Solar System Trade Networks: Insights from Maximum Entropy and the Gravity Model

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Abstract

This paper analyzes which economies emerge as the largest in equilibrium for two plausible early space trade networks. The two networks span the Earth-Moon System and the Earth-Moon-Mars System: the most relevant settings for early space industry. Adapting findings from research on the International Trade Network (ITN), network topology is modelled through a maximum entropy approach which constrains network density to roughly match that of the ITN; network weights follow a specification of the Gravity Model of trade where economically-relevant distance is defined by delta-v. Nodes grow as a function of trade and two equilibrium solutions are simulated (with static and dynamic topology). I find that various key transit points between Earth, Mars, Deimos, and the Moon are most fit to be economic leaders, but the imposed topology constrains their emergence. Concurrently, I relay that political sustainability is the greatest obstacle to space industry, hence the space industry narrative is highly impactful and economists well-positioned to advance it. This paper contributes by exploring the spatial structure of space industry, an important narrative component and infrastructure planning consideration. I invite extensions of the model and encourage further economics research into space industry.

Contents

1 Introduction

The Solar System is endowed with **billions** of times as many useful natural resources as Earth [6, 31]. For example, the main asteroid belt contains 1 billion times more metal than the Earth's crust and its largest asteroid, Ceres, on its own has 1 million times more water than Earth [31]. Likewise, the Sun releases 2 billion times more energy daily than what reaches Earth [31]. Accessing a fraction of the inner Solar System's natural resources could support millions of times the industrial capacity of the US in a century [33], opening avenues to eradicating poverty on Earth. Space industry-related infrastructure would make it economically feasible to rely on space-beamed solar power, which is arguably the best long-term solution to Earth's climate and energy crises [8, 22, 32]. The infrastructure would also transform the landscape of space-related scientific progress, allowing the collection of minute data as far as hundreds of light-years away [7, 32]. It would be a massive boost to humanity's efforts to uncover the unknowns of the universe. What's more, it's been estimated that bootstrapping space industry via a Moon-based economy is economically sound and imminently technically feasible [33]. The greatest obstacle to starting space development is convincing policymakers to allocate the necessary resources [32].

The root problem is that space industry is widely accepted to be science fiction and thus not a politically sustainable investment. To achieve the key ingredient of political sustainability, experts focus on practical projects that bring investors short-term profit and incrementally show leaders that space development prospects are real [32]; and on effectively building the narrative around space industry such that its profitability is clear [47]. Economists have the toolkit to be instrumental narrative builders in this phase of space industry. They can creatively adapt theory to build a clearer picture of what an economic system which extends to space might "look like". Accordingly, I adapt findings related to the International Trade Network (ITN) about the Gravity Model of trade and probabilistic models in network theory to answer the following question. **If we simulate economic growth over time in a plausible early space trade network, which nodes emerge as the economic centers (i.e., the largest economies) in equilibrium?**

I study this question for the two most relevant systems in early space industry: the Earth-Moon System (Figure 1) and the Earth-Moon-Mars System (Figure 2). This addresses a fundamental literature gap about the spatial structure of a Solar System economy. A clearer picture of the spatial development of Solar System industry is obviously policy-relevant because transporting mass in space is currently very expensive [37]. Knowing where to place critical infrastructure and for which types of environments technology should be designed can significantly reduce the costs of bootstrapping space industry. Moreover, this is also one of the most useful insights economics can provide to improve the narrative of space industry. Helping people visualize which places could be part of a Solar System-wide economy, how such vastly distant places could form networks of interaction, and which locations might emerge as "leaders" in these networks makes the idea that our economic sphere of influence could surpass the natural barriers of Earth less vague and far-fetched.

This is especially important because empirical questions like precisely estimating the benefits of starting space industry are intractable. One obstacle is missing data. Such a task would require detailed information about the physical makeup of objects around the Solar System, leading to a huge dataset. However, because of the current lack of space infrastructure, we have limited information even about

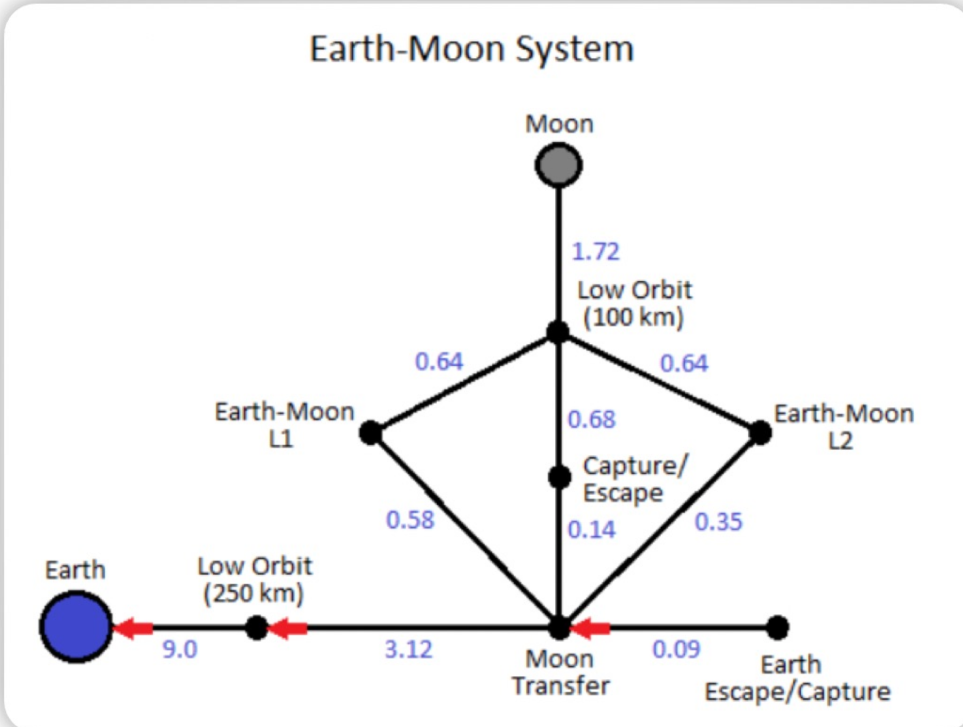

Figure 1: The Earth-Moon System with 9 nodes. Source: [47].

the makeup of the Moon, Earth's closest neighbor [6]. When scientists make claims about the transformative economic prospects of space industry, they can do so without very precise estimates because it's a physical certainty that various bodies are composed of specific materials and the available resources are orders of magnitude more abundant than on Earth. The second obstacle is uncertainty about what will be produced in space and hence what the benefits calculations would involve. Although there's research around the necessary activities of nascent space industry (e.g., a cis-lunar water economy [26]), the best early economic opportunities will only be revealed with more exact data about near-Earth objects and with trial and error from early projects. For longer-term development, the picture becomes more uncertain because of the likelihood of path dependency. Future production possibilities could be constrained by the earliest infrastructure investments if updating infrastructure comes at a significant cost.

In contrast, the tractability of the question addressed in this paper helps make it attractive. I make use of the rich body of research on building network models that reproduce the properties of the ITN. Specifically, the Gravity Model of trade reproduces the weights (i.e., trade volumes) of the ITN provided that the binary topology (i.e., who trades with whom) is pre-specified [42]. A probabilistic model that follows the principle of maximum entropy (an application of Occam's razor) reproduces the binary topology of the ITN [42]. I combine these findings to produce a network model where the topology is generated using a maximum entropy approach, while the weights are generated using the Gravity Model. Furthermore, the positive connection between exports and growth (and arguably the positive causal effect of trade on growth) is well-documented [41]. I argue that trade is essential to growth in a space economy and model growth as a function of marginal exports. This yields a system of differential/difference equations for the economic volumes (i.e., GDP) of the nodes which is solved in two ways.

