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Publication Date

2022

Copyright Information

Peer reviewed

73rd IAC international astronautical congress 2022 (IAC), Paris, France, 18-22 September 2022.

IAC-22-B6-10

echusOverlook (eO): Open-Source Knowledge-Base For Techno-Economic Analysis and Simulation of Human Exploration Operations

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ABSTRACT

Design practices and tools for human exploration missions have evolved in concert with mission complexity over the past half century of the space age. As collective thought turns toward the exploration of Mars and of the Moon, such as through the Artemis Program, technologies new and old have been proposed to address challenges in astronautics. However, the coordination of these challenges has lagged behind the advances of technologies themselves. Previous mission design tools limited users to choosing between hard-coded options. Yet, technologies with potential applications to space are rapidly emerging from fields outside of astronautics, such as synthetic biology. One of NASA's Space Technology Grand Challenges is bridging the space sciences and biological engineering communities. This drives our development of echusOverlook (eO), an open-source Python library that captures the feasible mission design space, standardizes the definition of mission components, and democratizes the technology selection process. Here we begin by outlining the echusOverlook software in the context of other mission design suites. We then outline the feedback from a preliminary consultation with a group of mission design specialists which is then used to develop initial user-stories and design specifications. We then provide an initial demonstration of the software package capabilities in terms of technoeconomic analysis and simulation methods. Finally, we take steps to outline a roadmap for future software development. However, input from a wider audience is needed to create a tool that can address the needs of the community. We invite all interested parties to send feedback or get in touch to please fill out this brief survey: https://forms.gle/xkXppqnhTJ9mhGVX8.

1 Introduction

Aspects of mission design have been explored across a number of software artifacts[1, 2, 3, 4]. Beginning in 1998 with Advanced Life Support Sizing Analysis Tool (ALSSAT)[1] in Microsoft Excel, the complexity of software has grown to include dynamic modeling methods to increase model fidelity. Software has been developed by both NASA and ESA, underscoring a lack of standardization between space agencies. Moreover, the development of recent tools has been outsourced either to private industries in the case of EcoSimPro[5] or to academic institutions, via V-Hab[6] or HabNet[7]. This has led to two primary issues with existing life support systems software: tools (1) operate on poorly-standardized mission architectures, methods, and data; (2) are predominately protected for academic priority or private financial concerns; (3) were not designed or maintained for use by people other than the creators, even if the code was made available.

The need for a new software paradigm arose with the recent development and design of a surface biomanufactory for sustaining a long-duration human exploration mission on Mars[8]. Emerging biological technologies were previously identified as critical to sustaining astronauts and the mission[9, 10]. So, the endeavor of Space Bioprocess Engineering (SBE)[11] includes operations that range from harnessing Mars atmospheric and regolith resources; to in situ manufacture of products like propellants and building materials; to the agriculture of plants and microbes for food and medicine [8]. Realizing these systems into an integrated platform for future work by NASA requires biological engineering, systems engineering, and computational modeling.

Unfortunately, many existing tools for this purpose were unavailable or unusable; others do not allow users to define and analyze new, experimental technologies of their own design. So, eO aims to become not only the most accessible tool for mission design, but also the most expressive.

eO would define the general space of feasible missions, provide a standard set of mission architectures, and equip users with the tools to describe and analyze ideas for new technologies as a part of a complete mission. With no predetermined and immutable data types, calculations, metrics, or simulations. The target is for eO is to model nearly *any* mission to Mars with any refer-

This roadmap is predicated on initial feedback from a selection of mission design specialists sourced from NASA and various academia laboratories. However, we recognize that more feedback is needed to better define the specifications for the echusOverlook tool. Thus, here we provide a link to a set of questions here: https://forms.gle/xkXppqnhTJ9mhGVX8. We invite all interested to please fill out this brief survey and sign up for future updates!

ence mission architecture, any set of processes, and any inventory could be described and modeled inside eO.

Here, we present the design and construction of the echusOverlook software and its progress evaluating mission architecture across a myriad of metrics common to Environmental Control and Life Support System (ECLSS)[12].

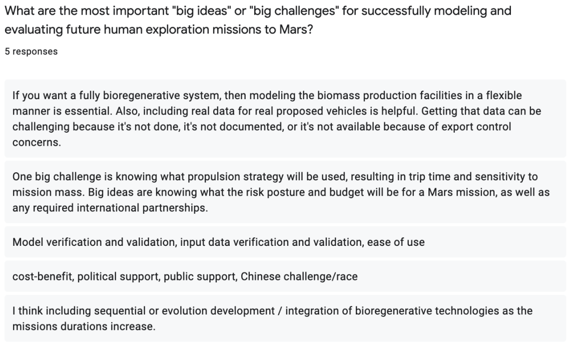
2 Preliminary Consultation

eO has been developed during the execution of a NASA Science Technology and Research Institute Grant. As the project matured, we were encouraged to formally engaged with NASA mission design specialists and in May of 2021, with the help of Dr. John Hogan (NASA Ames Research Center), we assembled a group of ∼10 NASA specialists spanning expertise across mission design, optimization, and deployment.

After much assistance from our NASA point-of-contact, Dr. John Hogan, we were able to schedule an initial meeting to

1. Form a community of mission planners, life support systems designers, espace scientists, and bioengineers;
2. Review what is known about possible mission specification or modeling that has been done for chemical and biotechnologies that support food, pharmaceutical and material production in space; and
3. Explore current Bioregenerative LSS and ECLSS and determine what elements have been missing from mission design.

