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Research Paper

The cis-lunar ecosystem — A systems model and scenarios of the resource industry and its impact

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ABSTRACT

Lunar resources is one of the many new putative business models that may transform space logistics. Yet it competes with Earth-based resources, in a complex trade-off involving both tech development & socioeconomic dynamics. This study models the size vs. time of a future resource ecosystem focused on water for exploration and satellite refueling, in cis-lunar space. We use a recently-developed multi-methodology concept based on System Dynamics and scenario planning, characterizing uncertainties. Top critical uncertainties include the accessibility of resource finds, and government investment into lunar resources, demarcating 2 particularly illustrative scenarios: *Moonopolis* and *Apollo 2.0* — a rosy and a low-resources future. Concurrently, a System Dynamics model with 7 interacting systems is developed: exploration, production, demand, satellite industry, R&D, natural resources, and government. It is based on models of other industries (e.g. oil) and can express the scenarios. Uncertainties in 25 variables are estimated, and sensitivity analysis of *ecosystem size* is performed globally using variance-based measures, including interaction effects. These show (a) systems are tightly coupled, (b) variable importance is sensitive to the baseline. Three variables are crucial: government support to production development, production firms' re-investment, and growth of the GEO telecom satellite industry. A lunar resources ecosystem with $32B economic impact after 20 years is plausible, given excellent government support to production capacity, high growth in GEO satellites, early demand and large initial resource discoveries. The main contributions are a novel holistic model of the dynamics of a space resources industry showing how to mix technical & socioeconomic parts, and a first case study of the methodology.

1. Introduction

Future satellite refueling might use either terrestrial or lunar resources. While propellants are more available on Earth, there is more transport "distance" (larger Δv) from Earth to orbit then from the Moon. This is a complex trade-off that depends on the geography (e.g. LEO vs. GEO), but also on investment, infrastructure, and attendant transportation (and extraction) costs. Unfortunately a pure engineering study cannot determine whether Earth or Moon-sourced propellant is "better" in the long run, because it depends on investment and socioeconomic dynamics. Yet, economic dynamics will themselves depend on technology development rates. Since technology and socioeconomic aspects are interdependent, an integrated approach is needed to capture this holistic trade-off. And so, we will show how to account for both halves of this problem, by merging scenario planning and System Dynamics.

Indeed lately in the space industry, nothing seems permanent except change. The sector is opening and privatizing, and the potential societal implications are many: technico-scientific, educational & inspirational, and economic — including acquiring resources, like orbits, spectrum, or raw materials. New services and business models in LEO include constellations for telecom & private Earth Observation, on-orbit servicing, a first debris removal contract, and the development of space tourism. Launcher reuse is decreasing costs, suborbital space is opening, and the impact of nano satellites continues to deepen, both directly and via training and research (opening to basic research at universities). Exploration targets have changed, with the ISS winding down and the Moon as next strategic target. Large-scale transportation systems are being readied, both private and also SLS & Orion. In situ resource utilization (ISRU), and in-space manufacturing are gaining in attention, and overall we see many changes in space logistics & resources systems.

Abbreviations: SD, System Dynamics; EML, Earth–Moon Lagrange point; CLD, Causal Loop Diagram; GSA, Global Sensitivity Analysis; FDN, Functional Dependency Network; NPV, Net Present Value

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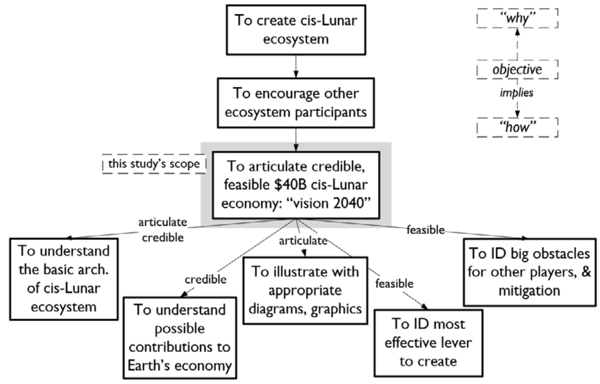

Fig. 1. Objectives tree of this work, iterated with industry consultations. The main objective is: *articulate a feasible vision*, for *potential participants*.

In this context, several private companies have been planning new business ecosystems in space, the most famous being SpaceX's Mars colonization plan. However, the Moon and cis-lunar space is a far more accessible target, and has drawn the attention of diverse public & private players in a nearer time horizon: space agencies, large firms, start-ups etc. (e.g. [1]) Indeed the Moon is well-placed near Earth, and its much shorter transit time is crucial for human operations. It has a relatively favorable geography for resources: a large, diverse geological body at an energetically advantageous location for space transport [2].

This study's goal is to clarify how a cis-lunar ecosystem might establish itself, using a recently-developed multi-methodology concept based on System Dynamics modeling and scenario planning [3]. We work with a leading small space company (ispace Inc.), and the ecosystem is envisioned to be around space resources, especially lunar water. Establishing a novel ecosystem is a very challenging task in future planning, requiring a profound understanding of societal dynamics, and interactions between tech development and the socioeconomic sphere. The goal from an industry point-of-view is to help create the ecosystem, by promoting stakeholder engagement with a logical vision, and understanding the key levers to creating it. Intellectually, this can help shed some light on the complex trade-off of Earth vs. Moon-sourced refueling. The research contributions are threefold: firstly, we create a novel holistic model of the dynamics of a nascent space resources industry, characterizing uncertainties. In so doing we help show engineers how to bring human-system modeling (here via System Dynamics) to technology planning, the second contribution. Thirdly, we test the multi-methodology framework in [3] with a case study.

1.1. Modeling the lunar resources ecosystem

This modeling project occurred largely from late 2017 to mid-2019, with data updated in 2021, representing >5 months' full-time modeling work spread over 14 months. Due to the ambiguity in any systems modeling project, and future lunar resources in particular, significant time was spent with stakeholders clarifying project and model purpose. For this an objectives tree was constructed, loosely following the method of Gibson et al. [4]. It is shown in Fig. 1, obtained after iterative industry consultation & feedback. Each box has an objective; the box connected above explains *why* this objective should be fulfilled, those linked below say *how*.

Starting at the top, the overriding objective, from many companies' point-of-view, is to create the cis-lunar ecosystem.[1] A simple illustration of a possible future resources ecosystem is shown in Fig. 2. As can be seen at bottom left, several types of vehicles are engaged in (multi-staged) geological exploration. The second phase, recovery, shows vehicles associated with open-pit mining on Earth (providing an incorrect but tangible image). Recovered ore is processed into useful products (e.g. water, oxygen, fuel) in a third stage at a refinery facility, which also has attendant infrastructure needs (here, power is shown). Next, the final product is transported — perhaps to a point of sale directly, e.g. a lunar base. Alternatively it may be launched, and go through another stage of in-space transport. It may be delivered to a facility (e.g a space station) or tug vehicle, before being used to refuel satellites.

How to create this? Here, we are concerned with the objective "To encourage other ecosystem participants" to join (Fig. 1) — the study beneficiaries. This is in turn accomplished with "*To articulate a credible, feasible $40B cis-lunar economy: 'vision 2040'*".[2] The latter is the main objective and scope of this study.

The main study objective is broken down into five sub-objectives, as shown in Fig. 1. Firstly, *understanding the basic architecture* of the cis-lunar ecosystem – its key technical and economic dynamics, hopefully several different possibilities – and utilizing the opinions of appropriate experts. The second enabling sub-objective is to understand the *contributions to Earth's economy* — the return on investment, or Net Present Value (NPV) of projects. What are the incentives? This should be done by listing and valuing the most promising major markets. Thirdly, to articulate this future ecosystem, a sub-objective is to *illustrate it with appropriate diagrams, graphics and calculations*. Thus the creation and selection of good visualizations is needed. Fourthly, the feasibility of the ecosystem must be addressed — what effective levers can be identified to create it? This requires *identifying and ranking levers*, and understanding various "transition paths" to this envisioned ecosystem. Lastly, still on feasibility, we must also understand major obstacles, including those faced by other actors, and how to mitigate these. This involves *identifying the relevant actors and stakeholders, understanding their incentives and barriers*, and proposing and testing solutions.

The rest of this paper is organized as follows. Section 2 surveys the literature on future planning methods and work on space ecosystems and resources; Section 3 explains the methodology of this study & its deployment; Section 4 presents modeling results (with the full model in the supplementary material), and Sections Section 5 & 6 discuss them and conclude, ending on future work.

2. Literature

2.1. Future planning & modeling

There are many methods to plan in strategy, business, & engineering, e.g. scenario planning and technology roadmapping. Though accurately forecasting the future is often impossible, considering various possibilities and characterizing uncertainties is valuable.

2.1.1. System dynamics

System Dynamics (SD) is time-based modeling often used in business & policy planning [5]. It has two key features: (a) it can visually show a problem's "dynamic structure", and (b) it models both social, soft variables and technical, hard ones. The fundamental premise of SD is that simple feedbacks, delays, and stocks & flows suffice to endogenously capture complex behaviors at large scales. Originating with Jay Forrester in the 1950s, it was popularized by the Club of Rome's *The Limits to Growth*. Peter Senge also championed SD [6], bringing the idea of *system archetypes*: simple, recurrent model structures (or *molecules*) found in diverse systems, representing common structures — like simple fixes having delayed negative consequences [7,8].