The first solution is analytical and thus directly delivers the equilibrium relative sizes of the economies, but assumes that network topology is static. Because the topology in the model is probabilistic, I

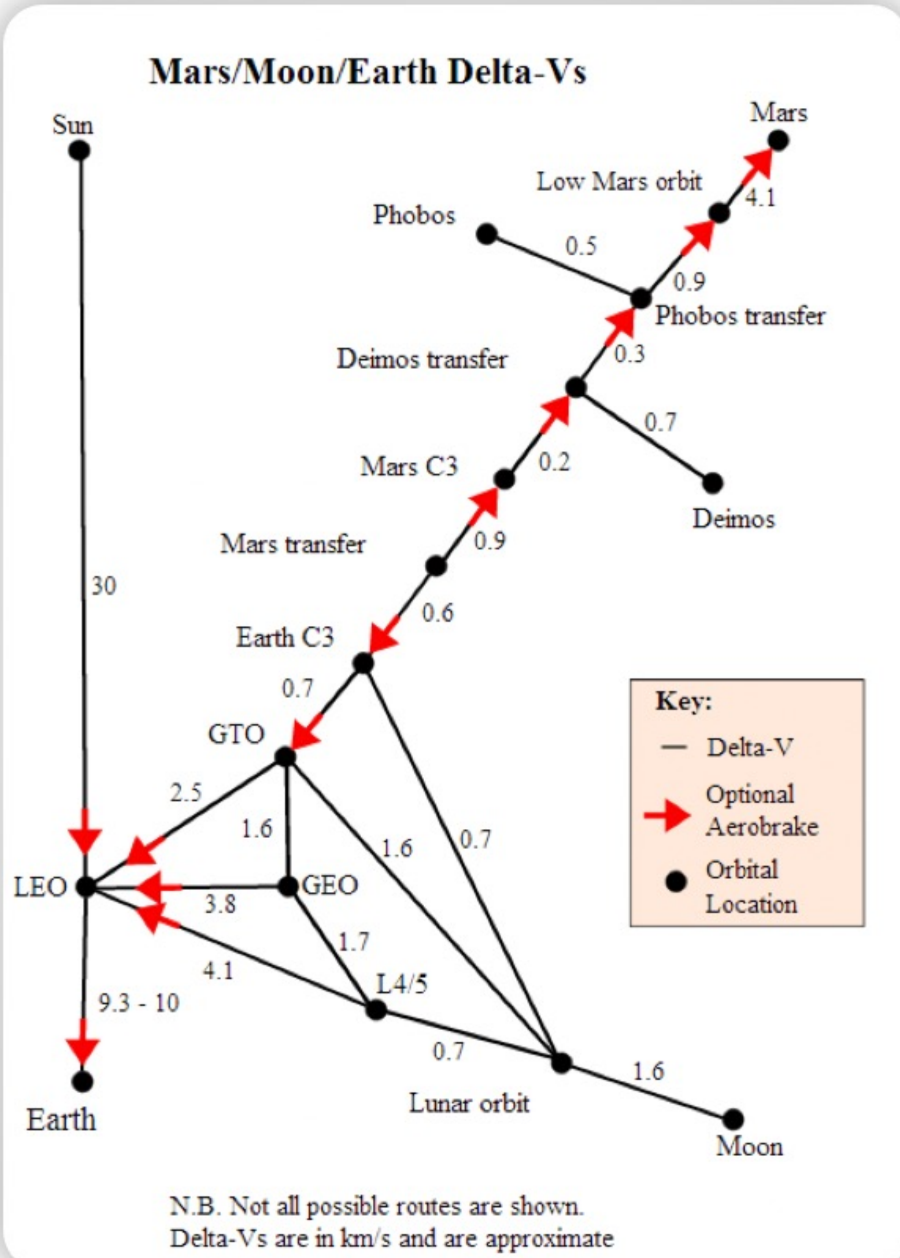

Figure 2: The Earth-Moon-Mars System with 17 nodes. Source: [47].

analyze a large sample of networks and deliver the distribution of results. The second solution simulates economic growth in the networks period-by-period until an equilibrium ordering of relative economic sizes is reached. This solution dynamically updates network topology, but loses the probabilistic aspect of topology in equilibrium (networks always converge to full connectivity). The two solutions deliver similar results. For the Earth-Moon System, I find that the nodes **Earth Escape/Capture** followed by **Moon Transfer Orbit** tend to emerge as economic centers. For the Earth-Moon-Mars System, I find that the nodes **Mars C3 = 0** followed by **Deimos Transfer Orbit** tend to emerge as economic centers. Notably, Earth never emerges as an economic center. All economic centers except Earth Escape/Capture are plausible in early space industry, but findings are limited by what information the model can reasonably include about the "economic suitability" of nodes given the scarcity of economically-relevant data. Nevertheless, the results convey stylized facts about the predicted shift in production away from Earth (for economic and environmental reasons) and which locations are economically favored by the transportation cost structure of the networks. Comparing results between the two types of solutions (which yield different topologies) allows us to see how the emergence of the most "economically suitable" centers is constrained by the imposed topology.

This paper is novel (to my knowledge) in mainly three ways. Firstly, it's the first paper that applies theoretical insights about trade networks on Earth to trade networks in space. I justify this adaptation of knowledge in Section 3.2. Secondly, it's the first paper that uses a hybrid (maximum entropy and Gravity) model for representing trade networks. This has been recognized as feasible, but argued to be inelegant and difficult to interpret [42]. I argue that this hybrid model is the best way for this paper to overcome the missing data which makes a full maximum entropy approach intractable. Moreover, in the second solution with dynamic topology (where interpretation is more problematic than the simpler first solution), I express the maximum entropy topology rule in terms of facts of the Gravity Model to improve cohesion. Thirdly, it's the first paper that uses the maximum entropy approach with hypothesized, rather than real, constraints. I justify this choice in Section 3.2, select constraints which are reasonable to hypothesize, and make the results robust by simulating over different constraint values.

The paper proceeds as follows. Section 2 discusses the literature around: the technical and economic feasibility of space industry, space economics, trade network models, and the links between trade and growth. Section 3 delves into the methodology behind network selection for the simulations, modelling their topology and weights, and relating growth to trade. Section 4 presents the model and demonstrates the two solution pathways. Section 5 presents the results for each network and type of solution over the full range of parameters tested. Section 6 discusses these results in the context of the stylized facts they convey, the timeline under study, and modelling limitations. Section 7 concludes. Section 8 is a PDF of the Mathematica notebook with my code, which defines the functions and procedures which generate the results.

2 Space Industry and Trade

2.1 Technical feasibility of space industry

The technical feasibility of Solar System trade networks is a prerequisite to delving into economic questions. This has been studied formally by a team of senior scientists at NASA, who outlined a technically realistic strategy for achieving an eventually self-expanding and self-sustaining Solar System economy [33]. The strategy is bootstrapping: launching robotics and hardware to the Moon that are programmed to construct new iterations of themselves, initiating a technological spiral whereby the sophistication of the industry and of the output produced increases until it matches the maturity of Earth's industry. This process requires launching mass and teleoperation by humans for roughly 2 decades, after which no more launches from Earth are required and autonomy is possible, meaning production can be unconstrained by inputs from Earth. In other words, this leads to a "self-sustaining, self-expanding lunar industry that will spread across the solar system at no further expense to the Earth's economy" [33].

These findings rest on two sound pillars. Firstly, the natural resources in the Solar System are distributed in a pattern that makes it feasible for space industry to expand outwards from near Earth and are abundant enough such that space industry can greatly surpass the scale of production on Earth. Our knowledge about the formation of the Solar System guarantees that there are resources like metals, ice, and solar energy near Earth which are abundant enough to power a self-expanding lunar industry that can eventually reach the entire System [17, 30]. In fact, the bootstrapping plan doesn't require exports of natural resources from Earth. Secondly, fields like robotics, 3D printing, and AI have seen an explosive rate of innovation in the past few decades, offering us the technical capabilities to begin bootstrapping now. For example, lunar mining robots were originally envisioned to weigh several tons [16], but were being built at 1/10 of a ton as early as 2014 [20]. Robot intelligence has quickly advanced through the equivalent of hundreds of millions of years of evolution: some industrial robots can learn a task overnight with the same accuracy as if programmed by an expert and share their mastery with other robots [23, 25, 34, 35]. Crucial technologies for nascent space industry are being validated already (e.g., see [11, 26, 48]). The first stages of bootstrapping can begin now, while the technological maturity required for the final stage may arrive before 2030 [32].