Prior to the meeting with the attendees, we solicited feedback to a set of questions designed to gauge the interest for the echusOverlook software for human exploration mission design and optimization (emphasizing biomanufactory-driven RMAs and technologies). We collected the responses and presented them back to the attendees at the meeting which was designed to explain our preliminary efforts, discuss struggles, collect needs, and learn of others we might need to interview. The responses are presented here in Figure 1, and in full at the end in Figure 6 -12.



What are the most important "big ideas" or "big challenges" for successfully modeling and evaluating future human exploration missions to Mars?

5 responses

If you want a fully bioregenerative system, then modeling the biomass production facilities in a flexible manner is essential. Also, including real data for real proposed vehicles is helpful. Getting that data can be challenging because it's not done, it's not documented, or it's not available because of export control concerns.

One big challenge is knowing what propulsion strategy will be used, resulting in trip time and sensitivity to mission mass. Big ideas are knowing what the risk posture and budget will be for a Mars mission, as well as any required international partnerships.

Model verification and validation, input data verification and validation, ease of use

cost-benefit, political support, public support, Chinese challenge/race

I think including sequential or evolution development / integration of bioregenerative technologies as the missions durations increase.

Figure 1: Survey response to question “What are the most important ”big ideas” or ”big challenges” for successfully modeling and evaluating future human exploration missions to Mars?”

We presented eO with a preliminary user story in which a user would want

1. to specify mission goals formally,
2. to be prompted towards inclusion of mission elements/processes to support those goals,
3. be able to efficiently populate those processes with possible inventories to support those processes and models of their operation, and
4. given these constraints to select from possible mission architectures that can support lift of these proceses to their sites of action.

Given these sets of possible alternatives to process, inventory and mission architecture, we proposed that the user would wish to be able to create more or less optimal scenario composed of these and compare them for tradeoffs against different mission metrics including standard mass, power requirements; modularity/ interoperability requirements, minimum waste and maximum recycling requirements, etc. The user story provided a preliminary design pathway in which the proposed story would be supported through:

1. Creation of a databases of processed, models, inventory elements, mission architectures that can be extended, and used together to create models of different mission scenarios
2. Allow building of multiple and community extension of models of mission elements ranging from

very top level ESM like models of their costs to detailed dynamical models of their operation

3. Allow model optimization, sensitivity/uncertainty analysis, and cross-model comparison for decision support.
4. Allow open, transparent, FAIR sharing of data, models and analysis among diverse communities to support effective comparison, incremental development, and ease of checking/rechecking results.

Following the preliminary meeting, we established a set of future goals:

1. Collecting and collating all known information about the physical specifications and form factors for operation of technological elements (life support, biomanufacturing, etc.) on-board transit craft, space-stations and surface elements.
2. Collecting and collated all known information about costs/models for operations of these platforms that affect the costs and operations of the tech support elements (how different rockets, etc. effect the cost of operations in 1.)
3. Collecting and collating all known actual and possible mission architectures for planned missions over the next 30 years to serve as templates for the RMA structures in echusOverlook
4. Collecting, improving, and testing different models of critical technological elements in the LSS, ECLSS, biomanufacturing space or other biologically-linked operations for test bedding the systsem and supporting the evolution of this community for driving innovation in these elements over the next decades.
5. Developing a community to ensure we are building a usable, accelerating software framework for the larger community even beyond space bioengineering;
6. Developing a clear communication and alliance with other mission planning and tech development groups so we remain relevant.

3 Software Package

eO models the parametric constraints on and tradeoffs among bioprocesses such that they meet or exceed mission need and are engineered to minimize the risk of failure under different orbital, crew, and landing site scenarios. Through the integration of both a knowledge-base and simulations, eO is designed to elucidate the critical system parameters for demonstrating the feasibility and advantages of biological engineering on a human exploration mission to Mars. The echusOverlook is being designed to be initially accessed via command line, Jupyter notebook, or text editor.

