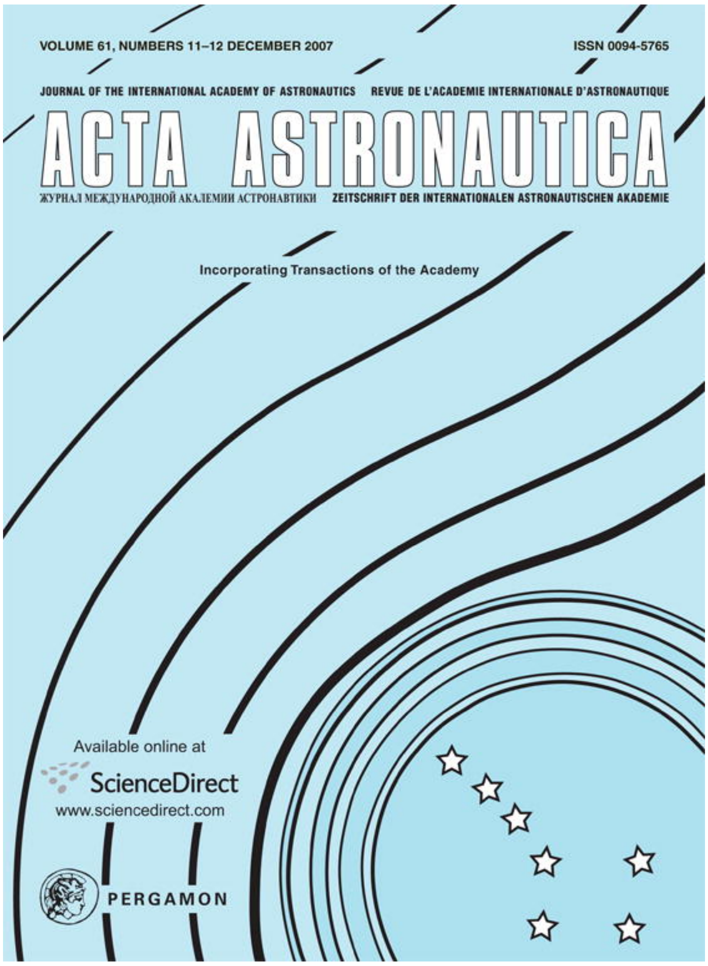
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Policy model for space economy infrastructure

Narayanan Komerath*, James Nally, Elizabeth Zilin Tang

School of Aerospace Engineering and Center for International Strategy, Technology and Policy, Georgia Institute of Technology, Atlanta, GA 30332-0150, USA

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Abstract

Extraterrestrial infrastructure is key to the development of a space economy. Means for accelerating transition from today's isolated projects to a broad-based economy are considered. A large system integration approach is proposed. The beginnings of an economic simulation model are presented, along with examples of how interactions and coordination bring down costs. A global organization focused on space infrastructure and economic expansion is proposed to plan, coordinate, fund and implement infrastructure construction. This entity also opens a way to raise low-cost capital and solve the legal and public policy issues of access to extraterrestrial resources.

1. Introduction

Fig. 1, from Ref. [1], summarizes how a self-sustaining Space Economy might develop and eventually become independent of Earth-based supplies or markets. The key is in developing interactions between the various projects. Such interactions lead to mutual support that reduces risk, provides cost-effective common services, and enables tertiary and higher order businesses comprising a broad economy. In turn, these will produce innovations. The basic question underlying this work is how to accelerate this process from centuries, to a few decades. A first step is to project and include such interactions in a quantitative model. A full-scale version of such a model may encourage participation by entrepreneurs to develop interacting, synergistic business plans.

Ref. [2] argued the following:

1. Large space infrastructure will fundamentally alter access and opportunities.
2. Global cooperation and participation is essential to build such infrastructure.
3. A modified European Space Agency (ESA) model may suit a global consortium to set policies and coordinate infrastructure development.

In this paper, there are two major issues:

1. Quantitative modeling for interacting business plans in a space economy.
2. Linking policy directions to economics to bring about such a massive advancement.

The questions posed are narrowed down to:

(a) How do interactions improve the net present value (NPV) of each business investment?
(b) How can an international collaborative environment be consistent with a free-enterprise model of accelerating innovation and economic growth?

* Corresponding author.
E-mail address: Narayanan.komerath@ae.gatech.edu (N. Komerath).