The process begins on the Moon because of its proximity to Earth, its natural resource endowment which can fuel bootstrapping, and the demonstrated feasibility of adapting relevant Earth-based mining, chemical processing, and metallurgy technologies to the lunar environment. However, it could also involve Near-Earth asteroids because they present similar natural resource endowments and proximity to Earth, limiting transportation costs and radio communications time delay [19]. This reveals that any realistic early space trade network would concentrate around the Earth-Moon System (and the objects within it).

2.2 Economic relevance of space industry

Multigenerational profitability is embedded in the bootstrapping model. The costs of bootstrapping are largely dependent on launch costs. A conservative estimate is that launch costs would command 2%-7% of the existing space budgets of ISS partner nations over 3 decades, while a lunar human outpost (which isn't necessary but highly desirable) would cost 22% of the existing space budgets [32]. These costs would grow prohibitively only if full closure (i.e., no more hardware imports from Earth are required) wasn't achieved by generation 4.0 in the bootstrapping model of [33], which is unlikely. In comparison, the economic benefits can't be overstated. The bootstrapping model projects space industry could have millions of times the industrial capacity of the US within decades. As our economic sphere of influence expands towards the asteroid belt, the resource endowment becomes overwhelming. It's been estimated that the resources of the asteroid belt [31] could support a population of tens of quadrillions of people [28]. Such estimates are hard to verify precisely because of the challenges mentioned in Section 1, but these estimates could be orders of magnitude off and still make the costs of bootstrapping space industry pale in comparison to the benefits. The biggest financial challenge is that the people allocating resources to bootstrapping may have to wait years to see returns on investment and will not live to experience the full returns in perpetuity. For this reason, attention has been dedicated to space projects that attract investors with short-term returns, but also advance our capabilities to establish space industry [32].

Equally important are the environmental benefits. Non-renewable energy sources which predominantly fuel activity on Earth are showing signs of eventual exhaustion [3, 9]. More importantly, the burning of fossil fuels has caused climate change significant enough that the habitability of our planet is threatened. Given Earth's population is estimated to reach 10 billion around 2050 and economic development will continue worldwide, Earth's resources will only be put under more strain [44]. Space industry would allow for space-beamed solar power to become significantly cheaper than environmentally-harmful energy sources and provide access to minerals which are in shortage on Earth but important to scaling up renewable energy [32]. Accessing the abundant resources of uninhabitable places around Earth would allow us to preserve the **only** habitable place. This is the best long term solution to Earth's climate and energy crises [32].

The scientific prospects also deserve attention. Space industry would radically improve data collection capabilities outside Earth; and the associated dramatic economic growth perhaps is the only way through which funding can grow to fulfill the increasingly advanced technological needs of space science [7, 32]. For example, space infrastructure could allow humans to make distributed telescopes 100 million miles in diameter and observe things the size of cars on exoplanets 100 light-years away on their laptops [40]. One can imagine that space industry might fuel a scientific revolution, given how many questions currently remain unanswered about our Solar System[1], not to mention the universe at large.

2.3 Space economics research

Economics literature on space development is very scarce. This is likely due to the challenges alluded to in Section 1, but it also appears that space industry is sometimes considered science fiction in the field [27, 46]. Sandler and Schulze investigated space economics in the 1980s [38], but their referenced framework of space development [36] is now outdated. Since then, radical technological innovations have made the input requirements of space industry orders of magnitude cheaper. More recent studies survey governance issues and what falls under the umbrella of the economics of space [29, 46].

Despite the dearth of economic research, there's a strong conceptual argument that the spatial structure of a Solar System economy can be explored through the lens of trade. While trade on Earth is highly beneficial for participating countries, trade in space is a virtual necessity. No trade nodes (other than Earth) could be autarkic. Environments outside Earth are more highly specialized in terms of natural resources and hostile to life. This lends itself to the proliferation of highly robotized nodes that each specialize in a few production processes, consistently with [33]. These economies would trade high volumes of raw materials, intermediate parts, and final products amongst themselves according to natural endowments and productive advantages. When human outposts are set up on a previously uninhabited node, they will necessarily rely on imports of life-sustaining technologies. In fact, the "economic settlement" of any node will require imports from already settled nodes and constant support as the newly settled node acquires production capabilities. Productive capabilities can't form independently somewhere without life and most nodes might not have the natural endowments or economic rationale to ever be self-reliant. Trade is the lifeblood of space industry.

2.4 Modelling trade networks

Literature from and outside the field of economics extensively investigates how to model trade networks that replicate the properties of their real counterparts. The network which researchers have most prominently used to measure theoretical models against is the International Trade Network (ITN). In network theory language, this is a weighted directed network. In any given year, the ITN conveys which countries export to which other countries (directed network) and how much (weighted network). For a review of the language of networks and the fundamental definitions of their properties, see [13]. For a review of how this network can be mathematically represented and where the data to build it is found, see [14]. For the ITN, theoretical models seek to replicate:

1. The binary topology: information about which countries export to and import from which other countries

2. The weights: information about how much is exported and imported

In empirical trade research, the workhorse model is the Gravity Model [18]. This model is due to Jan Tinbergen [43] and commonly defined as [42]:

$$E[w_{ij}] = G\frac{GDP_i^a GDP_j^b}{d_{ij}^\gamma}, \tag{1}$$

[1]For example, only 1% of the asteroids of the inner Solar System have been discovered by some estimates [31].

where w_{ij} is the export volume from node i to node j and d_{ij} is the economically-relevant distance from node i to node j. A wide range of microeconomic foundations have been shown to lead to formulations of the Gravity Model that match the stylized facts conveyed by equation 1 [2]. Importantly, the model has a decades-long track record of success in empirical explanatory power [5, 24]. Specifically, for the ITN, it has been shown that the Gravity Model reproduces the weights (i.e., the magnitude of exports) given that the topology (i.e., who exports to whom) is pre-specified [14, 42]. However, it is not successful in reproducing the topology of the ITN. The Gravity Model will predict that all countries trade with each other (since they have positive GDP and non-infinite distance between themselves). In fact, the empirical reality is that only roughly 50% of possible trade links exist each year on the ITN [14]. Thus, the Gravity Model is not enough to reproduce the properties of the ITN.

Network theory researchers have adopted the paradigm of probabilistic models of networks to solve this problem. Taking inspiration from statistical mechanics and quantum physics, [42] sought to generate a model for the ITN from the probability distribution that maximizes uncertainty about the ITN given some pre-specified properties of the network. This approach helps reveal which properties of the ITN are maximally informative about its structure (i.e., no other constraints need to be imposed to reproduce its relevant properties). It is known as the maximum entropy principle and follows the same idea as Occam's razor. Mathematically, we maximize Shannon's entropy

$$S \equiv -\sum_{A} P(A) \log P(A), \tag{2}$$

where A is a possible adjacency matrix of the ITN, subject to a set of constraints that represent our chosen pre-specified properties of the network [21]. The simplest constraint to impose is that the density Δ of the network is preserved, which delivers the Erdos-Rényi random graph model [12] where the probability that node i connects to node j is $p_{ij} = \Delta \ \forall i \neq j$.

With respect to the ITN, the only constraint needed to reproduce the topology of the network is the degree sequence, which is a vector specifying the number of trade partners for each country [42]. The implication is that the degree sequence is maximally informative about the topology of the ITN. In contrast, enforcing the strength sequence (i.e., a vector specifying how much each country trades with the rest of the world) as the constraint for the maximum entropy model doesn't reproduce the weights of the ITN. However, jointly using the degree sequence and strength sequence as constraints does reproduce the topology and weights of the ITN [42]. This shows that adding information about the binary topology is essential to reproducing the weights of the ITN (just like for the Gravity Model, where the added information must however be more detailed).