3.1 *User Story*

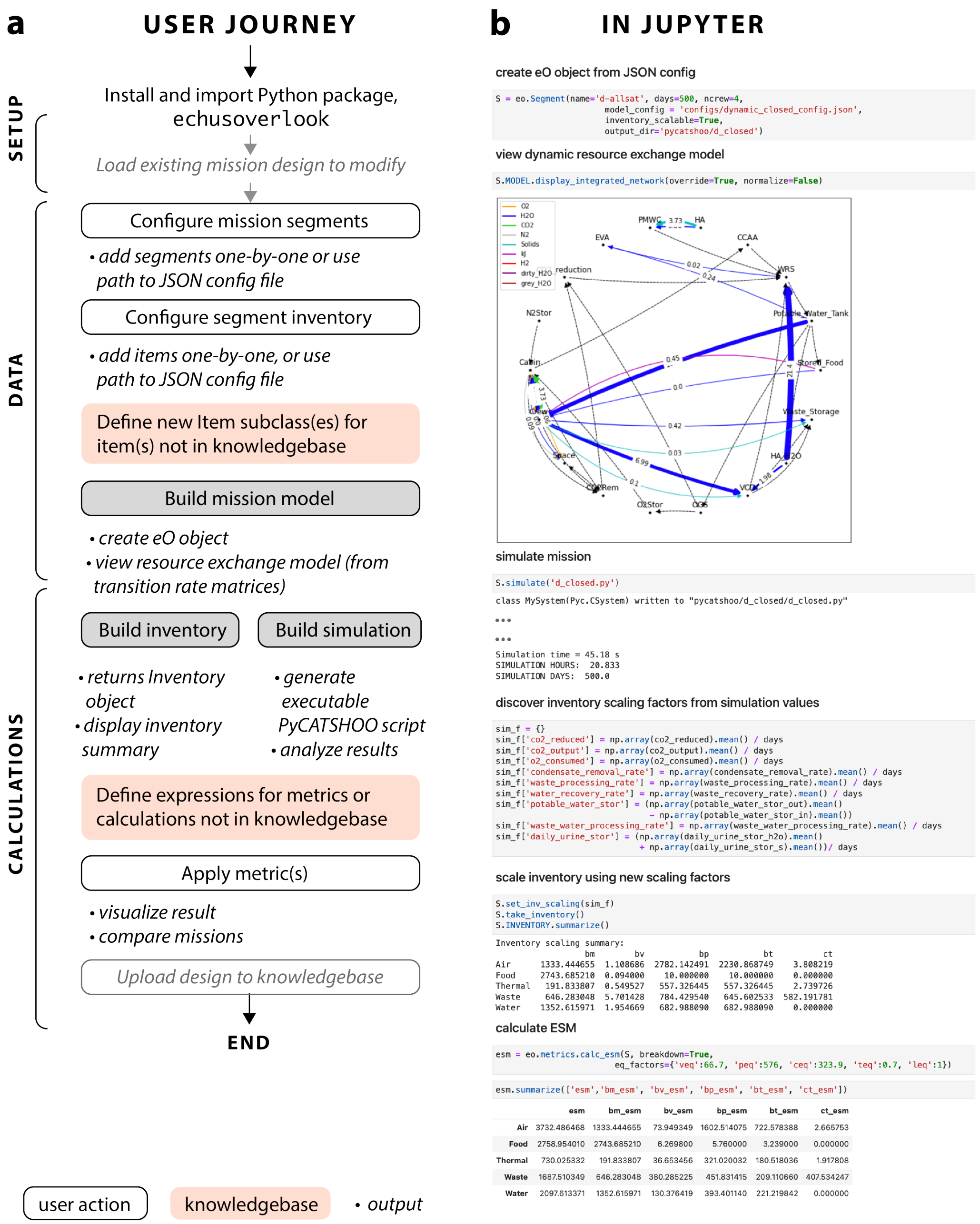
The user-story diagram describes how a user starts with the setup of "campaign" and proceeds through from design to the technoeconomic calculation through simulation and ends with either the submission of results back to the eO database or an adjusting of parameters for additional calculation and/or simulation (Fig. 2a). Users begin by creating a space logistics network (SLN) by selecting the data elements for use from existing data in eO which can then be modified. eO is initially seeded with a library of common ontologies, datasets, and operations, and the user community is encouraged to upload new components and their results. Each SLN is used to determine mission needs and constraints and is composed of operations across a series of mission segment with locations such as Earth, Low Earth Orbit (LEO), Cis-lunar Space, Luna, Interplanetary Space, Martian Orbit, Mars, etc. Default mission data packages are available as a starting point for users to not only decrease the barrier of entry to space mission design, but also to standardize the use of eO across multiple instances. The user can easily create additional ontologies, variables, and models by uploading new types of information, allowing for the freedom to construct a mission component using any data type necessary to describe it. Once a SLN has been validated, the user can perform downstream a variety technoeconomic analyses and/or initiate a simulation for exploring the dynamics of their system.

3.2 *Systems Architecture*

The eO data module acts as a knowledgebase to describe the mission parameters – both user-defined and calculated – and can be considered as the set of instructions from which simulations are first constructed, parametrized, and run – and later as the container in which simulation results are added. The interactions of these components (Fig. 2b) are governed by a number of modules including `OrbitalMechanics`, `MartianEnviornment`, `Processes`, `Inventory`, and `Crew`. A number of "start-up" examples are provided in the knowledgebase and include complete reference mission architectures and other case studies such as inventory constructs from NASA's ALSSAT[13] and BVAD[14] and sortie and outpost surface missions described in HabNet[7].

3.2.1 *Technoeconomic Analysis*

After establishing the framework to formulate novel mission designs, eO must provide methods for studying,



create eO object from JSON config

```
S = eo.Segment(name='d-allsat', days=500, ncrew=4,
                  model_config = 'configs/dynamic_closed_config.json',
                  inventory_scalable=True,
                  output_dir='pycatshoo/d_closed')
```

view dynamic resource exchange model

```
S.MODEL.display_integrated_network(override=True, normalize=False)
```

simulate mission

```
S.simulate('d_closed.py')
```

```
class MySystem(Pyc.CSystem) written to "pycatshoo/d_closed/d_closed.py"

•••

•••

Simulation time = 45.18 s
SIMULATION HOURS:  20.833
SIMULATION DAYS:  500.0
```

discover inventory scaling factors from simulation values

```
sim_f = {}
sim_f['co2_reduced'] = np.array(co2_reduced).mean() / days
sim_f['co2_output'] = np.array(co2_output).mean() / days
sim_f['o2_consumed'] = np.array(o2_consumed).mean() / days
sim_f['condensate_removal_rate'] = np.array(condensate_removal_rate).mean() / days
sim_f['waste_processing_rate'] = np.array(waste_processing_rate).mean() / days
sim_f['water_recovery_rate'] = np.array(waste_recovery_rate).mean() / days
sim_f['potable_water_stor'] = (np.array(potable_water_stor_out).mean()
                               - np.array(potable_water_stor_in).mean())
sim_f['waste_water_processing_rate'] = np.array(waste_water_processing_rate).mean() / days
sim_f['daily_urine_stor'] = (np.array(daily_urine_stor_h2o).mean()
                             + np.array(daily_urine_stor_s).mean())/ days
```