Many SD models (and molecules) related to system development & innovation diffusion exist. Sterman [5], the standard text, presents SD

[1] *Ecosystem* here is a *group of interacting sociotechnical systems*.

[2] The target economic value is not precise, but order-of-magnitude.

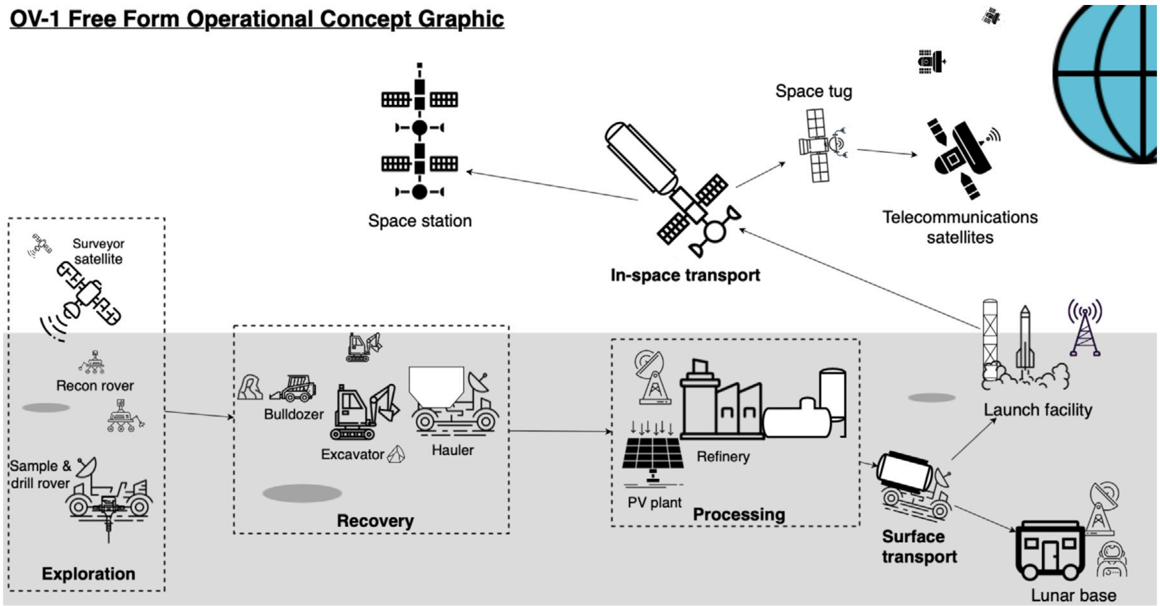

Fig. 2. A conceptual illustration of the future cis-lunar resources ecosystem, in the spirit of an "OV-1" diagram or "ConOps".

models of product diffusion, durable goods replacement (aging chains), and positive feedbacks in corporate growth — and many others. Weil [9] gives 5 models for corporate strategy, including the stock-flow structure of R&D. Davidsen et al. [10] and Sterman et al. [11] give a classic model of the oil industry, applicable to other resources, which explores the long-term dynamics of exploration, production, technology, demand and prices. Lee et al. [12] introduces utilizing functional architecture of a system as a basis for an SD model. However, few SD models incorporate engineering design parameters, and if so do not link to product diffusion & hence profitability. Likewise, no SD or Systems Thinking applications integrating technological & socioeconomic parts for lunar or space (resource) industries are known to us.

2.1.2. Scenario planning

Formal scenario planning and foresight as a discipline grew out of planning in the Second World War, tackling the problem of how to make key decisions about the future when uncertainty constrains us. Scenarios have a long history in military science, but their first major private-sector adoption was by Shell, which was subsequently better-prepared for the OPEC oil shocks of the 1970s [13]. Shell emerged as one of the stronger oil majors, and scenario planning emerged as a burgeoning field of research [14].

Scenarios are imaginative, holistic, history-like narratives of the future, intended to articulate plausible futures and isolate key decisions. They can demonstrate uncertainty and allow interpolation by presenting vivid alternatives with clear assumptions. There are formalized methods to generate scenarios [13], such as identifying "driving forces" across society, including pre-determined elements (e.g. aging of the population) and key uncertainties (e.g. immigration policy) for the point of interest (e.g. labor-force makeup). Thus we can articulate distinct, meaningful future narratives (e.g. a closed society with labor shortages vs. an open one with friction on immigration).

Scenarios are an attractive complement to the dynamic structure representation and simulation capability of SD (or other) models [13]. Scenarios provide narrative interpretation that may ease stakeholder understanding of model behavior, clarifying assumptions and parameter values — thus forming a bridge between models and users.

2.2. Space & lunar ecosystems, resources, & logistics

Traditionally, expansion in space has been driven by governments. The International Space Exploration Coordination Group (ISECG), a grouping of major space agencies, recently published a consensus plan for follow-up space exploration, infrastructure etc. after the ISS in the Global Exploration Roadmap [15]. According to the roadmap, we are entering the second of three phases, focusing on the Moon with up to 50 missions into the 2030s, with the Lunar Gateway station and surface missions. NASA is an international driver, with ~3/4 of all government investment in space exploration [16]. NASA characterizes this "Proving Ground" phase by the Lunar Gateway habitat, Orion spacecraft and SLS launcher, and defines explicit objectives: e.g. *Deep Space Operations* & *Habitation*, *In-Situ Resource Utilization*, and *In-Space Propulsion*.

Recently, several private firms have proposed visions & plans for lunar ecosystems, often related to resources: e.g. ispace, SpaceX, and ULA [17]. Indeed, the 2009 remote detection of water by India's Chandrayaan-1 orbiter and NASA's Lunar Reconnaissance Orbiter focused attention on lunar resources [2], [18]. The U.S. Geological Survey is taking first steps to evaluate regolith as reserves [19]. Water may be used for refueling [20]; several companies have begun planning its extraction, and envisioning the novel ecosystem needed [1]. Though these organizations may lack the financial means of space agencies, they bring renewed interest in sustainable, continuous operations, vs. the traditional mission-based mode [21].

Accordingly, technologies and systems are being prepared [17], including novel extraction concepts like thermal mining [1]. Demand for resources could come not only from exploration needs, but refueling satellites [20], [2]. A key enabler is on-orbit refueling and servicing, for which commercial services have begun, and which may gain important market share [22]. These developments clearly affect the various plans for lunar resources, which have deep uncertainties. Yet no holistic model of its dynamics at an ecosystem level, characterizing the main uncertainties, is known to the authors.

Another key aspect of establishing more permanent, sustainable space operations is logistics [23]. Indeed, though shifting exploration targets to the Moon considerably complicates space logistics needs, space resource industries promise some relief, at the expense of more logistical complexity. This new sophistication requires research. Such an ecosystem will also potentially have a wider impact on the economy [24].

3. Methodology

We deployed the method described in [3], with some tailoring. Section 3.1 briefly describes the construction process of the SD model, Sections 3.2 & 3.3 its relation to scenario building and Global Sensitivity Analysis, and Section 3.4 how the above was deployed in practice, on a systems consulting project.

3.1. System Dynamics model-building methodology

Following on Chavy-Macdonald et al. [25] and the authoritative Sterman [5], to construct a SD model we used both bottoms-up and top-down approaches, in addition to the natural progression from Causal Loop Diagram to full executable model.

3.1.1. System Dynamics molecules

A first step in SD model-building is to determine its scope, time horizon, and identify key phenomena to capture, aided by narratives & market data. Similarly, likely SD models or model molecules are listed, and then matched to key phenomena [25]. Molecules were shortlisted for inclusion based on their utility in explaining identified phenomena.

3.1.2. Functional Dependency Network

A next step is to integrate the molecules, also using a network of the essential functions of the product (Functional Dependency Network, FDN — for details see [12]). To construct the FDN, firstly the elements and functions of the system and associated systems are identified, and a functional decomposition created. Dependencies between functions are assessed, forming a network. This is in order to create a SD model of the product interacting with its System-of-Systems — it forms the "skeleton" of the SD model (details in [12], [26]). Functional dependency was assessed using the same question as in [27]: *is Function A necessary to fully or partially perform Function B?* If so, B depends on A.

Functions are converted to functional measures; each is then modeled as a SD variable indicating the function's level of performance (itself relatable to design choices). Finally once the model is integrated, numerical calibration is done, using established parameter values for model molecules wherever possible.

3.2. Relation to scenario planning

The System Dynamics and scenario planning processes have many similarities and complementarities across three phases: (1) building the model and scenarios, (2) simulating and writing the stories, and (3) organizing the output [3]. Firstly during building, models and scenarios need similar inputs. The scenario "building blocks" – *pre-existing elements*, *critical uncertainties*, and *driving forces* – likely ought to be prominent on the Causal Loop Diagram (CLD), particularly if a driving force. SD parameters which are key but difficult to accurately quantify are plausibly *critical uncertainties*. Perhaps most importantly, the entire CLD structure itself should be more or less a visual representation of the main plot line in associated scenarios. Thus, there are "economies of scope" in creating both — and they may also help each other catch errors or omissions.