The above findings provide a unified approach to reproducing the weights **and** topology of the ITN, which the Gravity Model can't achieve. We can also use a hybrid approach where the topology of a network is modelled using the maximum entropy principle, while the weights are established using a Gravity Model. We can reconcile the Gravity Model with the maximum entropy approach by expressing p_{ij} in terms of the facts of the Gravity Model [42]:

$$p_{ij} = \frac{zGDP_i GDP_j e^{-\gamma d_{ij}}}{1 + zGDP_i GDP_j e^{-\gamma d_{ij}}}, \tag{3}$$

where z and γ are parameters fixed by imposing that $E[\Delta] = \Delta$ and $E[F] = F$, where $F \equiv \sum_{ij} a_{ij} d_{ij}$ is a measure of the filling of space by the network ($a_{ij} = 1$ if there is a link from node i to node j, 0 otherwise). Strikingly, the model produced by equation 3 reproduces the binary topology of the ITN [42]. Meanwhile, an expression for the maximum entropy-derived weights of the ITN in terms of the Gravity Model hasn't been empirically tested.

2.5 Trade and economic growth

The relationship between trade and economic growth has been widely investigated in the field of economics both by empirical and theoretical researchers. Two highlighted papers are [15] and [45]. [15] uses a gravity model and finds that trade has a quantitatively large positive effect on a country's income. The authors suggest trade raises income by stimulating the accumulation of physical and human capital and increasing output per given levels of capital. [45] suggests that a group of East Asian export-oriented economies which have grown at history-defying high rates have done so by using exports to counteract the cooling effects of diminishing marginal returns to capital.

[41] provides a comprehensive review of the empirical evidence connecting trade to growth. He finds that "the macroeconomic evidence provides dominant support for the positive and significant effects of trade on output and growth, while the microeconomic evidence lends larger support to the exogenous effects of productivity on trade, as compared to the effects of trade on productivity" [41]. While noting the methodological challenges to estimating the effect of trade on growth, the most important takeaway for this paper is the consistently positive association between economic growth and trade, particularly as measured by exports.

3 Methodology

3.1 Network selection

No trade networks outside of Earth exist, so an important first question is which possible network configurations should be analyzed. We've established that nascent space industry would revolve around near-Earth objects like the Moon. Importantly, the layout of natural resources in the Solar System hasn't been precisely mapped, and even if it had, there is uncertainty about which natural resources will be most sought out decades/centuries in the future when Solar System trade matures. Thus, it's reasonable to select potential trade networks extending from the Earth-Moon system with nodes which are well-studied and circulated. The benefit of picking these well-studied nodes is twofold. Firstly, it means that relevant distance information about them for the purposes of network modelling is accessible. Secondly, it's reasonable to assume that space trade and the associated infrastructure will be built out on the routes that experts are already familiar with in order to minimize transportation risks.

It's reasonable to have planetary and orbital nodes in such trade networks. The rationale for planetary nodes is immediate, as even some planetary surfaces other than Earth can sustain human populations, especially if terraformed. The rationale for orbital nodes is more subtle. Because of the gravitational pull of planets, supply chains which don't have to lift off from planetary surfaces save significant energy. Thus, it'd be ideal for supply chains and production to happen in orbit, and for goods to reach planetary surfaces only if that's their final destination or a part of the supply chain can only be carried out on the planet. For example, the Mars surface is a poor candidate to be an exporter of manufacturing goods for this gravitational reason [32]. What's more, travelling from an orbit to a planet requires less energy than travelling from said planet to said orbit if the planet has an atmosphere, which helps aircraft save fuel slowing down. Thus, it's not as costly for goods to be produced in orbit then transported to consumers on planetary surfaces with atmospheres.

The first network to be analyzed (Figure 1) is the most relevant to nascent space industry, as it studies the Earth-Moon System with 9 proposed nodes. Table 1 lists the nodes in the order in which they appear in computations. Aside from Earth and the Moon, there are 7 nodes representing widely circulated orbits between the two bodies. The numbers associated to links between the nodes represent the delta-v required to travel between them. Delta-v measures the impulse per unit of spacecraft mass required to perform a maneuver [10]. The maneuver assumed by the delta-v values uses a Hohmann transfer orbit, which often uses the least amount of fuel in travelling between two orbits [1]. The red arrows signify the links and direction on which Earth's atmosphere can be taken advantage of to reduce the required delta-v. There is no universal amount by which delta-v can be reduced between any two nodes because it depends on the aircraft aerodynamics. However, from expert discussions,

Node Number	Earth-Moon System Node
1	Earth
2	Low Earth Orbit
3	Moon Transfer Orbit
4	Earth Escape/Capture
5	Earth-Moon L1
6	Lunar Escape/Capture
7	Earth-Moon L2
8	Low Lunar Orbit
9	Moon

Table 1: The 9 nodes in the Earth-Moon System in the order in which they appear in computations.

Node Number	Earth-Moon-Mars System Node
1	Earth
2	Low Earth Orbit
3	Earth-Moon L4/5
4	Geostationary Orbit
5	Geostationary Transfer Orbit
6	Low Lunar Orbit
7	Moon
8	Earth C3 = 0
9	Mars Transfer Orbit
10	Mars C3 = 0
11	Deimos Transfer Orbit
12	Deimos
13	Phobos Transfer Orbit
14	Phobos
15	Low Mars Orbit
16	Mars
17	Sun

Table 2: The 17 nodes in the Earth-Moon-Mars System in the order in which they appear in computations.

a reasonable rule of thumb is that each red arrow indicates a 50% reduction in required delta-v over the link in its direction [47]. Finally, to travel between any two non-neighboring nodes, we add up delta-v's along the lowest delta-v network path from one node to the other.

The second network to be analyzed extends the system to Mars and related orbits (Figure 2). Table 2 lists the nodes in the order in which they appear in computations. The Sun is not a realistic productive node, but is included in the network to illustrate the unattractiveness of trade with high delta-v. Mars is the most important extension to the Earth-Moon System. It's uniquely endowed to support human colonization, it's the closest planet to Earth (other than Venus, whose environment is extremely hostile), and it's the closest inner planet to the wealthy asteroid belt [49, 50]. It's the subject of nearly as many scientific studies and engineering projects as the Moon, and SpaceX has a plan to build a city on Mars within the next few decades [4]. As the prime target for human colonization and the key node connecting humans to the asteroid belt, Mars plays an essential role in early space trade networks.

These two networks are good representations of the regions involved in early Solar System trade. Networks that are even larger than the one in Figure 2 would extend to the asteroid belt and Outer Solar System. Such distant places would only be reached when the industry matures, in the more distant future. Thus, analyzing networks including such nodes is beyond the purposes of this paper, which explores early space trade networks. Analyzing such distant nodes will likely only become imminently relevant after near-Earth space development, at which point there will be much more empirical and theoretical knowledge to inform trade modelling.

3.2 Topology of Solar System trade networks

I simulate the topology of the networks using the maximum entropy framework. This is successful for the topology of the ITN, as stated in Section 2.4. However, when it comes to Solar System trade networks, the lack of empirical data presents a challenge. There are no observed degree or strength sequences to employ as constraints in the maximum entropy approach for my networks, and there is no theoretical basis upon which to reasonably assume the degrees and strength of nodes (other than perhaps Earth). With respect to the topology specification given in Equation 3, there are no existing GDP figures for nodes other than Earth, and again no theoretical basis upon which to reasonably project such figures.

Nevertheless, the research on the ITN is still enlightening for this work. The lack of precise empirical constraints for the maximum entropy approach is overcome by the following argument. The maximum entropy approach is a conceptually satisfying approach to modelling uncertainty in networks because it makes explicit and minimizes the assumptions we make. Moreover, if we use this approach with the simplest constraint that fixes the density Δ of the network, we get the Erdos-Rényi random graph model: $p_{ij} = \Delta \; \forall i \neq j$. This random model is both mathematically convenient for simulation and intellectually satisfying. It captures the intuition that such networks are projected to activate far enough in the future that there's high uncertainty about the likely properties of the networks. For example, there's no basis to argue that any given pair of nodes would always trade or never trade (restricting p_{ij} for some $i \neq j$). As such, there is no loss of information in using the random model of networks. Finally, although there is no observed density for these networks, this constraint is much easier to reasonably assume than the degree or strength sequence. Density is scalar rather than a vector and requires much less specificity in assumptions about network structure.