scale inventory using new scaling factors

```
S.set_inv_scaling(sim_f)
S.take_inventory()
S.INVENTORY.summarize()
```

```
Inventory scaling summary:
                 bm        bv           bp           bt          ct
Air      1333.444655  1.108686  2782.142491  2230.868749    3.808219
Food     2743.685210  0.094000    10.000000    10.000000    0.000000
Thermal   191.833807  0.549527   557.326445   557.326445    2.739726
Waste     646.283048  5.701428   784.429540   645.602533  582.191781
Water    1352.615971  1.954669   682.988090   682.988090    0.000000
```

calculate ESM

```
esm = eo.metrics.calc_esm(S, breakdown=True,
                          eq_factors={'veq':66.7, 'peq':576, 'ceq':323.9, 'teq':0.7, 'leq':1})
```

```
esm.summarize(['esm','bm_esm', 'bv_esm', 'bp_esm', 'bt_esm', 'ct_esm'])
```

	esm	bm_esm	bv_esm	bp_esm	bt_esm	ct_esm
Air	3732.486468	1333.444655	73.949349	1602.514075	722.578388	2.665753
Food	2758.954010	2743.685210	6.269800	5.760000	3.239000	0.000000
Thermal	730.025332	191.833807	36.653456	321.020032	180.518036	1.917808
Waste	1687.510349	646.283048	380.285225	451.831415	209.110660	407.534247
Water	2097.613371	1352.615971	130.376419	393.401140	221.219842	0.000000

Figure 2: **Using eO.** (a) User story concept. (b) eO in practice: screenshots of an example Jupyter notebook. A dynamic resource exchange model (missing values indicated by dashed black line) has an unknown inventory. The mission was simulated to discover the dynamic values, from which inventory scaling factors were calculated. Then, the inventory was be generated, and ESM was calculated.

comparing, and scoring the quality of proposals through their technoeconomic analysis (TEA). This aims to extend and accommodate the functions of existing tools such as the ALSSAT[13] in the form of sizing, trade studies, and the inclusion of mission design metrics[15, 16]. The history of space mission design is replete with a number of such metrics that range in scope and complexity. ECLSS technology selection was initially carried out

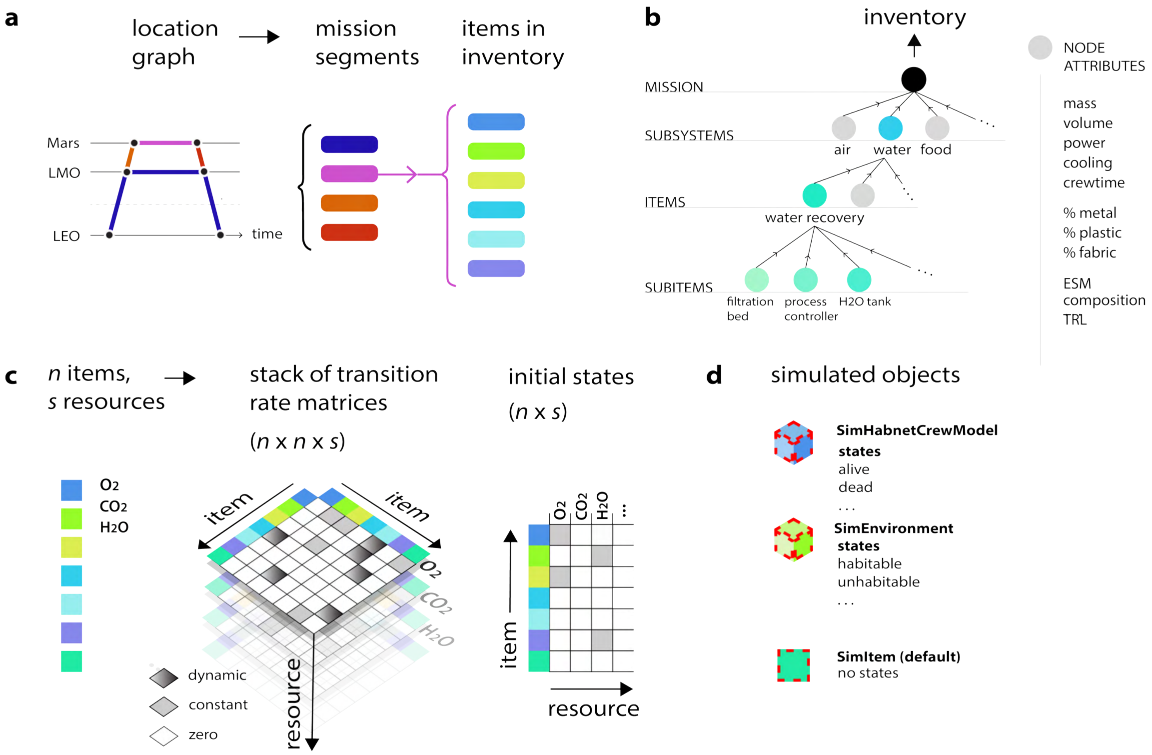


Figure 3: **Data structures in eO.** (a) A graph object represents mission segments (edges) and locations (nodes). Each mission segment may contain a unique inventory. (b) A tree object represents mission inventory. Each node contains the items that descend from it, and thus accumulate attributes like mass, volume, composition, and ESM. (c) A stack of matrices models the resource exchange and mass balancing of a mission. Entries can be a constant value or a dynamically evaluated value, which is computed during simulation. (d) Simulated objects are written as PyCATSHOO objects, which contain states, transitions, and variables for each entry in the mass balancing model.

by assigning a Technology Readiness Level (TRL)[17] value and has evolved to account for Integration and Systems Readiness (IRL, SRL)[18, 19, 20, 21]. However, despite the standardization of TRL criteria[22, 23], such "mangagement" metrics are often considered lacking in objectivity[24] and do not readily lend themselves to optimization.