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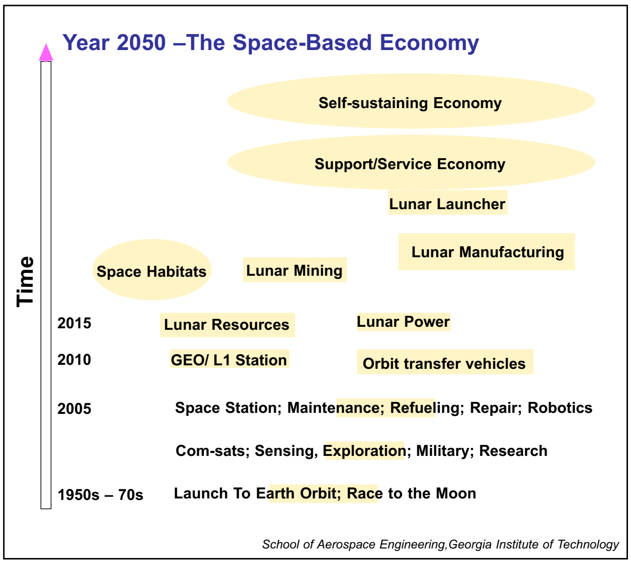

Fig. 1. Progression towards a space-based economy.

(c) How can the fundamental disagreement between free enterprise and "the common province of Humanity" thesis be resolved, and permit resource exploitation?

2. Background

Some of the ideas discussed in Ref. [2] are reiterated here. The basic premise of this work is that a viable economic rationale is essential to the health and growth of the human exploration and development of space. This idea in turn led to conceptualizing a space-based economy, and ways to get there from today's realities.

Previous work on the economic and legal environment of the space enterprise is summarized in the Commercial Space Transportation Study by US industries [2], the AIAA "Progress Series" compilation [3] on Space Economics, an International Institute of Space Law volume on Space Law [4] and the Reports of the Presidential Commissions on the State of the US Aerospace Industry [5], and the Implementation of United States Space Exploration Policy [6], respectively. These lay the groundwork. Recently, much attention has been devoted to projecting markets for suborbital and orbital tourism, and some to orbital hotels. Cost estimation for lunar and Martian missions is also a hot topic, as the adequacy of the NASA budget for the New Vision initiative is debated. Meanwhile, the commercial satellite industry and the launch business are in such deep trouble due to insufficient demand, that intervention by national defense departments appears imminent to preserve strategic national capabilities.

Ref. [2] argued for economic expansion as the rationale for space endeavor, as distinct from the idea of economic spinoffs from a discovery-focused program. A significant departure is the development of "space-based" businesses, whose suppliers, facilities and customers and all located beyond Earth, and are hence only peripherally tied to Earth-based markets or resources. Ref. [3] deferred consideration of such a development in market assessment *because it would change the assumptions of all the other markets*.

2.1. Interactions as market enabler

As Fig. 1 shows, the key feature in such a business expansion is interaction between projects, leading to secondary, tertiary and more general enterprises serving numerous customer projects. Ref. [2] reasoned qualitatively that such an iteration would produce substantially different cost and market growth projections. Two reasons are the mutual support resulting in order-of-magnitude risk reduction, and lowered access barriers for a large number of entrepreneurs outside aerospace specialization. Table 1 from Ref. [2] shows a sample 4-level evolution. In the present paper we will quantify some of this with methodology and examples.

In other work our team is developing a concept to build massive objects from extra-terrestrial material automatically, in the plannable future, so that our view of massive space infrastructure is very different from that of those who imagine that all mass must be shipped from Earth [7,8].

Three other points from Ref. [2] are reiterated.

2.1.1. Need for in-space infrastructure

Examples of large infrastructure with little science glamour are large pressurized volumes for use as storage facilities; housing and docking facilities, orbit transfer services, repair, resupply and evacuation services, space debris removal and ultimately, radiation-shielded habitats. Such infrastructure is essential to lower barriers to entry of smaller, innovative entities. These will not get built under current space program selection criteria that optimize science payoffs. Obtaining, sustaining and expanding public support and investments in technological and human capital for such an effort is the challenge.

2.1.2. Need for international collaboration

Ref. [2] listed three reasons why global collaboration is needed to build a space economy: the need for massive long-term investment, need for global participation for global buy-in and the fear of being left out. Examples of global collaboration already exist in airport and

Table 1
Evolution of a space economy

Level 1: isolated projects	Launch vehicles, lunar exploration, military reconnaissance, ISS & STS, Hubble telescope, crew exploration vehicle, deep space science, weather sensing, GEO television, telephone/internet, remote sensing, GPS, GLONASS, Galileo, LEO science missions, sounding rockets, suborbital tourism
Level 2: inter-action	Orbit reboost packages, refueling, repair, orbit transfer vehicles, orbit-on-demand common cargo vehicles, tethers, new Earth-based enterprises
Level 3: extra-terrestrial resource	Lunar oxygen factory, Lunar/space solar power station, lunar metal mining and extraction, lunar metal parts fabrication, lunar radiation shielding production, lunar landing and launch facility, lunar orbit transit station, Mars/asteroidal cyclers
Level 4: derivative space-based business	Long-term habitats, food growth, food supply, water supply, LEO fuel transfer depot, facility repairs/spares, space junk removal, Tourist/hotel facilities, lunar prospecting laboratories, NEO sampling labs, Space training, ... (hundreds more)

seaport infrastructure, container and railway standards, medical facilities and universities. These have developed common terminology, procedures and relatively open access within their global communities.