I "borrow" the fact that $\Delta \approx .5$ on the ITN [14] as the constraint for the maximum entropy framework. To account for the fact that I'm "borrowing", I run simulations with two constraints:

- $\Delta = .5$
- $\Delta = .6$,

to see how reasonable changes in the key constraint affect the final solution. Because we're working with small networks, imposing that Δ is significantly higher (lower) than these values delivers an almost fully connected (unconnected) network. Neither of these situations is very reasonable. On the one hand, it's hard to imagine an almost fully connected network in a space setting, where transportation costs are so significant. On the other hand, it's hard to imagine an almost fully unconnected network in a setting with highly specialized nodes that (largely) can't be autarkic and for which infrastructure is developed in a centralized manner.

Moreover, we could assume Earth imports from many other nodes because Earth is where the vast majority of consumers will live. Thus, we can segregate simulations where Earth imports from many sources from the larger sample and compare the results between the two. Let the rule for selection into a "realistic sample" be that Earth has an in-degree of at least $\Delta * (N-1)$, where N is the number of nodes in a network. This is the expected in-degree of Earth, so this isn't a prohibitively high threshold.

As a caveat, one of the solutions to the model in Section 4 allows us to simulate the relative GDP volumes of nodes in our networks without needing to make accurate projections of these figures. This allows us to use the topology rule given in Equation 3. The practical choice of parameters is discussed in Section 4.2.

3.3 Network weights and trade-based growth

Section 2.4 establishes that the Gravity Model is successful in reproducing the weights of the ITN. I use a specification of the Gravity Model conceptualized by [47] for space trade networks to model the weights (i.e., trade flows) of the networks under study. It's reasonable to think trade volumes in a Solar System network would follow a Gravity-like model. In fact, for the foreseeable future, it's even easier to see the debilitating effect on trade of distance because transporting mass in space is much more expensive and technologically-complex than on Earth.

Section 2.5 establishes the positive link between exports and economic growth. Macroeconomic studies of this link, which are most relevant with respect to our discussion of the Gravity Model, predominantly suggest that exports have a positive causal effect on economic growth [41]. Notably, all that's strictly required for modelling purposes is that the positive relationship between trade and growth is well-established. This gives us a basis to express economic growth for the nodes in our networks as a function of marginal exports. Economic growth is trade-driven in the model.

4 The Model

The following model follows [47]. Let the trade flows (i.e., exports) from node i to node j in a trade network be

$$f_{ij} = G\frac{V_i V_j}{D_{ij}^b}, \tag{4}$$

where V_k is the economic volume (i.e., GDP) of node k and D_{ij} is the economic distance from node i to node j. The model assumes this economic distance is measured by delta-v. A simplifying effect of this is that economic distance is mass-independent. The reasoning for this assumption comes from the nature of orbits. An object in orbit constantly changes its position relative to an object in another orbit, so if productive units are placed at a fixed point in orbit, trade is complicated (and sometimes made impossible) by the fact that the economic distance between them is ever-changing. A solution which would allow trade to happen at any time is that (small) productive units are spread across the entire orbit. In this case, higher trade volumes are achieved by sending more units of a standardized mass rather than a higher mass of goods, which removes the mass-dependence of the economic distance [47].

The marginal trade flows of node i with node j are then defined as

$$\phi_{ij} = \frac{\partial f_{ij}}{\partial V_i} = G\frac{V_j}{D_{ij}^b}. \tag{5}$$

In the model, economic growth is trade driven, so we have

$$\frac{\partial V_i}{\partial t} = \gamma \sum_j \phi_{ij}. \tag{6}$$

Equivalently, for the vector of economic volumes,

$$\frac{\partial \vec{V}}{\partial t} = \gamma G \tilde{D}.\vec{V}. \tag{7}$$

$\tilde{\mathrm{D}}$ is a matrix containing not just the elements D_{ij}^{-b}, but also the topology of a network. Specifically,

$$\tilde{D}_{ij} = \begin{cases} 0 & \text{if node i doesn't export to node j,} \\ D_{ij}^{-b} & \text{otherwise.} \end{cases} \tag{8}$$

There are two ways to deliver the potential economic centers of a network from this model.

4.1 Analytical static solution

The first approach looks at the form of the solution to Equation 7. The solution is given by [47]

$$\vec{V}[t] = e^{\gamma G \tilde{D}} \vec{V}[0]. \tag{9}$$

By spectral decomposition, it can be shown that the dominant component of this solution is the largest eigenvalue of $\tilde{\mathrm{D}}$, say d_{max}. The nodes grow economically at the common rate $\gamma G d_{max}$. The relative economic sizes of the nodes in the network are given by the components of the eigenvector corresponding to d_{max}, say $\vec{p}^{max}$ [47].

This solution assumes that the topology of the network is constant over time, i.e., $\tilde{\mathrm{D}}$ stays the same. We can rationalize this by imagining that, since bootstrapping space industry requires centralized commitments, the topology of the trade network would be pre-determined in order to solve an optimization problem and maintained throughout the period of our study (early space industry). We could also maintain that the topology of the network in each period is generated through the maximum entropy approach with a constant constraint.[2]

This solution suggests that the determinant of economic centers for our Solar System networks is $\tilde{\mathrm{D}}$: the interaction between the topology of the network and the economic distances (measured in delta-v) between the nodes.

Because the topology of the network is given by a matrix of $N(N-1)$ random variables ($p_{ii} = 0 \ \forall i$), I simulate 10,000 topology matrices for each of the 2 proposed constraints ($\Delta = .5$ and $\Delta = .6$) and piece-wise multiply them with the delta-v matrix D to arrive at $\tilde{\mathrm{D}}$. The economic distances need to be taken to the power $-b$ to formulate $\tilde{\mathrm{D}}$, so we must select a value for b. The economic distance between nodes is a measure of the energy required for travel, and according to [47], transportation costs in space increase convexly with distance. If a rocket trip requires more delta-v, fuel must be added for the extra energy expenditure, and some more fuel must be added because of the extra weight of the increased fuel stock. This suggests $b > 1$.[3] I carry out each simulation for $b = 1.5$ and $b = 2$. I bound b upwards at 2 by analogy with Newton's law of universal gravitation, but more formally it's unrealistic that transportation costs are more convex than this, given the physical origin of the convexity.

4.2 Iterative gravity solution

The second type of solution allows for the topology of the network in question to be updated periodically according to Equation 3, reformulated for this solution as:

$$p_{ij} = \frac{z V_i V_j e^{-\tau d_{ij}}}{1 + z V_i V_j e^{-\tau d_{ij}}}. \tag{10}$$

[2] However, that wouldn't quite deliver the same topology each period, just the same imposed network properties.

[3] For reference, estimations of b for the ITN (on Earth) suggest $b \approx 1$ [42].

I determine the initial topology of a network using this rule, given an initial vector of economic volumes $\vec{V}[0]$. I use Equation 6 to calculate economic growth for each node based on this topology. The solution continues iteratively:

1. Given a network topology, run through 5 periods of economic growth according to Equation 6;

2. Then re-determine the topology according to Equation 10 and go back to step 1.

There is no strict indication for a stopping point, so I verify relative economic volumes throughout the loop and stop when a pattern is well-established. The topology updates less frequently than the economic volumes. Conceptually, this is because trade relationships take time to develop and dissolve, so it's reasonable to have nodes trading with the same partners for a number of periods, just like on Earth. Practically, this helps delay the point at which the network in question is fully connected,[4] which happens with probability 1 as economic volumes grow.

This approach requires me to choose $\vec{V}[0]$, z and τ in Equation 10, and G, γ, and b in Equation 6. To avoid requiring a prohibitively high number of simulations for interpretability, we must be selective.