The impact of specific technology choices are usually evaluated through the more quantifiable metric of the equivalent system mass (ESM)[25] which provides a method for distilling the mass of all of the resources of a larger system. In Figure 4, we demonstrate using eO to calculate and compare ESM across different inventory configurations.

3.2.2 *Simulation Methods*

Central to eO is the ability to simulate a proposed mission design and predict its outcome. The nature of manned missions and their components can be modeled by hybrid systems that mix two kinds of behaviours: (1) the discrete and stochastic behaviour which is in general due to failures and repairs of the system's constituents and (2) the continuous and deterministic physical phenomena which evolve inside the system. eO was designed to support similar types of calculations as those found in HabNet[7], and thus requires methods for defining and running simulations of both individual systems for exploring the deep subsystem-specific parameters and their local optima and entire campaigns composed of many systems in order to understand their dynamics and interoperabilities globally.

Simulations in eO are carried out using the PyCATSHOO framework[26, 27, 28] for Piecewise Deterministic Markov Processes (PDMPs)[29]. PyCATSHOO is a modeling tool for distributed hybrid stochastic automata. To create a baseline simulation, eO can directly convert resource exchange events defined in eO's transition rate matrices (such as in 4) to PyCATSHOO objects, attributes, and variables. Custom simulatable behavior beyond mass-balancing range from the failures and repairs of Inventory objects and the continuous products of