In phase (2), a scenario narrative explains a simulation run, its key assumptions and modes of behavior, as well as implications. On the other hand, a narrative can be clarified & made precise with visual aids and semi-quantification of important values.

Finally in (3), the "Schwartz/GBN" 2 × 2 matrix for scenarios [13] is a valuable way to choose and organize both narratives, *and* simulation runs. It is constructed by selecting the two most critical uncertainties to form axes, spanning the uncertainties' extrema. The quadrants delineate 4 distinct worlds, a good basis for selecting principal scenario narratives, or meaningful simulation runs — clearly showing key assumptions.

In this study, scenario building blocks were identified in literature and management interviews, aided by the "PESTe" acronym[3]; variables were then ranked for uncertainty and impact [13]. They were closely connected to the SD modeling process, with some SD variables/phenomena included in the model because of importance testing via scenario techniques. This testing is often qualitatively assessing the sensitivity, e.g. by considering the impact of extreme variable settings.

3.3. Global Sensitivity Analysis

As in Chavy-Macdonald et al. [3], we seek to mitigate the weaknesses of a semi-qualitative System Dynamics model with large uncertainties: e.g. how to improve the credibility of numerical output? Sensitivity analysis is helpful here, as "*the study of how uncertainty in the output of a model can be apportioned to different sources of uncertainty in the model input.*" [28]. However, it is typically done locally, with One-At-a-Time variable methods, in order to avoid the factorial explosion in computational requirements. Recently, Global Sensitivity Analysis (GSA) methods[4] have been developed allowing comprehensive, rigorous exploration of many-dimensional solution spaces with large uncertainties, computationally inexpensively (using Design of Experiments techniques) [28]. They have been demonstrated in System-of-Systems design support, albeit without societal variables [29]. Here, we deployed variance-based sensitivity measures – Sobol' and Saltelli indices – to characterize model factors, using a Python library [30]. Translating the SD model to Python using a new library [31] greatly reduces the computational burden, and 80 000 (carefully designed, pseudorandom) simulations can be easily run in 1 h on a simple machine.

3.4. Deployment methodology & narrowing

This study was a fairly loosely-defined systems modeling projet initially, and the methodology from Chavy-Macdonald et al. [3] unproven; thus a systems & deployment method was sought. According to Gibson et al. [4], the generic six-phase process of any systems study is:

1. *Determine goals of system.*
2. *Establish criteria for ranking alternative candidates.*
3. *Develop alternative solutions.*
4. *Rank alternative candidates.*
5. *Iterate.*
6. *Action.*

Each of these steps has more detailed sub-steps, particularly the first two, which are critical for a systems analysis. The method of this case study is to deploy the technique–oriented methodology [3] within this broader Systems Analysis iterative framework [4] (and other model-building resources [5]), to help define the problem to model. The initial, most critical part of the study is determining the goals, KPIs & scope of the system (the ecosystem model & vision) & project (the creation of the model), from the perspective of the client and beneficiaries (ecosystem participants). This is done via interviews with ispace management; step-by-step we generalize the initial question to understand its context and purpose, develop dynamic descriptions of the current status and desired outcome, describe the values of potential participants, and identify the variables and problem scope. An objectives tree for the project synthesizes this outcome in Fig. 1.

In selecting modeling methods, the process from Chavy-Macdonald et al. [3] was tailored, with FDN not initially used. Most modeling iteration was done with CLDs. These were ranked using the KPIs, via interviews with stakeholders. Leading CLDs are expanded into full SD models and populated with interview & other data. The lens of scenario planning helps showcase main drivers & uncertainties to model, and later significant simulation cases.

Another key point is to list & prioritize the primary markets (economic bases for the purported ecosystem) to be examined. There are

[3] Political, Economic, Social, Technological & environmental [13].

[4] Included in the currently fashionable "Data Analytics".

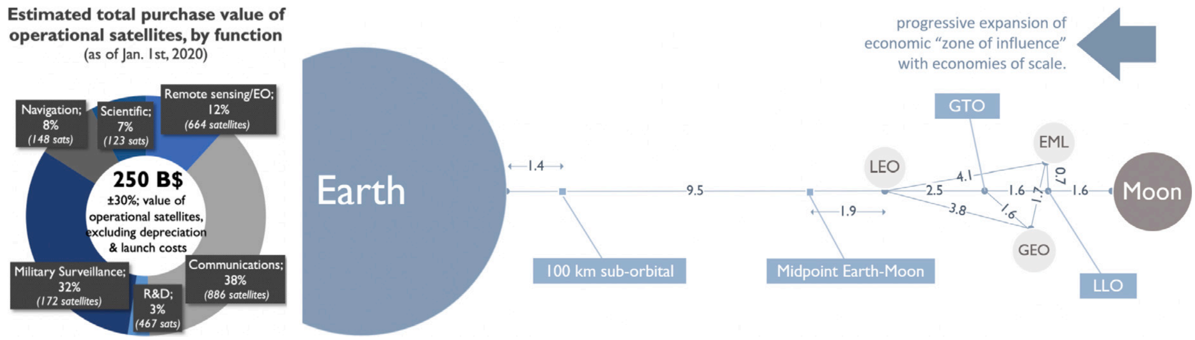

Fig. 3. Left: satellites' manufacturing value by function. Right: locations of major orbits. Like an Earth map, this Δv scale can be read as "distance is ~ energy need". Communications satellites were typically at GEO (constellations now also at LEO/MEO); Earth Observation at LEO.

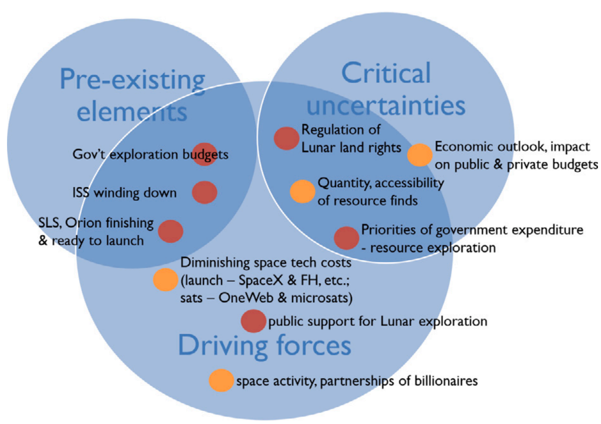

Fig. 4. Supply side of lunar resources scenario building blocks. Note the importance of government and public elements (in red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

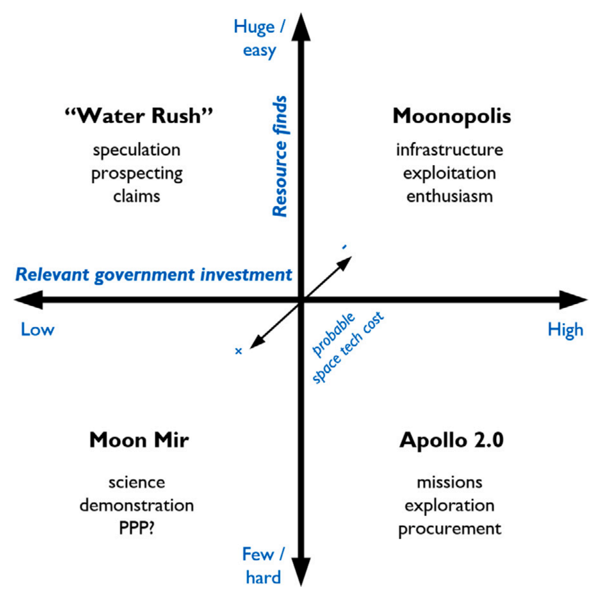

Fig. 5. A matrix with the 2 key supply-side uncertainties as axes: *government investment* and *resource finds*, delineating 4 future worlds.

many possible segments related to lunar water – the principal envisioned resource for e.g. ispace and Crawford [2] – but limited study time, and a clear trade-off in modeling depth & breadth. Several rapid assessments were done for triage, focusing firstly on the near-term (hypothetical) size of market opportunities, then on the possible future dynamics of the segments.

4. Results

Firstly, apart from the objectives (Fig. 1), the first output of this study is the KPIs/ranking criteria for a "good" ecosystem model. They loosely flow from the objectives, and are (a) *credibility & market size* (credibility measured by expert assessment), (b) *value returned to Earth* (economic impact, expected NPV), (c) *clarity of mechanisms* (by group vote), (d) *feasibility of levers* (assessment by experienced professionals).

4.1. Narrowing approximations, model scoping

Effort is needed to frame and understand the problem, and then rationally narrow-down candidate markets. Candidate markets for lunar water include (i) satellite refueling segments (GEO telecom — stationkeeping & apogee-raising; non-GEO ("NGSO") constellations; military surveillance; Earth Observation; exploration & other government — e.g. Mars mission fueling); (ii) cis-lunar base segments (astronauts in near-lunar orbit, or on the surface; EML-1 (Earth–Moon Lagrange point) stationkeeping, ascent from lunar base). The initial calculation was an estimate of the *total value* of satellites at each segment.[5] We note that over one third of satellites are communications [32]; together with Earth Observation these account for nearly two thirds the total. R&D and navigation together account for another quarter, the other functions for less.