The $\vec{V}[0]$ component in the solution to Equation 9 doesn't dominate, so the choice doesn't meaningfully affect the final system [47]. Thus, we can simulate with only 1 instance of $\vec{V}[0]$. However, $\vec{V}[0]$ must have only non-zero components in this model in order to avoid having nodes which always have $V_i = 0$. It's reasonable that Earth has a much larger initial economic volume than any other node. Thus, Earth will be assigned a high random initial volume, while the other nodes will be assigned a low random initial volume.[5]

The parameters G and γ only influence the common growth rate, so they won't change the ordering of economic centers [47]. I set $G = \gamma = 1$ for simplicity. The simulations either use both values of b as discussed in Section 4.1 or just one of them, depending on whether b affects the conclusions of the first solution. Finally, z and τ are fit in studies of the ITN to match the properties of the observed network, so they will significantly affect (at least) the initial topology of a network. I simulate for two values (low and high) of each[6] and compare results. Because the networks always tend to full connectivity, the randomness of topology is effectively eliminated by the time stable orderings emerge, so there's no need to create samples of networks for this solution.

5 Results

5.1 Analytical static solution results

5.1.1 Earth-Moon System

Table 3 summarizes insights about the economic centers for each combination of parameters and points out whether the "realistic" sample (as defined in Section 3.2) gives different results. For each combination of parameters, nodes 4 (Earth Escape/Capture), 3 (Moon Transfer), and 6 (Lunar Escape/Capture) dominate. Increasing Δ appears to exacerbate the dominance of nodes 4 and 3. This suggests that the delta-v structure of the network favors these locations, since increasing Δ extends trade connection opportunities equally for all nodes on average. Meanwhile, whether $b = 1.5$ or $b = 2$ doesn't meaningfully affect the results. Finally, restricting the sample to "realistic" networks (i.e., $D_{in_{Earth}} \geq \Delta(N-1)$) eliminates roughly 40% of networks from the sample, but it doesn't meaningfully affect results either.

For illustrative purposes, Figure 3 shows the relative economic sizes of the nodes in the Earth-Moon

[4] Another way to achieve this would be to introduce periodic random negative shocks in some nodes' economic volumes.
[5] I make no assumption distinguishing any of the non-Earth nodes amongst themselves due to uncertainty.
[6] A more complex procedure would be to fit z and τ at each topology-updating step so that a hypothesized constraint about the network is satisfied, but this somewhat restricts the topology from being truly dynamic.

Parameters	Largest Economy	Second Largest Economy	Realistic Sample Differences
$\Delta = .5, b = 1.5$	$4(51\%) > 3(27\%)$	$3(36\%) > 6(26\%)$	Negligible
$\Delta = .5, b = 2$	$4(51\%) > 3(27\%)$	$3(37\%) > 6(25\%)$	Negligible
$\Delta = .6, b = 1.5$	$4(61\%) > 3(24\%)$	$3(46\%) > 6(28\%)$	Negligible
$\Delta = .6, b = 2$	$4(61\%) > 3(24\%)$	$3(47\%) > 6(28\%)$	Negligible

Table 3: Simulation results regarding economic centers in the Earth-Moon System. Nodes 4 (Earth Escape/Capture), 3 (Moon Transfer), and 6 (Lunar Escape/Capture) dominate. Source: Values from Mathematica notebook.

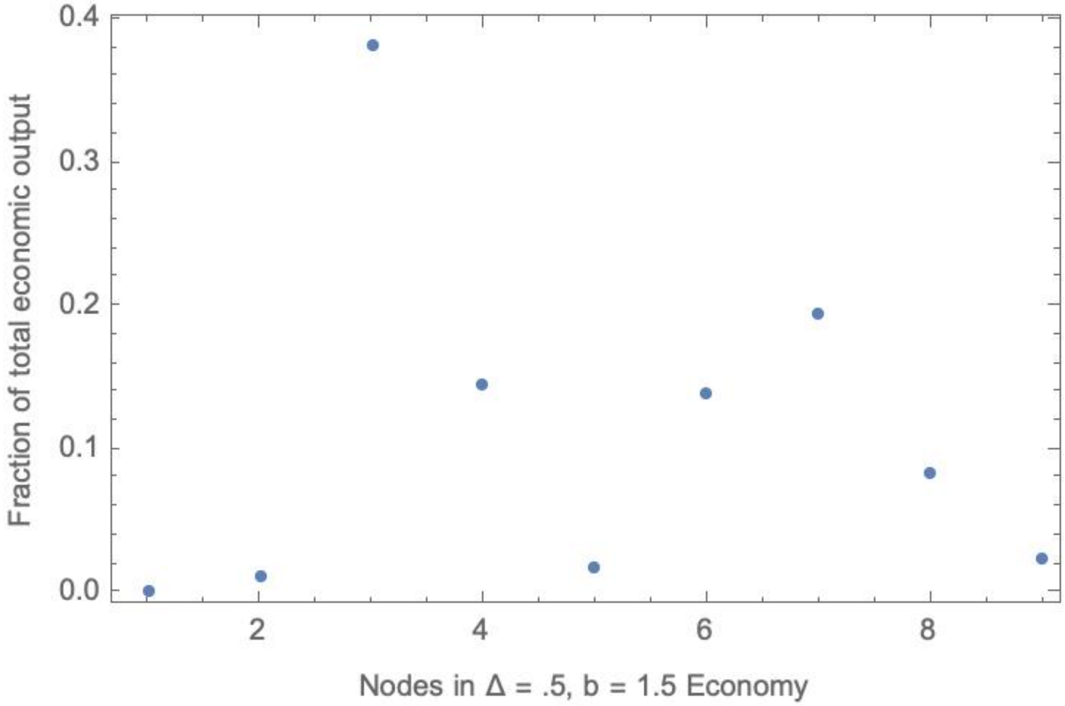

Figure 3: Relative economic volumes for a randomly chosen Earth-Moon System network from the sample with $\Delta = .5$ and $b = 1.5$. Source: Mathematica notebook.

System for a randomly-chosen network in the sample with $b = 1.5, \Delta = .5$. For this draw, nodes 3 (Moon Transfer Orbit) and 7 (Earth-Moon L2) account for nearly 60% of total output. Strikingly, Earth (node 1) is a relative economic backwater. This is, in fact, the norm over the samples studied.

Figures and computations for all results mentioned in this section can be found in Section 8.1.1 of the Appendix.

5.1.2 Earth-Moon-Mars System

I carry out simulations for the same combinations of parameters for the Earth-Moon-Mars System in Figure 2. The results about economic centers are summarized in Table 4. Nodes 10 (Mars C3 = 0), 11 (Deimos Transfer), and 13 (Phobos Transfer) dominate. We come to the same conclusions about the parameters Δ and b and about restricting the sample to "realistic" networks as in Section 5.1.1. Specifically, the delta-v structure of the network appears to favor nodes 10 and 11.

For illustrative purposes, Figure 4 shows the relative economic sizes of the nodes in the Earth-Moon-Mars System for a randomly-chosen network in the sample with $b = 2, \Delta = .6$. For this draw, nodes 10 (Mars C3 = 0) and 13 (Phobos Transfer) account for roughly 55% of the total economic output. Once again, Earth (node 1) is an economic backwater, which is also the norm for this network.

Parameters	Largest Economy	Second Largest Economy	Realistic Sample Differences
$\Delta = .5, b = 1.5$	10(53%) > 11(31%)	11(38%) > 13(22%)	Negligible
$\Delta = .5, b = 2$	10(53%) > 11(32%)	11(38%) > 13(23%)	Negligible
$\Delta = .6, b = 1.5$	10(62%) > 11(29%)	11(50%) > 13(22%)	Negligible
$\Delta = .6, b = 2$	10(63%) > 11(30%)	11(50%) > 13(22%)	Negligible

Table 4: Simulation results regarding economic centers in the Earth-Moon-Mars System. Nodes 10 (Mars C3), 11 (Deimos Transfer), and 13 (Phobos Transfer) dominate. Source: Values from Mathematica notebook.