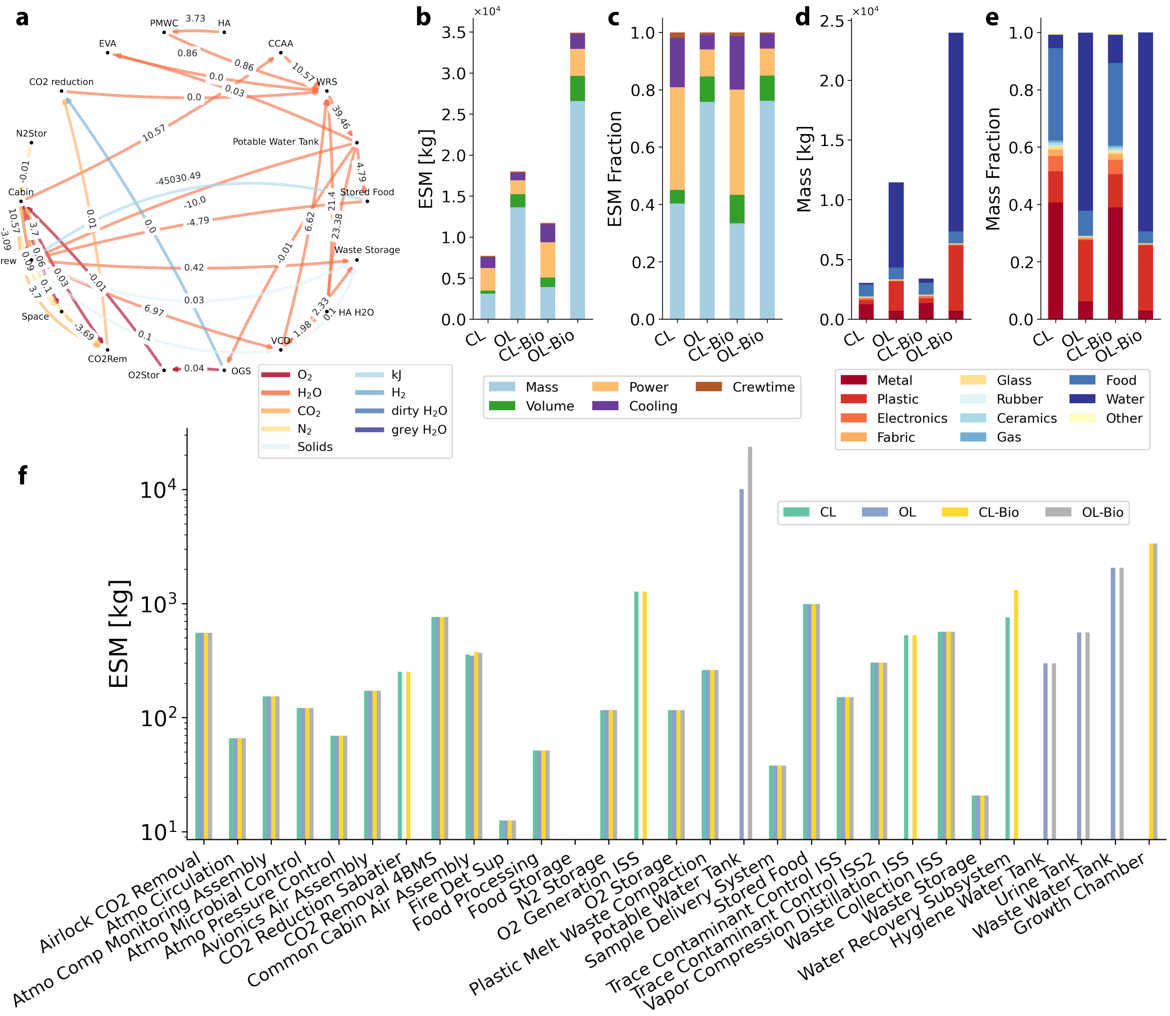
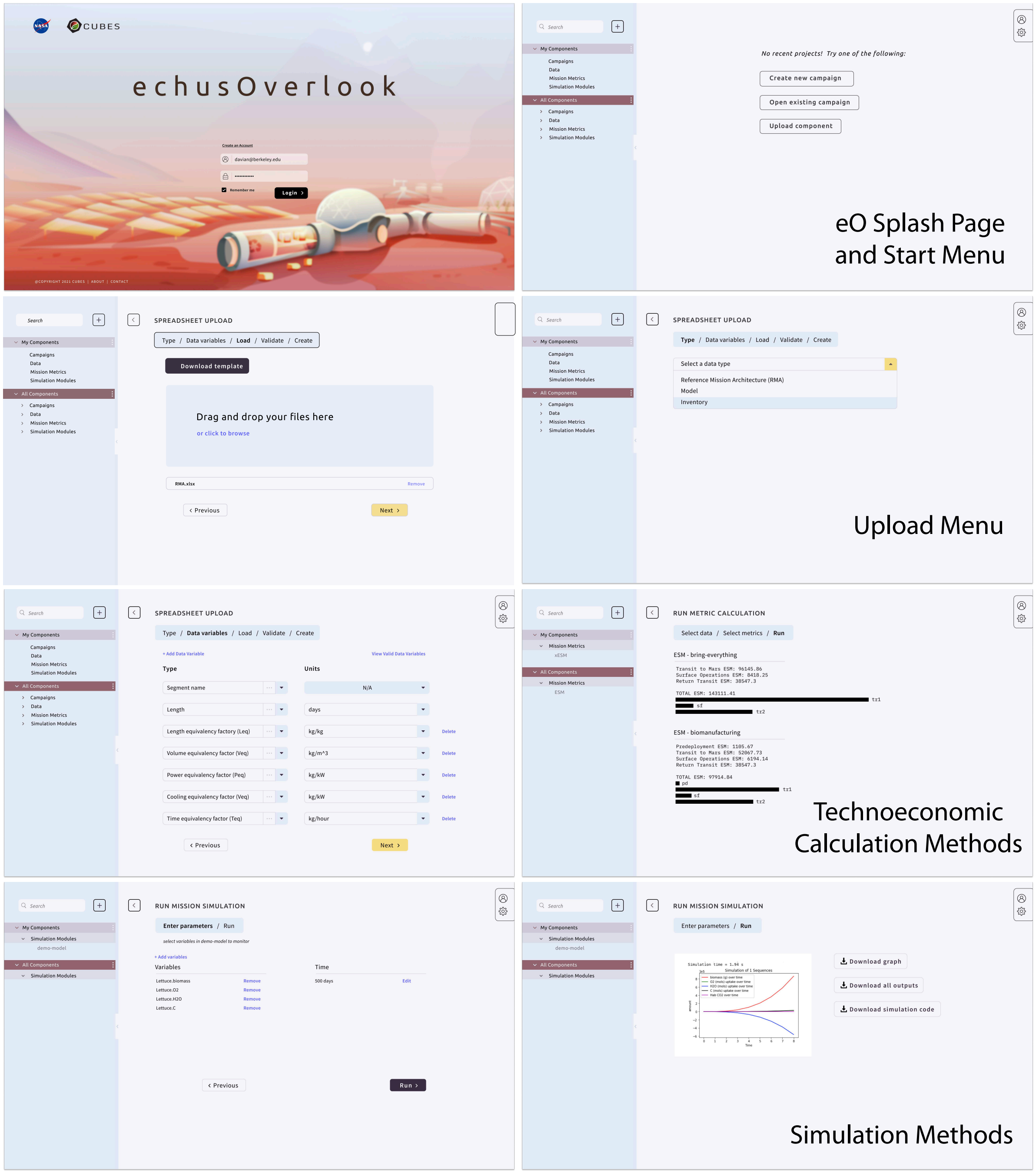


Figure 4: **Technoeconomic Validation of eO against the NASA ALSSAT**. **(a)** Visualized resource exchange entries in the transition matrix for closed loop "bring everything" scenario. **(b)** Bar chart demonstrating eO calculation and comparison of 4 scenarios in terms of the standard ESM metric using a breakdown of ESM by components such as Mass, Volume, Power, Cooling, and Crew Time. **(c)** Bar chart with same comparisons as (b) using ESM fraction. **(d)** Bar chart demonstrating eO calculation and comparison of 4 scenarios in terms of the standard ESM metric using a breakdown of ESM by material composition in terms of metal, plastic electronics, water, etc. **(e)** Bar chart with same comparisons as (d) using Mass fraction. (f) Bar chart comparison of subsystems for each scenario.

chemical and physical reactions carried out during surface operations. Mission reliability is calculated by PyCATSHOO as the expected duration of time that mission parameters are within safety margins. Cases resulting in mission failure as described by Do *et al.* in HabNet[7] included the following: crew starvation, crew dehydration, crew hypoxia, crew hyperoxia, crew CO_2 poisoning, cabin pressure, high fire risk, and crop death. Therefore, while simulating a mission, PyCATSHOO tracks and plots CO_2 levels, O_2 levels, pressure, and amount of food over time.