The approximate manufacturing value of the segments was estimated using values accumulated from Bryce Space and Technology [32], Dolgopolov et al. [33], Dolgopolov et al. [34], Bryce Space and Technology [35] and 3 previous years. This refers to the price of the satellite as delivered on the ground, and excludes launch costs & depreciation. The total manufacturing value of satellites on orbit as of Jan. 1st 2020 is roughly estimated to be \$250B ±30%. Communications and military surveillance account for over 2/3 of the total — see Fig. 3, left. Average error is roughly ± 1/3 of each percentage, but we note the discrepancy with Euroconsult [22] is larger. Thus telecom satellites and possibly military surveillance seem to be the most promising segments to investigate initially — in addition, commercial on-orbit servicing of GEO telecom satellites is already underway [33].

Now we look at the locations and accessibility of these market segments, to a first approximation. Fig. 3 (right) shows the major

[5] We approximate that the average refueling market size will be limited by, at most, some fraction of the total satellite value, since operators are *de facto* purchasing satellite-years by refueling.

utilized orbits on a Δv (velocity increment) scale, allowing similar reasoning as for an Earth-based topographical map. Such a map shows the immutable geography only – infrastructure would be overlain – but allows intuition on relative profitability of refueling locations, by imitating the implicit assumption for Earth maps that *distance is a proxy for effort*. The most economically important orbit classes – LEO, GEO, EML – are shown between the Earth and Moon. As we can see, LEO is actually "closer" to the Moon than Earth. This is where Earth Observation and surveillance satellite markets are located. GEO, where most of the telecom market is located, is *much* closer to the Moon. GTO is the location of most telecom apogee-raising, while Earth–Moon Lagrange points (EML) are likely points for exploration markets.[6]

Thus we have some initial appreciation for the maximum size of the various satellite refueling *present* markets, and their relative "locations" (Fig. 3). This gives some intuition about which are easiest to serve. We can imagine overlaying infrastructure ("highways", transportation systems) on this unchanging geography, amending transport economics. However, knowing that the Earth & Moon are both possible sources of satellite fuel, with Earth being cheaper for the foreseeable future, the economic "sphere of influence" of the Moon is unlikely to extend to the midpoint (Fig. 3). Thus lunar resources are *much* less competitive (vs. Earth resources) in the LEO refueling market segment, than in EML or GEO — almost regardless of infrastructure. In fact, infrastructure overlaid on Fig. 3 is considerably likelier to cheapen the Earth-LEO edge than the LEO-Moon one.[7] The profoundly distinct physical and economic geographies, and evolution prospects make for entirely different paradigms at LEO & GEO.

Market segments were roughly & qualitatively rated with the KPIs. This focused on credible market size, and business & technical feasibility with researchers & practitioners (ispace management) — suitable to early-phase rapid assessment. Clustering the results yielded a distinct group with significantly higher potential: GEO telecom and exploration markets,[8] wherever they are. Others had one or more weaknesses, e.g. market size & business feasibility at LEO orbits. As a first step, the top group is chosen as modeling focus; further study might better examine the others, e.g. LEO constellations.

4.2. Scenario elements & System Dynamics molecules

We divide into demand & supply-side modeling of lunar resources, approximately for the period 2020–2040. In this paper we focus on the supply side and its dynamics, set of building blocks & uncertainties. Variables or factors influencing *supply of lunar resources* (our variable of interest) are shown in Fig. 4, having been mapped in the same way as [3] and [13]. We note the large number of red building block elements — those related to government and public action. These are also important to the demand side, with exploration missions (e.g. fueling for Mars missions).

We assess the critical uncertainties' impact on *supply of lunar resources* [13]. Perhaps unsurprisingly, we rank *Quantity & accessibility of resource finds* as the most critical uncertainty. Next is less clear, but we find *Priorities of government expenditure on resource exploration* is the top, considering the guiding role of government in space [18]. Although government investment is a given to an extent (*Government exploration budgets* as a pre-existing element in Fig. 4), the amount & type is unclear. Possible medium-term targets include an orbital station or lunar surface base, ISRU investments, preparation for a Mars mission, etc. However, *Regulation of lunar land rights* is also impactful and sensitive — but we posit that a well-financed, legally gray exploration campaign is slightly more auspicious than the reverse.

[6] Several EML orbits are shown superimposed due to Δv proximity.
[7] One exception may be electric propulsion, for in-space edges.
[8] No explicit objective function was made to weight KPIs, yet.

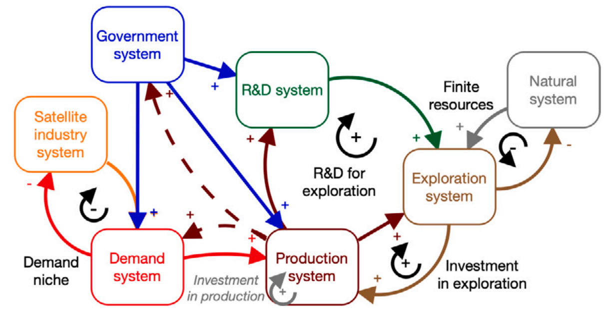

Fig. 6. The whole SD model; the ecosystem is composed of 7 systems and 5 feedback loops. The dotted arrows are effects implied but not modeled; the gray loop is internal to the production system.

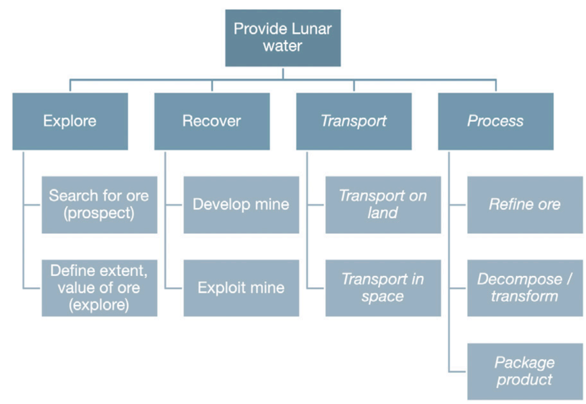

Fig. 7. The functional decomposition starting the Functional Dependency Network (FDN), and Causal Loop Diagram (CLD) [36].

Fig. 5 shows the mapping of these critical uncertainties to a "Schwartz/GBN" matrix [13]. We have tried to give evocative names and keywords to the four futures created. We have also added a pseudo-axis, *probable space tech cost*, to indicate that this variable also seems broadly correlated with the others.

A system-level view of the ecosystem SD model and its main interactions is in Fig. 6, clarifying the scope & structure of the whole system being modeled. It consists of 7 systems and 5 principal feedback loops. It focuses on the supply-side dynamics of lunar resources, and is primarily 4 interacting systems, shown by different colors: a resources *exploration system*, with main state variables *exploration* (campaigns/year), and *discoveries* (tonnes of water); a *production system* (supply) focused on sales of these resources, with main variables *production rate*, *revenue*, and *economic impact* & *ecosystem size* (our 2 main outputs); an *R&D system* increasing the level of technology in the exploration system, with main state variable *fraction discoverable* (of resources); and a *demand system* (with underlying *satellite industry*), having main state variable *refueling resource demand*. To these we add the simpler *natural (resources) system* (with amounts of resources), and *government system*; the latter is primitively modeled here only as a source of exogenous interventions. Notable omissions include *transport* and *legal* systems. The principal dynamics are positive feedback loops between exploration and production systems (production invests in & buys from exploration), and with R&D (the industry spends on R&D for exploration). Internally, the production system also invests in capacity and increases revenue, if demand is significant. Negative feedbacks include finite resources: as exploration proceeds, the natural system contains fewer undiscovered resources (Fig. 6). Similarly, demand for refueling is a niche market *within* the satellite industry: the more satellites use the service, the fewer remain as potential customers. Finally, the government system may impact demand (via purchasing

