future analog development or advancement of current facilities highlighted by this work. For example, analog facilities tend to lack high-fidelity simulations of medical capabilities, with most including little more than a first aid kit. While some polar stations have medical facilities, there is an opportunity for analogs with a lower barrier to entry to develop a test platform for medical technologies and procedures. In the case study we see a range of different optimal facilities, from dessert to polar environments, depending on considerations that aren't directly related to medical capabilities in the facility. As in-house equipment is implemented in facilities over time, such as base medical equipment for planetary missions, more features can be added to the model to optimize experiment-facility matching. There is also a need for facilities with an ability to represent different architectures and crew sizes, as larger missions become feasible [5]. With this comes an opportunity to conduct architecture-level studies by implementing a structured approach to testing equipment and standards across missions within a facility, to provide experimental control for other facility features. This work also highlights specific gaps that are not addressed in many facilities that if improved at a given facility, could largely improve the viability of testing relevant experiments at that facility. Aspects such as fine control of the gravity environment for micro, lunar, or Martian gravity simulations could largely benefit experiments. Improved control of dust or particulates in the atmosphere is another gap not covered well by analog facilities that would contribute to more realistic simulations and target a large problem posed by the harsh lunar and Martian environments. Similar to updating research priorities, analog facility capabilities can also be updated to best represent the levels to which the facilities simulate space environments.

Implementation of the priority alignment method proposed here enables a standardized approach to experiment selection and approvals across analog facilities, to reduce the impact of fidelity limitations of student analogs compared to established

research facilities. The overall goal of this framework is to move beyond the "mission of opportunity" approach currently employed in analog experiment selection, towards an approach that targets optimizing selection for high-value research that utilizes the unique features of a given facility.

Future work for this model includes refining the user interface to better suit general use by researchers and facility operators. Inclusion of more analog facilities and revisions to existing data on listed facilities will also be conducted and kept up to date. As facilities and experiments develop, additional features may be added to best represent the critical infrastructure included in analog testing. In the future, in addition to the STMD shortfall list quantification and HRP risk quantification, the experimental value model could be updated to include other scoring parameters as they are developed for additional areas of space research.

Data statement

The data and models used in this paper are part of an ongoing study and may be obtained upon requested. Models will be made publicly available after revisions are made for ease of public use.

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Conflicts of interests

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Appendix A: Sensitivity Analysis Inputs and Outputs

Category	Assigned Importance Value
Exploration Conditions	5
Field Science	1
Human Science	5
Isolation and Risk	3
Reliance on Technology	5

Category	Feature	Desired Feature ?	Assigned Importance Value	Adjusted Importance Value
Exploration Conditions	Precipitation	☐	1	-1
	Diurnal Temperature Variation	☑	2	2
	Seasonal Temperature Variation	☐	1	-1
	Dust	☐	1	-1
	Terrain Slope Variation	☑	2	2
	Unknown Terrain	☑	2	2
	Limited Mobility	☑	3	3
	Limited Comms	☑	3	3
	Limited Visibility	☑	1	1
	Restricted Access	☑	2	2
	Geologic Diversity	☑	1	1
	Gravity	☑	3	3
Field Science	Geomorphology	N/A	1	1
	Geochemistry	N/A	1	1
	Exobiology	N/A	1	1
Human Science	Astronaut-Like Population	☐	5	-5
	Psychology	N/A	1	1
	Large Crew Size	☑	3	3
Isolation and Risk	Distance to Medical Facility	N/A	3	3
	Complexity to Reach Healthcare	N/A	2	2
	Risk Environment	☐	2	-2
Reliance on Technology	EVA Suits / Procedure	☑	5	5
	Mission Control	☑	4	4
	Life Support	☑	5	5

Figure 6. Medical experiment sensitivity inputs.

Facility	Score
AATC Habitat 1.0	0.49
Amundsen–Scott South Pole Station	0.43
Aquarius (NEEMO)	0.35
Asclepios	0.78
CHAPEA	0.12
Concordia	0.79
Devon Island: FMARS	0.47
Devon Island: HMP	0.49
CHILL-ICE	0.76
Habitat Marte	0.83
HERA	0.10
HESTIA	0.10
Hi-SEAS	0.51
ILMAH	0.40
LunAres	0.42
MDRS	0.70
McMurdo	0.62
Palmer	0.53
SAM Biosphere 2	1.07

Figure 7. Medical experiment sensitivity outputs.