3.3 *Technoeconomic Analysis and Validation of Mass-Balanced Inventories*

Preliminary RMAs propose 30 sols of surface operations driven by an opposition-class transit by a small crew of 4-6 astronauts[30]. Such short-term missions do not led themselves construction and operation of biomanufactory-based set of technologies and instead opt for a "bring everything" (BE) scenario in which the majority of consumables such as food, tools, and medicine are packaged turn-key and transported via pre-deployment or as cargo on the primary mission vehicle[8, 31]. Given that the BE scenario serves as a stan-



Type	Units
Segment name	N/A
Length	days
Length equivalency factory (Leq)	kg/kg
Volume equivalency factor (Veq)	kg/m^3
Power equivalency factor (Peq)	kg/kW
Cooling equivalency factor (Veq)	kg/kW
Time equivalency factor (Teq)	kg/hour

ESM - bring-everything

```
Transit to Mars ESM: 96145.86
Surface Operations ESM: 8418.25
Return Transit ESM: 38547.3

TOTAL ESM: 143111.41
```

ESM - biomanufacturing

```
Predeployment ESM: 1105.67
Transit to Mars ESM: 52067.73
Surface Operations ESM: 6194.14
Return Transit ESM: 38547.3

TOTAL ESM: 97914.84
```

Variables	Time
Lettuce.biomass	500 days
Lettuce.O2	
Lettuce.H2O	
Lettuce.C	

Figure 5: Mockup of accessing echusOverlook through a website via the user's internet browser. The top row depicts the eO webapp splash page and start menu. The next row features two screen-captures of the eO upload menus for drag and dropping files and assigning variable values and parameters. The next row features two screen-captures of the technoeconomic calculation methods. Depicted here are preliminary results for ESM calculations as described above. The final row features screen-captures of preliminary simulation methods, as described above.

dard for RMA design, we leverage the existing literature for programmatic representation of a 500 sol surface mission with an initial inventory population to demonstrate the validation of eO's TEA module. Validations of the eO TEA capabilities are presented in Figure 4 as a comparison across a myriad mission architectures using the metrics. Each RMA was constructed by assigning standard mission variables such as crew-number and mission duration, a "scenario" such as open loop (OL) or closed-loop (CL), and technology choices the corresponding variable specification for air, food, thermal and waste subsystems. The comparison of eO's calculated ESM values against those from the ALSSAT validate our agency in constructing the distribution of BE scenarios.

The basic schema for carrying out ESM-based TEA in eO is shown in Figure 2 in which resources such as O_2 are used to populate stocks of transition matrices given some initial states. The transition matrices (Figure 4a) serve as the starting point for all TEA calculations. Transition matrices can be visualized in eO as a combined directed graphic showing the transfer of resources. Here we show an example transition matrix for a closed loop (CL) BE scenario with resources of O_2, H_2O, CO_2, N_2, solids (define), and energy in [kJ]. In Figure 4b we demonstrate eO's agency in calculating and comparing 4 scenarios in terms of the standard ESM metric, and we further compare each scenario using a breakdown of ESM by components such as Mass, Volume, Power, Cooling, and Crew Time. In Figure 4c we breakdown the same elements from 4b using ESM fraction rather than pure ESM which allows for a more in depth comparison of ESM components on a standardized scale. In Figures 4d,e we further compare each scenario using a breakdown of Mass and Mass Fraction (respectively) by element such as structural metal, plastic, water, biomass, electronics, etc. This demonstrates eO's extensibility beyond the standard ALSSAT. In Figure 4f we further expand the subsystem hardware to compare each scenario.

To facilitate the space mission planning community and democratize the field such that it can be assessed by bioengineers, we outline the echusOverlook web-application tool (Figure 5). Here we present a mock-up of a web-based eO application which includes a splash page and start menu, upload menu, technoeconomic calculation methods, and simulation methods.

4 Moving Forward

In moving forward with the goal of eO to foster both Standardization of mission elements and operations by the space science and engineering community and Democratization of novel biological system elements by the biological science and engineering community to meet the needs and requirements of both user-groups, we conclude with a brief roadmap:

Y_1 eO v.α

- Release Python library and create initial website
- Easily build, simulate, and collaborate on campaigns
- Add preloaded RMAs, inventories, and processes from literature

Y_1 eO v.β

- User testing, back and front ends.

Y_{2-4} eO v.1

- Expand biomanufacturing processes
- Expand logistics to include Artemis missions
- New tools for dynamic process simulation, parameter estimation/sensitivity analysis, mission optimization, decision support, and mission comparison

Y_{4-10} eO v.2

- Gamify system
- Setup eO-NASA challenges (tentative)
- Test eO for actual mission planning for a launched 'system' (tentative)

This roadmap is predicated on initial feedback from a selection of mission design specialists at NASA and various academic laboratories. However, input from a wider audience is needed to create a tool that can address the needs of the community. We invite all interested sending feedback or getting in touch to please fill out this brief survey: https://forms.gle/xkXppqnhTJ9mhGVX8.

Acknowledgements

This work is supported by the grant from the National Aeronautics and Space Administration (NASA, award number NNX17AJ31G).

Authorship Contributions

All authors developed, wrote, and edited the manuscript.

Competing Interests

All authors declare that they have no conflicts of interest.

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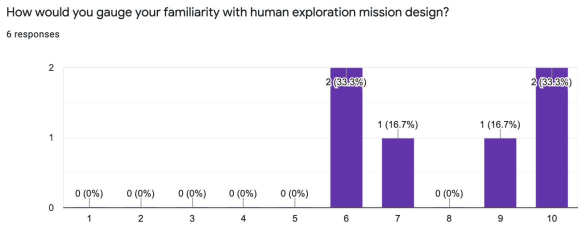
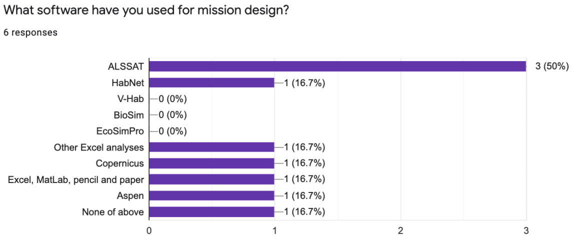

How would you gauge your familiarity with human exploration mission design?