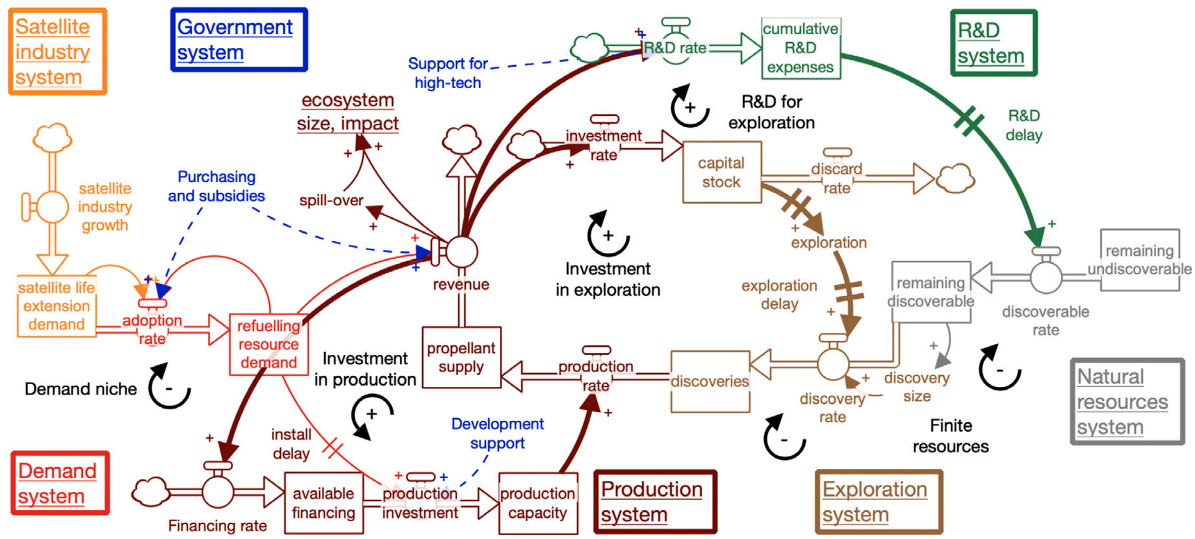

Fig. 8. A Causal Loop Diagram (CLD) showing the main dynamics of the potential cis-lunar ecosystem. Note the target variable *ecosystem size*, the 2 dominant positive feedback loops describing key dynamics: *investment in exploration* & *production*, and several balancing (finite resources & niches) loops. The notation can be read as follows. Other then systems and loops, each term refers to a variable. Simple arrows from one variable to another reads "tends to increase" (+) or "tends to decrease" (–. Boxed variables are stocks, or accumulations — they are filled by "taps", or flows. Thus, natural resources in the *remaining undiscoverable* stock will flow into *discoverable*, then be discovered, produced into propellant and sold.

for a Lunar base or Mars mission), production, and R&D in this model. Purchasing is modeled as a resources "loss" for the production system, but does not impact the government and demand systems.

As in Chavy-Macdonald et al. [3], a functional decomposition and FDN form the skeleton of the SD model. Fig. 7 shows a part, focusing on the high-level functions of a resources industry, *Explore*, *Recover*, *Transport*, and *Process* [36]. We focused on the first two to form the skeleton of later SD models.

Utilizing the variable classifications (Section 3.2), FDN, and molecules, we constructed CLDs capturing various relevant dynamics. Several were iterated with industry feedback. They were typically based on the Bass, R&D, aging chain and other molecules (Chavy-Macdonald et al. [25], Sterman [5], Weil [9]), with strong influence from resource exploration SD structures [10].

4.3. System Dynamics model

Causal Loop Diagram. A matured CLD – a qualitative, simplified view of a SD model – is shown in Fig. 8; it results from iterating with expert & client comments, adding new SD model molecules within the scope of Fig. 6, and comparing with the FDN (Fig. 7). The central loop is *investment in exploration*, similar to the new product development positive feedback loop [5], with revenue leading to more investment (in exploration equipment) and thence discoveries and revenue, after some delay. The main output variables are "*ecosystem size, impact*", measuring economic activity — our KPI (Fig. 1). We model both revenue and "spill-over" effects on suppliers, the industry etc. — thought to be especially key for high-tech [24]. R&D here increases the fraction of resources discoverable; *R&D for exploration* is another positive feedback loop, with some revenue reinvested in R&D, which improves exploration productivity via resource discoverability. The oil industry models of Davidsen et al. [10] and Sterman et al. [11] are the main inspiration for this part of the model. The many positive feedback loops do not ensure success — there is still the difficult point of starting the ecosystem.

Other key features of the CLD in Fig. 8 include the "aging chain" structure for resources [5], and the other stock-flow representing demand: companies in the market niche for satellite refueling can adopt this new service — *refueling by space resources*. The niche itself grows with the satellite industry. This CLD can capture the four "futures" of Fig. 5, e.g. with its variables (discoverable & undiscoverable) *resources*, and the various government *support* and *purchasing*.

The CLD (Fig. 8) is only a simple implementation, with several "systems" represented only by one or two variables, and "first-order" effects. It should be iteratively improved as needed, and these systems might each have entire dedicated SD modules. We first understand global behavior of the simplified system, and via sensitivity analysis prioritize *which* systems need modeling at higher fidelity.

Executable model. From the CLD, an executable SD model was created, with variables added and equations at each node, following from the molecule where possible. The philosophy of SD is for the math to be visible in the notation (Fig. 8), thus the equations at each node should be simple (e.g. + or ×). The CLD is a "visual representation" capturing the underlying 5th-order system of nonlinear ordinary differential equations. All model equations (19), constants (30), and variables (59) are fully documented in the supplementary materials and [26]; we list principal variables (by type), assumptions, and limitations by system in Table 1. Table 1 lists 49 of the variables across the 6 systems of the model. They are categorized as 28 endogenous (outputs), 21 exogenous (inputs), plus some excluded variables or factors. Key outputs are underlined, and some comments and assumptions are listed. Most parameters are not fixed, but varied over wide ranges; the goal is not numerical accuracy, but ranges that encompass the true value. All delays are 3rd-order [5].

For brevity and due to their limited importance, we present only a few equations here, to try to give a sense for the principal dynamics. As described in Fig. 8 caption, one key feature is a fixed total number of resources, conserved until it may be sold:

$$\begin{aligned}&remaining\ undiscoverable + remaining\ discoverable\\&+ discoveries + propellant\ supply = -\int revenue\ dt\end{aligned}$$

with resources "flowing" between the successive variables. The discovery of resources is at the core of the model, given by (& limited by

Table 1
Main model variables, and model boundary: "exogenous" are input parameters, "endogenous" are output, key ones are underlined.

System	Endogenous	Exogenous	Excluded	Comments, assumptions
Natural	*discoverable rate*	*recoverable resources;*	unrecoverable resources;	total resources are 0–6B tonnes [2], $\sim \frac{1}{1000}$ are recoverable;
	remaining (un)discoverable	*max average lode size*	orbit carrying capacity	a "full discovery" is 20–500k tonnes, ≤1% of discoverable
R&D	*R&D rate; cumulative R&D; fraction discoverable*	*R&D effectiveness; R&D delay; max/min discoverable*	R&D for production, lifetime, or lower costs; exogenous R&D	*cumulative R&D* smoothly improves *fraction discoverable* 30%–90%, with 2–10-year delay (models industry-wide scales; calibrated by [10])
Exploration	*capital stock; discard rate; exploration; discovery size; discovery rate; discoveries*	*exploration cost; exploration delay; equipment lifetime*	discovery size variance; exploration efficiency (not cost); expected NPV	Equipment (for exploration) builds up, with a 3-year lifetime. A full, average campaign finds 1 economic deposit, taking 3–12 years, \$90M–5B (from mining industry [36] + space premium)
Production	*financing rate; available financing; production investment, capacity, & rate; propellant supply; sales; revenue; investment rate; spill-over; economic impact; ecosystem size*	*re-investment fraction; install delay; development cost; price; fraction invested (in exploration); procurement delay*	operating production cost; sustained extraneous financing; production efficiency, +R&D impact; processing or storage (separately); expected NPV	capacity tracks demand with 2–8-year *install delay*, costs \$2-7M/tonne/year [37]; operating costs are not modeled, government aid is assumed; price is 0.5 M\$/tonne; *spill-over* is 2.8×*revenue*; *ecosystem size* – the main model output – is *revenue+spill-over*; *economic impact* is 6×*revenue* [24]; 2-year procurement delay (for exploration equipment, fixed) [10]
Demand & satellite industry	*refueling resource demand; adoption rate; satellite life extension demand; demand for capacity* (for production)	*satellite industry growth; refueling attractivity*	satellite industry segments; LEO constellations; market share; demand for space telecom services; orbit congestion	niche diffuses from 0 to 0-3k+ tonnes/year [17]; industry grows ~0-30%/year; no processing or transport or tugs or Earth-based (or any) competition
Government		*R&D support; development support; supplies purchasing; adoption subsidies*	decisions or feedback; own finds; need or budget; political support; international	development support (for production) varies 0%–100%; R&D support is 20-200M\$/year (from NASA budget, for exploration tech only); purchasing is 0–220 tonnes/year (Mars fuel etc. [17]);
Transportation *(excluded)*	transport volumes	launch, on-orbit, surface costs	infrastructure; launch industry	All excluded except via exploration and development costs & delays
Legal *(excluded)*	land claims/zones	exclusivity rights	speculation	Legal issues are pivotal, may vary

remaining discoverable):

$$discovery\ rate = DELAY3(exploration; exploration\ delay)$$
$$\text{with } exploration = \frac{capital\ stock}{equipment\ lifetime \times exploration\ cost}$$
$$\text{and } capital\ stock = \int (investment\ rate - discard\ rate)dt$$
$$\text{and } investment\ rate = DELAY3(fraction\ invested \times revenue; procurement\ delay)$$

with *capital stock* referring to exploration equipment (e.g. surveyor spacecraft, rovers — Fig. 2). *DELAY3(X;Y)* is an in-built function roughly yielding X after time Y (via a 3rd-order Erlang distribution) [5].