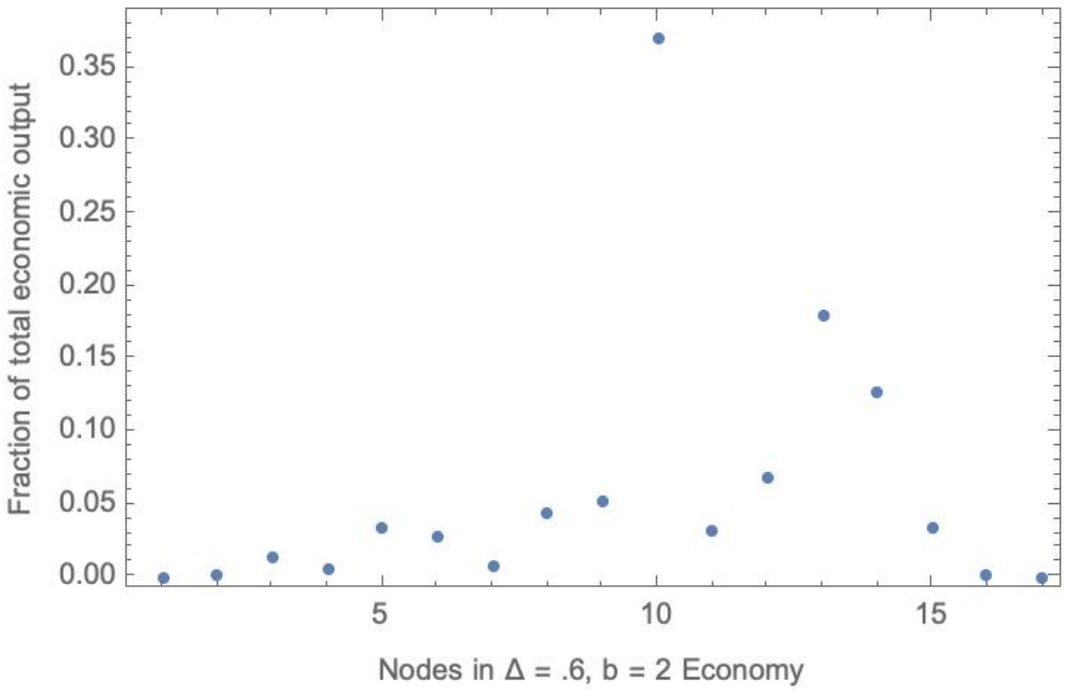

Figure 4: Relative economic volumes for a randomly chosen Earth-Moon-Mars network from the sample with $\Delta = .6$ and $b = 2$. Source: Mathematica notebook.

Unsurprisingly, the Sun (node 17) is also an economic backwater.

Figures and computations for all results mentioned in this section can be found in Section 8.1.2 of the Appendix.

5.2 Iterative gravity solution results

Since the value of b doesn't impact the simulation results in Section 5.1, I simulate here with $b = 1.5$. This reduces the number of required simulations from 16 to 8, allowing us to focus on the more impactful parameters of z and τ. The simulation values for z are 0.1 and 0.03. The simulation values for τ are 1 and 2. These were chosen heuristically such that the initial topology delivers neither a nearly fully connected network nor a nearly fully unconnected network, which are unreasonable configurations. I simulate 15 periods of economic growth for each combination of parameters, which corresponds to 2 topology updates (after period 5 and period 10). This is enough for stable orderings of economic centers to emerge.

5.2.1 Earth-Moon System

We would expect a lower z and a higher τ to make the initial network configurations scarcer. This is indeed the case, and the initial network topology is highly dependent on the values of z and τ.

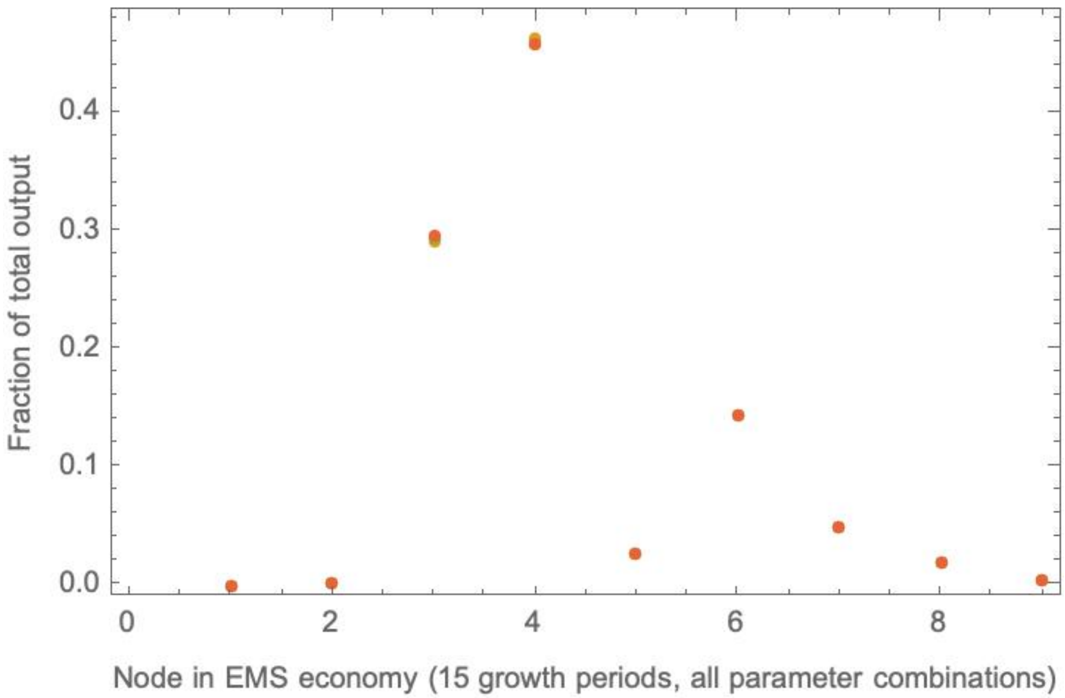

Figure 5: Overlapping equilibrium relative economic sizes of nodes in the Earth-Moon System under all 4 parameter combinations. Source: Mathematica notebook.

However, for every parameter combination trialled, after at most 10 periods of growth (and thus 1-2 topology updates), the network is fully connected. Moreover, the relative economic sizes of the nodes are strikingly similar for all 4 parameter combinations (Figure 5). There is minuscule disagreement about the sizes of the 2 biggest economies, but the ordering and approximate sizes are preserved. We know this is an equilibrium ordering because a fully-connected network rules out ordering reversals in this model. Notably, these results are consistent with the static solution in Section 5.1.1 where node 4 is most frequently the largest economy and node 3 is most frequently the second largest economy. The difference is that in this iterative solution, this always happens.

While the parameters z and τ don't meaningfully affect the final conclusion about economic centers for this network, they can affect how quickly the conclusion is reached. With $z = .1$ and $\tau = 1$, a fully connected network emerged after 5 periods, while it took 10 periods under every other parameter combination. Full connectivity happens unavoidably with fixed z and τ, because the economic volumes $\vec{V}[t]$ grow to values high enough that the probability of each link existing is effectively 1. This suggests that using the topology rule given by Equation 10 might not be as suitable for evolving networks. Nonetheless, this solution is useful in that it shows how economic centers develop under a changing topology (from a somewhat scarce network to a complete network).

Figures and computations for all results mentioned in this section can be found in Section 8.2.1 of the Appendix.

5.2.2 Earth-Moon-Mars System

The conclusions here are nearly identical to Section 5.2.1. In the simulations with $\tau = 2$, full connectivity isn't reached after 2 topology updates, as the Sun is excluded from trade relationships. However, the economic distances to the Sun are so large that extending the simulations until a fully connected network is reached wouldn't affect the results about economic centers. Thus, after 15 periods of growth, we obtain the equilibrium relative economic sizes given in Figure 6. The result is consistent with the result in Section 5.1.2: node 10 is the largest economy, while node 11 is the second largest.