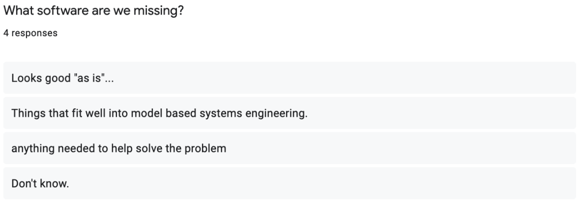
6 responses

Figure 6: Survey response to question "How would you gauge your familiarity with human exploration mission design?"


What software have you used for mission design?

6 responses

Figure 7: Survey response to question "What software have you used for mission design?"


What software are we missing?

4 responses

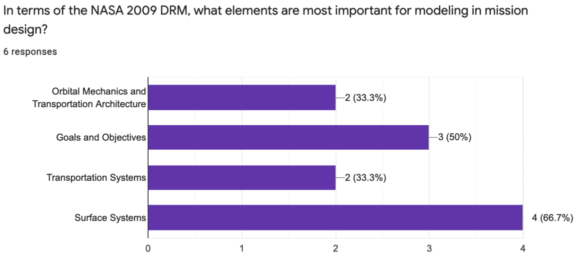
Looks good "as is"...

Things that fit well into model based systems engineering.

anything needed to help solve the problem

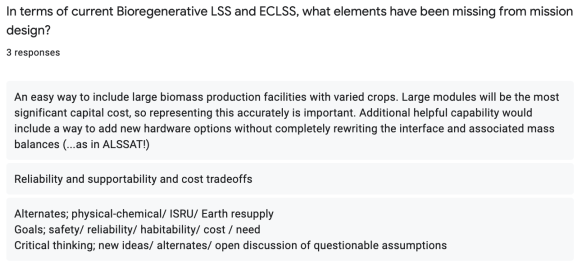
Don't know.

Figure 8: Survey response to question "What software are we missing?"


In terms of the NASA 2009 DRM, what elements are most important for modeling in mission design?

6 responses

Figure 9: Survey response to question "In terms of the NASA 2009 DRM[30], what elements are most important for modeling in mission design?"


In terms of current Bioregenerative LSS and ECLSS, what elements have been missing from mission design?

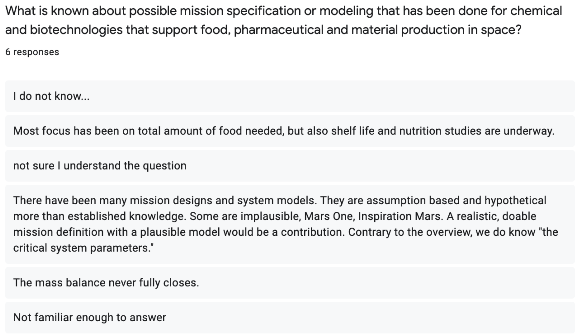
3 responses

An easy way to include large biomass production facilities with varied crops. Large modules will be the most significant capital cost, so representing this accurately is important. Additional helpful capability would include a way to add new hardware options without completely rewriting the interface and associated mass balances (...as in ALSSAT!)

Reliability and supportability and cost tradeoffs

Alternates; physical-chemical/ ISRU/ Earth resupply
Goals; safety/ reliability/ habitability/ cost / need
Critical thinking; new ideas/ alternates/ open discussion of questionable assumptions

Figure 10: Survey response to question "In terms of current Bioregenerative LSS and ECLSS, what elements have been missing from mission design?"


What is known about possible mission specification or modeling that has been done for chemical and biotechnologies that support food, pharmaceutical and material production in space?

6 responses

I do not know...

Most focus has been on total amount of food needed, but also shelf life and nutrition studies are underway.

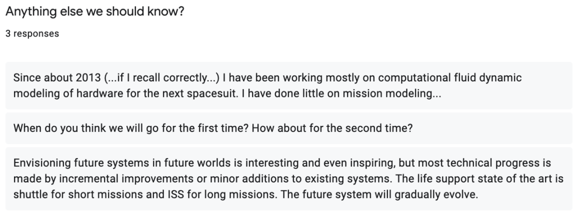
not sure I understand the question

There have been many mission designs and system models. They are assumption based and hypothetical more than established knowledge. Some are implausible, Mars One, Inspiration Mars. A realistic, doable mission definition with a plausible model would be a contribution. Contrary to the overview, we do know "the critical system parameters."

The mass balance never fully closes.

Not familiar enough to answer

Figure 11: Survey response to question "What is known about possible mission specification or modeling that has been done for chemical and biotechnologies that support food, pharmaceutical and material production in space?"


Anything else we should know?

3 responses

Since about 2013 (...if I recall correctly...) I have been working mostly on computational fluid dynamic modeling of hardware for the next spacesuit. I have done little on mission modeling...

When do you think we will go for the first time? How about for the second time?

Envisioning future systems in future worlds is interesting and even inspiring, but most technical progress is made by incremental improvements or minor additions to existing systems. The life support state of the art is shuttle for short missions and ISS for long missions. The future system will gradually evolve.

Figure 12: Survey response to question "Anything else we should know?"