This closes the main positive feedback loop, *investment in exploration*. As for production, we have conservation of financing (for production capacity):

$$available\ financing + production\ capacity = \int financing\ rate\ dt$$
$$with\ financing\ rate = revenue \times re\text{–}investment\ fraction$$

with *production investment* (the term decreasing *available financing* and increasing *production capacity*) being controlled by (delayed) demand, under a substantial capacity *install delay*. Finally, for demand we have a

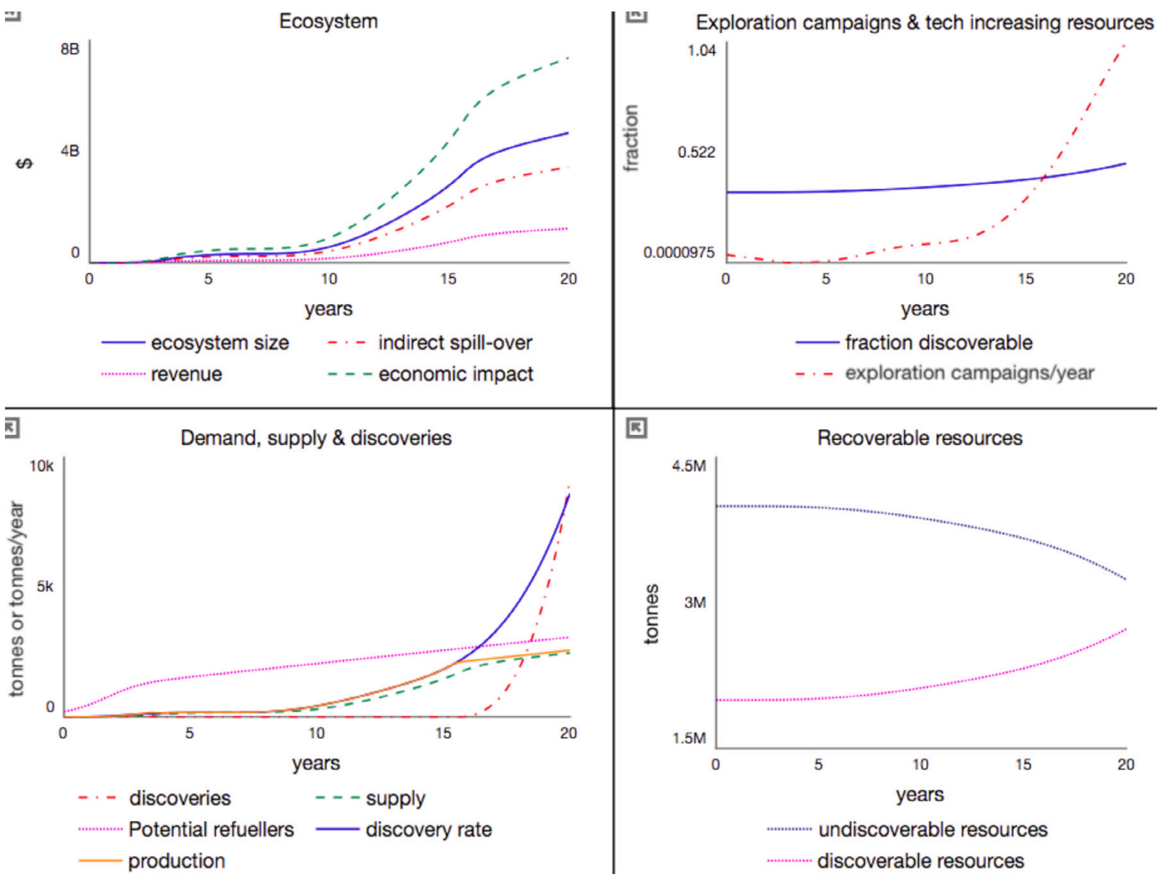

Fig. 9. *Moonopolis* scenario. Initially exploration-constrained, fuel demand is the ultimate limiting factor to growth — see Year 16, "production".

market niche for life-extension propellant (using the estimate from Morris and Sowers [17]), which grows at the satellite industry growth rate. The lunar-resource refueling service is adopted by simple innovation diffusion [5], and thus demand is conserved:

$$life\ extension\ demand + refueling\ resource\ demand = \int satellite\ industry\ growth\ dt$$

while $revenue = sales \times price$ and

$$sales = MIN(refueling\ resource\ demand + supplies\ purchasing; propellant\ supply)$$

Model testing & confidence. This study models a non-existent complex industry, and so must aim for more modest model confidence then usual; some speculation is unavoidable. Unlike for a typical SD (or other) model, we cannot calibrate with historical data. For this reason, we use a 3-part confidence-building approach: we (1) emphasize pre-existing, calibrated SD models & molecules, (2) apply global model tests whenever possible, and (3) supplement SD with scenario planning and GSA. We also note that for our use – articulating a vision, and characterizing large uncertainties – it is not necessary to establish numerical parameters precisely.

Assembling the model from validated model molecules and their associated parameters gives us "local confidence" in the model's subsystems, to pass the "plausibility test". For example the R&D system uses an oil industry model [10], with the key parameter *R&D effectiveness* varying by 2 orders of magnitude about the oil industry's value. For details, the reader is directed to the supplementary material to this article, with the full documented model.

"Global confidence" in the model is trickier to establish given the absence of historical data. We used the 12 standard model tests from Table 21-4 of Sterman [5]; of these, 8 were applied (with 5 especially thoroughly), 3 done in a limited way or not at all, and 1 is essentially not applicable (as the lunar resource ecosystem does not yet exist). In particular: iterative *boundary adequacy* & *structure assessment* tests pass but still yield areas for improvement (Section 6); *parameter assessment* was often difficult but facilitated by our use of ranges; *sensitivity analysis* is a focus of this study; *extreme conditions* tests were applied to most equations; *integration errors* were caught and fixed via running the model on 3 setups (Stella, Vensim, Python); and loops were checked individually via molecule use. We did not calibrate the model globally for other resource industries. *Behavior reproduction* and *surprise* tests could only be done in a limited way. We applied tests that emphasize checking model structure not parameters; they yield the most common modeling errors [5].

Thirdly, our use of scenarios & GSA provides strong extra checks; scenario planning independently builds futures, and gets consistent results. GSA finds model errors [28], and uses parameter ranges (not values — and thoroughly checks them, Section 3.3), leading to a shift in focus to model *structure* (Fig. 8), not precise numerics.

Finally, as discussed in future work, a model interface has been created and distributed. Specialists are continuously challenging the model in an on-going process; the recorded interaction data (and feedback!) generated will direct further modeling effort.

4.4. Scenarios & simulations

Figs. 9 & 10 are simulations representing scenarios.

4.4.1. The Moonopolis scenario

The "Moonopolis" scenario is characterized by plentiful resource finds, strong government support for production, and on the demand side, a significant private on-orbit refueling market (see Figs. 5 & 9). Exploration begins with only a few rovers (Fig. 9, top right) — and

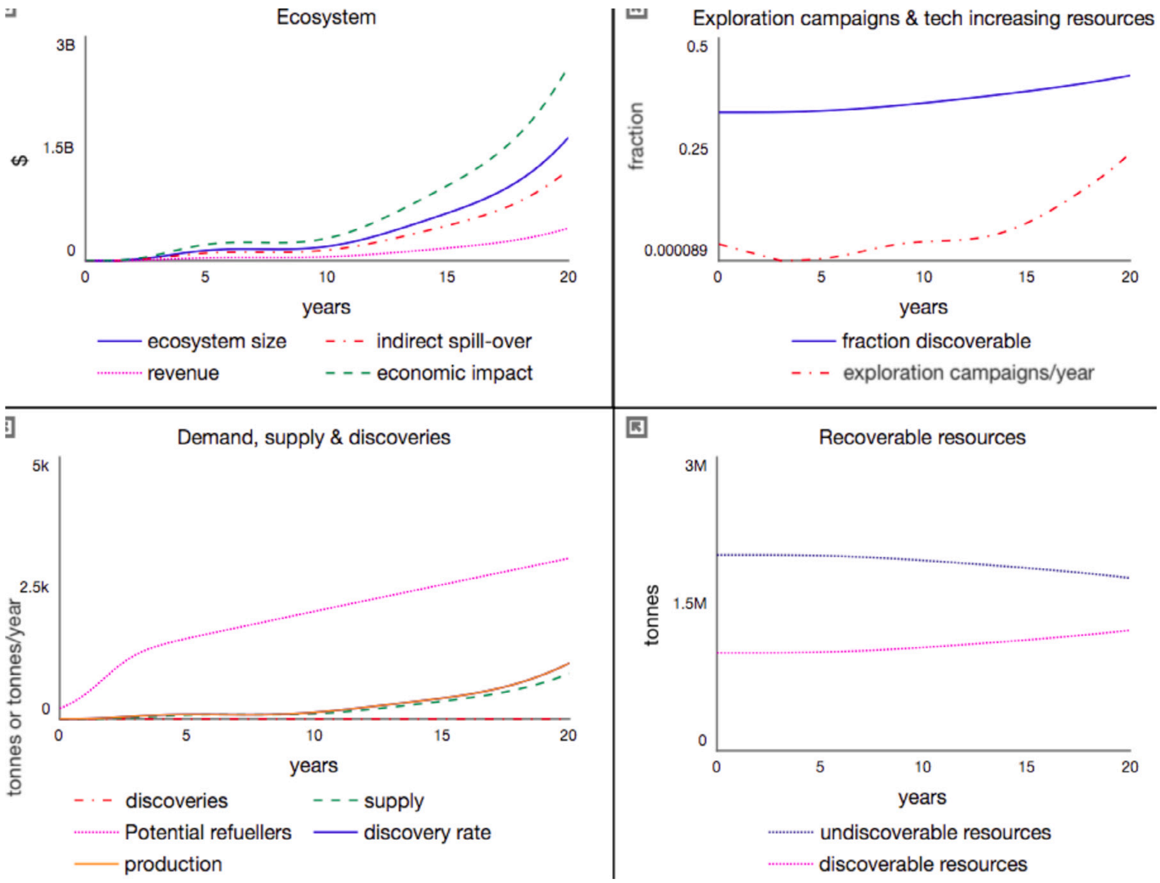

Fig. 10. Apollo 2.0 scenario. Exploration becomes the limiting factor, with ample production capacity (government-supported).