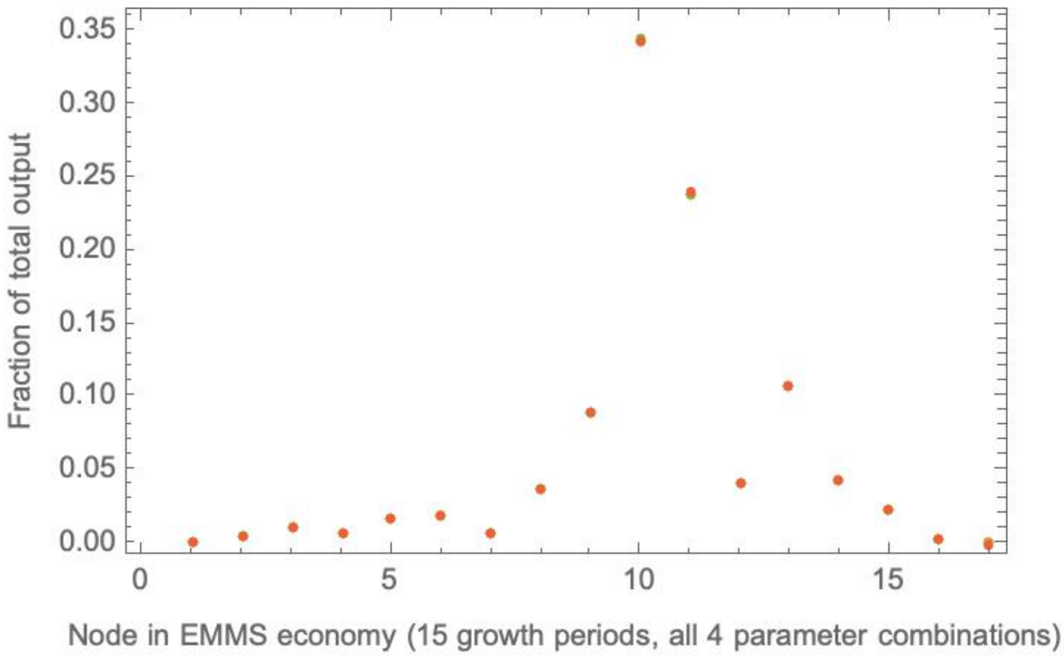

Figure 6: Overlapping equilibrium relative economic sizes of nodes in the Earth-Moon-Mars System under all 4 parameter combinations. Source: Mathematica notebook.

Figures and computations for all results mentioned in this section can be found in Section 8.2.2 of the Appendix.

6 Discussion

Comparing the results in Section 5.1 and 5.2 demonstrates that the topology of a trade network constrains the formation of the most "economically sound" productive centers in equilibrium. In Section 5.2, as the EMS (EMMS) trade network became fully connected in equilibrium, we saw nodes 4 and 3 (10 and 11) become economic centers in equilibrium with probability 1. This suggests that the economically-relevant structure of the network (in this case largely determined through delta-v) favors these nodes. These nodes were most frequently dominant in the static topology solution of Section 5.1 too, but not always. For network realizations in which they weren't dominant, it must be the case that the Erdos-Rényi topology was unfavorable to them.

Is there a theoretical justification for the findings of the simulation about the observed economic centers? For the Earth-Moon System, node 4 (Earth Escape/Capture) represents the key transit point to the rest of the Solar System. In a Solar System where industry extends as far as the asteroid belt, this result would make sense, as the rest of the Solar System is much more resource-rich than the Earth-Moon System. However, in the context of early space industry (where economic infrastructure might not extend beyond the Earth-Moon System), this result doesn't make as much sense, because we'd imagine production is concentrated around the Earth, Moon, and near-Earth asteroids. The model is, of course, unaware of this. The second most dominant node of the simulations, node 3 (Moon transfer), is more theoretically justified. It's analogous to a region with hub airports connecting Earth and the Moon [47], which would reasonably be highly circulated and see heavy infrastructure development. For the Earth-Moon-Mars System, node 10 (Mars C3 = 0) represents a pathway away from Mars towards the rest of the system under analysis. This would make sense as the location of an economic center if significant production were to be distributed outward from the vicinity of Mars to Earth and near-Earth locations. This is not an impossible scenario, given the high amount of asteroids between Earth and Mars [39]. Node 11 (Deimos transfer) is suitable as an economic center if Deimos becomes an important source of resources. Although much smaller than the Moon, it has been identified as a target for in-situ resource utilization because of its useful physical properties [39].

These results are notably limited by the fact that we can only use the delta-v structure of the network as a determinant of the economic "viability" of nodes. The limitation is evident from the outcomes for Earth. Although Earth begins the simulations in Section 5.2 with the largest economic volume by far, it always figures as an economic backwater in equilibrium. It could be the case that the vast majority of production happens off Earth in a mature Solar System economy, as humanity can respect Earth's competitive advantage (habitability) and outsource production to uninhabitable places. However, Earth wouldn't play such a small productive role in early space industry, which is the focus of the studied networks. Nevertheless, the results of the simulation incidentally capture the following facts:

1. non-Earth nodes have the physical capacity (via natural resource volume, lower opportunity cost of exploitation, and literal space) to produce output on a much larger scale than Earth, and

2. non-Earth nodes can economically grow at much higher rates than Earth, especially in early space industry.

7 Conclusion

Bootstrapping space industry is technically feasible and affordable, and it presents transformational economic, environmental, and scientific benefits for humanity. To my knowledge, no other investment can present (long-term) returns as great as this. The greatest obstacle to space industry is political sustainability: decision-makers need to be convinced that space industry is within reach and a good investment. Because of this, the space industry narrative that circulates society is highly influential. Economists are authoritative and politically influential voices on matters related to the allocation of resources and policymaking. They have the tools and exposure to play a main role in shaping the space industry narrative.

This paper explores the potential spatial structure of two early space trade networks connecting Earth with the Moon and Mars, the two most important settings for early space industry. Specifically, I find which nodes in trade networks spanning the Earth-Moon System and Earth-Moon-Mars System emerge as economic centers in equilibrium. For the Earth-Moon System, I find that orbits which serve as key transit points between (1) Earth and the Moon and between (2) the Earth-Moon System and the rest of the Solar System emerge as economic centers. For the Earth-Moon-Mars System, I find that orbits which serve as key points connecting the system with (3) Mars and (4) Deimos respectively emerge as economic leaders. All results except (2) are plausible in the context of early space industry.

To model the topology and weights of the networks under study, I adapt findings from research on the International Trade Network (ITN) for the space setting. A maximum entropy approach wherein the assumed knowledge about the system is network density (Δ) delivers a topology where the probability node i exports to node j is $p_{ij} = \Delta \; \forall i \neq j$. A specification of the Gravity Model of trade using delta-v to measure the economically-relevant distance between nodes determines network weights. I note the empirically and conceptually well-established positive relationship between trade and growth and make the case that trade is even more instrumental to growth in space networks. Thus, to simulate the economic evolution of the networks, growth is a function of marginal trade flows in the model. Two solutions for the equilibrium are presented. One assumes static topology and delivers economic centers from the analytical solution to Equation 7. The other simulates period-by-period growth in the networks, allowing the topology to dynamically update. Comparing these solutions reveals how a network's topology constrains the formation of the most "economically sound" productive centers.

These findings can be valuable to policymakers and anyone else involved in space infrastructure investment and/or technology development for industrial activities in space. For example, they would suggest that more research into the productive potential of Deimos is eventually warranted as infrastructure extends out towards Mars. Equally (if not more) importantly, this paper hopes to improve the narrative of space industry as it relates to the field of economics; and encourage economists to find creative ways to adapt insights from their areas of expertise to space settings.

Modelling and simulation choices were limited, so many possible extensions can improve the informativeness of the results. A more complex model would strive to include more information about the "economic suitability" of nodes in a network in addition to delta-v (though this is fraught with empirical challenges and uncertainty). Similarly, if more detailed constraints for the maximum entropy approach can be justified, this could deliver more realistic/detailed network topologies. Finally, a more complex iterative solution might include more sophisticated topology rules, random shocks to economic growth, and simulation over more values for key parameters. Some extensions could be pursued with current knowledge. However, the full picture about the spatial structure of space industry will likely only be revealed once bootstrapping begins and richer data can inform more sophisticated models.

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8 Appendix

Below is a PDF of the Mathematica notebook with my code, which defines the functions and procedures which generate the results of Section 5. The $17x17$ matrix outputs don't fit the page format, but this doesn't conceal any meaningful results. The Mathematica document, which is more malleable, is available upon request.