then diminishes, as vehicles etc. are discarded in ~ 3 years (*capital stock*, Figs. 8, 2, 9). But first discoveries are made, signaling probably abundant natural resources! (Fig. 9 bottom left, spread over a 6-year effort) Initial production is online within 5 years, to widespread, feverish enthusiasm. Investment is helped by (1) strong signals of private demand: the SES-ULA contract convinces most telecom operators by 2025; (2) government support for demonstrators via repurposed ISS budgets and large SLS deliveries; and (3) legal clarity on resource finds, from the landmark 2024 mining rights case. All is underpinned by public excitement, with young engineers & entrepreneurs flocking to the industry, and its new symbol of hope & progress. Revenues bring further exploration (Fig. 9, top), after procurement delays, with ever-smaller firms joining the fray. Supplied resources then slowly but steadily increase, bringing more revenue and exploration, helped by steady ~ 10% growth in the GEO satellite industry keeping up expectations. Around Year 9, the last of the 2nd generation exploration systems officially retire, and the effort stagnates (inflection point, top right). Production is limited by discoveries until Year 15, when they begin accumulating and production growth tapers off, for fear of overcapacity. Indeed production tracks demand with a 5-year lag, due to installation delays and muted competition. This creates a downward inflection in revenue, and hence ecosystem size, which nonetheless exceeds $4B/year. Meanwhile rover sensors improve markedly due to experimentation and R&D from reinvested revenue (Fig. 5, bottom right). This helps the discovery rate rise even faster, but due to the ease of finding economic deposits with full campaigns, it has limited impact. No resource depletion effects are noticeable, and ecosystem size is now constrained by demand, via growth in the satellite industry — which stays at GEO. Older systems are repurposed, and the lunar resources industry becomes a vision of resilience & sustainability.

4.4.2. The Apollo 2.0 scenario

"Apollo 2.0" is a low-resources scenario (half of *Moonopolis*'), which nonetheless has robust government support for production, following major human missions to the Moon (see Figs. 5 & 10). From a similar exploration start as *Moonopolis*, initial discoveries are only about half — leaving doubts about its viability. This is driven by smaller finds and fewer discoverable resources in the natural system, and some discoveries facing strong legal barriers, like overlapping "exclusion zones". Negative press probably contributes to growing public opposition to "carving up" the Moon, and to the lack of sustainable thinking in this "colonization" endeavor led by the military-industrial complex. Protests result; the flow of talent to the sector becomes a trickle. Half the revenue as *Moonopolis* leads to half the exploration effort in 5–10 years with 2nd-generation systems (and vanishingly few new entrants), leading to still fewer discoveries, and middling revenues despite government (Fig. 10). Investors are loth to commit, with an uncertain future to the sector beyond initially planned missions — Mars beckons, after all. As a result, though exploration & production pick up by Year 20, production is still far below demand, at only ~ $1.5B/year. Rover tech also improves slowly, with less industry-driven R&D due to lower revenue, and fewer new ideas. Real advances and great expectations from the first human missions look likely to be deflated *à la Skylab* (to the mockery of the tech industry), leaving a controversial "militarized Moon" legacy, from an ambitious but ultimately unsustainable program.

4.5. Sensitivity analysis

Fig. 11 (left) is the result of a local "One-At-a-Time" sensitivity analysis of *ecosystem size* (the main target variable) to each function, around the *Moonopolis* baseline (Fig. 9 & Section 4.4.1). It firstly required

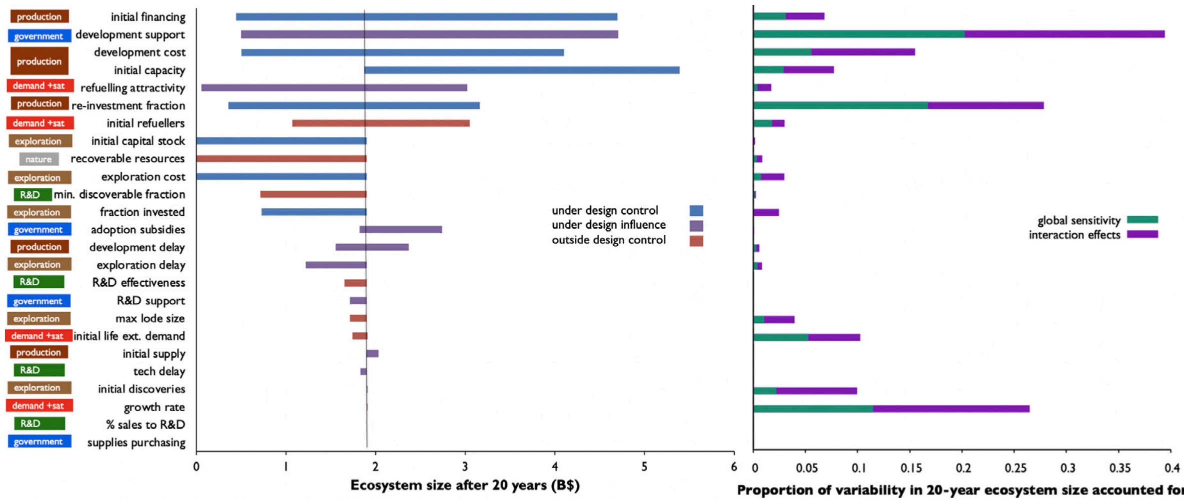

Fig. 11. Tornado plots showing the sensitivity to 25 functional measures & factors locally (left, around *Moonopolis*) and globally (right).

careful, iterative definition of a "large but plausible range of input variation" for each functional measure (on the y-axis), using literature, calibrated values for model molecules, and expert assessment. Fig. 11 (left) means: (a) since tornado width varies a lot, some factors are far more important than others for 20-year ecosystem size. (b) The top half of factors can *each* impact ecosystem size by a factor of 2 or more — thus *Moonopolis* is very sensitive to inputs, and has plenty of upside & downside potential. (c) *Production* dominates these uncertainties (see labels at far left), along with a government "production support" function, and only one factor each from the demand, exploration, natural, and R&D systems. To improve locally on *Moonopolis*, focus on production.

Fig. 11 shows that ecosystem size is relatively less sensitive to exploration factors: investment or R&D levels, exploration costs or delays. This is because we evaluate size after 20 years, and these factors might only create transient delays. This local analysis also assumes substantial discoverable resources, easing exploration requirements.[9] Rather, demand and production are important. For the latter, though we have not yet modeled the production costs, they may not be economical without substantial government funding [2].

Importance also depends on risk posture — the tornado is sorted in a risk-neutral fashion (by width, Fig. 11). The tornado bars are color-coded by whether the associated functional measure is: (1) subject to design by resource firms, (3) almost entirely outside control, (2) somewhere between the two. Many important functions are subject to design or influence, thus this may inform design order and resource allocation.

The right side of Fig. 11 shows a Global Sensitivity Analysis using Sobol' indices. The indices are less intuitive to interpret; the "global sensitivity" (green) represents *the proportion of the variability over the entire output space accounted for by that factor's uncertainty*.[10] They are thus the equivalent of the local tornado over *all possible baselines* within the 25 parameters' ranges. "Interaction effects" show the extra impact of varying many factors simultaneously ($\sim \times 2$ in many cases), over the entire 25-dimensional solution space.[11] Interaction effects may account for almost half the variation. Fig. 11 (right) means: (i) there are large differences in global importance between factors: 3 are crucial, 5 more are important, and 9 insignificant. (ii) Many of the factors important locally are also globally, but not all — and several locally unimportant factors are globally important. Thus, the sensitivity analysis is somewhat sensitive to the choice of baseline, and *Moonopolis* is in a particular regime. (iii) There are strong interaction effects, also *between* systems; broadly, globally important factors interact strongly with others. (iv) Production-related factors remain the most important globally, but demand-related are too, e.g. *satellite industry growth rate*. Thus these loops dominate over "finite resources".

Thus, the structure of the problem seems to be a series of bottlenecks to growth. Production appears to be the main bottleneck locally & globally, with the government support level (for production) also key. Then comes demand, with more muted local & global potential. Resources & exploration effort together form a third bottleneck, though less key in most of the solution space, since often not the chief problem; locally at *Moonopolis* they only have downside potential. R&D (for exploration) is the last bottleneck, apparent only rarely.

5. Discussion

5.1. Insights & significance

We see there are multiple distinct, plausible paths towards a lunar resources ecosystem. This is due to many large uncertainties – technological, economic, natural and policy – each of which may greatly alter ecosystem size and timing. Resolving these uncertainties in various combinations yields different dynamics. Strong interaction effects (nearly doubling many factors' impact) *across* systems show the need to model their coupling.

Our next insight is that using simple physical and economic arguments, the most promising markets for Moon-sourced refueling appear to be GEO telecom and exploration, and possibly GTO apogee-raising. Lower orbits are less likely to be competitive with Earth-sourced propellant, and may have smaller markets — unless LEO constellations fully take over satellite telecom.

Next for the supply side, 2 critical uncertainties stand out, distinguishing 4 futures: the magnitude & accessibility of finds, and the scale of government investment in lunar resources. Others include lunar land rights, and the ability to install production capacity. The former was identified mainly in the scenarios process, the latter in SD model-building — using different ways of thinking: in the first case, by qualitatively assessing the *first* critical uncertainties encountered in time; in the second, by modeling the fully functioning ecosystem, thus

[9] Roughly, if initial fraction discoverable is $\lesssim 0.2$, for $\lesssim$ 1M tonnes of *recoverable resources*, exploration becomes the limiting factor.

[10] They sum to < 1 because there is also "2nd-order" output variability not attributable to a *single* factor, but due to a *combination*.

[11] They sum to > 1 because each term includes the 2nd- (and 3rd- etc.) order interaction effects involving it, thus double-counting them.

focusing attention on its entire lifecycle.[12] The scenarios and model express that the uncertainties may be plausibly resolved in various ways, linked to broader societal trends. Explicit characterization of uncertainties helps consider multiple possible futures, limiting dogmatic arguments about likelihood.

The dynamics of the ecosystem reveal cycles arising from the delays and feedbacks inherent in a new industry. Indeed, considerable delays are inescapable in procuring space missions, carrying out geological exploration, and developing extraction (and processing!) infrastructure. Barring speculation (not yet modeled), further exploration campaigns will need to wait for extraction firms' financing. This positive feedback loop at the root of the ecosystem may take 7–22 years, consistent with other resource industries. Production is unlikely to catch up to exploration due to a later start and greater financing needed. Interestingly, the R&D feedback loop is relatively not so important, as seen in Fig. 11. Indeed, it is overwhelmed by the other uncertainties, like *recoverable resources*: the latter may be very plentiful, obviating the need for much R&D, or non-existent, also rendering exploration R&D useless. Only in the "edge case" of resources is this R&D critical, in the shorter term. Finally, the negative feedbacks due to finite resources and the demand niche ultimately limit the ecosystem size. This leads to the high global importance of *satellite industry growth rate* - implicitly GEO telecom — and initial demand. Thus, the constellation vs. GEO bifurcation of satellite telecom is key.

A maximum $20B ecosystem size[13] is achievable by setting a few factors to the best case: government's production *development support* & *satellite industry growth rate* (both crucial), *initial discoveries* & *life extension demand* (both important), and *initial refuellers* & *service attractivity* (less important, not insignificant). The first 4 alone suffice for a $16B ecosystem: 8× the baseline *Moonopolis*. Many factor combinations can easily stop it as well. The most promising early signposts may be a strong government pledge of support for production, followed by a demonstrator of low production cost, then large early discoveries and demand for satellite life extension — factors from all systems.

Some results of Fig. 11 are artifacts of GSA sample construction: evenly spread over uncertainty intervals, it implicitly assumes uniform probability densities. This is appropriate for many factors but not others, e.g. the plausible amount of recoverable resources varies over 8 orders of magnitude.

KPIs & fulfillment of study objectives. Using Fig. 1 and the KPIs (Section 4, top), we can assess achievement of our objectives. The CLDs & scenarios are largely focused on *clarity of mechanisms* of the ecosystem, which was assessed positively by the practitioner group. The *economic impact* variable measures *value returned to Earth*, which in the best cases performed well for industry expectations, albeit short of the $40B goal. However, no expected NPV calculations were made for the various firms, though it remains relatively easy.[14] Market size, with a maximum of $20B/year, is "fine" but also somewhat less than hoped for by some industry proponents. Including other markets, such as other resource sales, land speculation, and space tourism may be necessary; more modeling detail may also be. Credibility is rated "fairly good" due to the uncertainty quantification, and thus *credibility & market size* scores reasonably. Finally, main levers identified include influencing governments to support production development – which they are already doing somewhat – (re-)designing for low production cost, and pushing for large finds as soon as possible (and early production capacity). Exploration effort takes priority over exploration R&D, currently. Thus, *feasibility of levers* is considered "moderate", the lowest-rated KPI.

Wider insights about the lunar resources ecosystem. Some very simple information is highlighted by the system model: e.g., delays for exploration firm cashflows will be considerable, if they wait for resource purchase by production companies. This is clear simply by verifying ranges of durations for exploration campaigns and production capacity expansion across various resource industries. Thus, any early cashflows for exploration firms will likely have to be based on speculation or futures contracts, or government procurement.

Government support is usually most effective via aid to production development. But this is also much more costly, and not a "fair" (equal-resources) comparison of methods. Where production costs are low and financing available, it is less important.

5.2. Evaluation of methodology & deployment

Considering the study's broad scope and limited resources, many steps were done very summarily. In particular the initial narrowing of candidate markets was due to constraints and the need to prioritize, as much as clear-cut rationale. It is a starting point of study focus after a perfunctory assessment, and *not* a full evaluation of e.g. the constellation refueling market.

Deployment results for the methodology in industry indicate that the up-front data gathering and goal-setting process is quite labor-intensive, perhaps unsurprisingly. Co-creation is deemed necessary, rather than strict data acquisition, and in this process substantial effort must be expended on visualizations and communication of provisional results, to maintain stakeholder engagement and elicit feedback and "buy-in". This may be unavoidable in any strategic decision-making, where high engagement from diverse stakeholders, and clear communication are needed. The framework from Chavy-Macdonald et al. [3] can be fairly well integrated into a broader Systems Analysis and consulting process, though more development would be beneficial, particularly on systematizing interviews with diverse actors, KPIs and model evaluation, and more, better, semi-automated visualizations. Tailoring the process to the project and client at hand is very important [4], [5], and a short "menu" of modeling options with this study's methods might be beneficial to rationalize and improve deployment. A suite of software tools, which probably exist already, can help here. Effective knowledge capture is also a challenge. Overall, key stakeholders maintained good engagement.

Thus the methodology [3] can successfully model and analyze the future of a complex ecosystem, showing engineers how to bring human-system modeling to technology planning. Sensitivity analysis identifies critical uncertainties, useful as design priorities, and prioritizing further modeling effort. Scenarios help explicate assumptions, parameter values, & model context, improving stakeholder understanding & engagement.

6. Conclusion

The primary contribution of this study is a System Dynamics (SD) model & scenarios clarifying the logic of a lunar resource-based ecosystem, integrating technological and socioeconomic dynamics. We treat it similarly to Earth-based resource industries, while apprehending uncertainties — not simply resolving them prematurely ("best guess" approach). In so doing, we help show engineers how to connect human-system modeling & technology planning, when the variables are interdependent, for future planning of a space *ecosystem*. Another research contribution is the first successful operationalization of the original modeling methodology recently developed [3], with a full practical case study based on the needs of a real industrial client. Finally, we help shed light on the complex trade-off of Earth vs. Moon-sourced refueling.

In summary, we have combined societal & technical variables and captured knowledge from dozens of experts to create a holistic model of a future, complex ecosystem around lunar resources. The model is shown intuitively enough to co-create and confront with non-technical

12 But, the GSA for resources suffers from bounds over 8 orders of magnitude, due to geological uncertainties, and hindering sampling.

13 Annual revenue+suppliers; $32B total economic impact (+staff)

14 Long timelines before net revenue, and likely high production costs, suggest projects at commercial discount rates will be ≤ 0 eNPV.

decision-makers; yet it represents a 5th-order system of coupled nonlinear ordinary differential equations. Global sensitivity analysis is then used to provide insight ("importance" for ecosystem size) about the behavior of a 25-dimension solution space, yielding a mathematically rigorous characterization of the soft complex problem. Key variables, priorities, and futures were identified, and strong coupling and interaction effects support the need for a holistic approach. Furthermore, we find futures but also factor *importance* are sensitive to initial assumptions; using variable *ranges* and *global* sensitivity analysis is recommended. The main difficulty is whether one accepts the model structure, and numerical bounds (the input uncertainty ranges).

Further work. Further work includes a dynamic, online interface allowing users to engage with and understand the problem — hopefully also improving the model and analytics. The interaction of this resources ecosystem with the rest of space logistics – constellations, in-orbit refueling, launch costs, debris – warrants examination. More systems and markets should also be added — production operating costs, processing and transport, the impact of land speculators, and especially evolving space law. Fig. 11 prioritizes further modeling and Global Sensitivity Analysis, which should be iterated.

Game theoretic aspects of the different stakeholders would be interesting & potentially valuable to explore, with their individual incentives (e.g. project NPV). Finally, the exceptionally large uncertainties involved likely mean valuable Real Options exist, perhaps in technology development. These should be evaluated.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.actaastro.2021.06.017.

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