2.1.3. Technological rationale

The most significant difference in a large space economy will be the participation of numerous businesses far removed from the traditional aerospace marketplace, such as mining, road-building, energy and food production. Large-system integration technology and lifecycle simulation tools provide a new ability to do coordinated business planning. Participating entities can "game" and optimize their business plans in the context of what everyone else brings to the table. Such a capability did not exist 10 years ago.

3. Part 1: economic modeling of interactions

Planned interaction is a dramatic enabler of concepts. This is because the "waste by-product" of one isolated enterprise is precious to another. A (simplified) example is lunar metal extraction. Hydrogen for the reduction process costs at least $6M/MT delivered to the Moon. This could be completely recovered if there is a market for the water generated, at just $0.7M/MT—compared to the $6M/MT that water would cost otherwise. As a result, a Moon base and other water consumers would be enabled, and can buy more steel and power—improving NPV for all businesses. This paper starts the process of modeling this idea quantitatively to include other time-dependent costs and benefits.

3.1. General methodology

Table 2 shows a set of core, secondary and tertiary industries. Data sources used include the Space Access Society [9], Commercial Space Markets data [10], a US Federal Aviation Administration report on the economic impact of Space Transportation on the US economy [11] and a paper on economic analysis tools for mineral projects in space [12]. Cox [13] considers commercial activities that might develop in space, and agrees with the need for organized private–public ventures to enable both long-term infrastructure projects and short-term entrepreneurship. Maness and Hendrickson [14] give comparative cost figures for several types of power generation enterprises.

The above are extensions of current industries/activities and are hence projected to evolve in much the same manner as they have to date. As starting blocks to build a model, we assume that independent plans can be developed for each. The economics of Space Tourism and Space Power have been the subjects of many analyses, for instance that by Nagotomo and Collins [15]. They conclude, however, that transportation cost has to come down to 10,000 Yen (less than $100) per kg to low Earth orbit, an unrealistic prospect. Reynerson discussed a Space Tourism Platform [16] that sustains humans in LEO, or at lunar or Martian orbital libration points. Lindskold [17] considers the demand curve for space tourism and space hotels, while Matsumoto et al. [18] and Sherwood et al. [19] consider the cost structure for this industry.

At the next level, 16 secondary enterprises are considered, all of which depend on the presence of two or more of the core items. Activities, processes and products for a permanent lunar [20] or space [21] colony and concepts for lunar oxygen [22] production have been listed. The American Institute for International Steel [23] provides pricing and demand data for that industry in Earth's economy.

Tertiary enterprises are then listed as a small subset example, but in this paper, these are not analyzed. While

Table 2
Example 3-level model

	Businesses/industries
Core	Transportation, production and supply, energy, tourism, hotels, mining, science missions, communications, military/reconnaissance, remote sensing
Secondary	Reboost packages, refueling, fuel depot, lunar fuel extraction, orbit transfer vehicles, water supply, satellite repair, space power, on-orbit assembly, orbital storage, tether building, junk removal, lunar surface transport, microgravity processing, modular habitats, agriculture, space observatory
Tertiary	Government, general merchandise stores, chemical plants, agriculture, banking accounting, apparel manufacturing, law, medical services, fitness, education, employment services, insurance, real estate, construction, architects, entertainment, robotics, advertising and public relations services, management, scientific, technical consulting services

"government" seems a dubious addition to "industry", note that it is a critically important and large customer.

3.2. Modeling tools

In order to build the fully integrated space based economy, the dynamic modeling software known as STELLA [24] was used. This software integrates control processing with simulation and analysis tools in order to model complex real-world systems and their variations over time. Individual process models were built first so as to have a baseline case with no interactions. Each sub-model was combined in the overall model of the core, secondary, and tertiary industries. Interactions were then added by varying price elasticities according to an increase in supply and/or demand for the inputs and outputs of a specific process. These interactions also included services, risk variability, and technology transfers.

Once the secondary industries are fully in place (though analysis was not done on the development of the secondary industries), the full operationally independent economy is analyzed. This two-part structure is designed so that a supply and demand analysis may be used to analyze the interactions. From the supply side, the inputs needed are branched out either to other industries' products, linked with the inputs of other industries, or separated from other inputs due to an exclusive nature. In the last case, the interaction based model will not apply, but there are trickle down effects that may dramatically reduce the cost of these inputs. The objective is to show that for those processes whose inputs feed directly from other processes' outputs or products, the cost and associated project risk decline dramatically—and to examine the assumptions needed for this.

Fig. 2 shows a section of the overall model linkages. The subsets of industries are set to be the inputs within each. The core, secondary and tertiary economy all contribute to Net Income flow. Total Economic Growth serves as a reservoir for all the inputs.

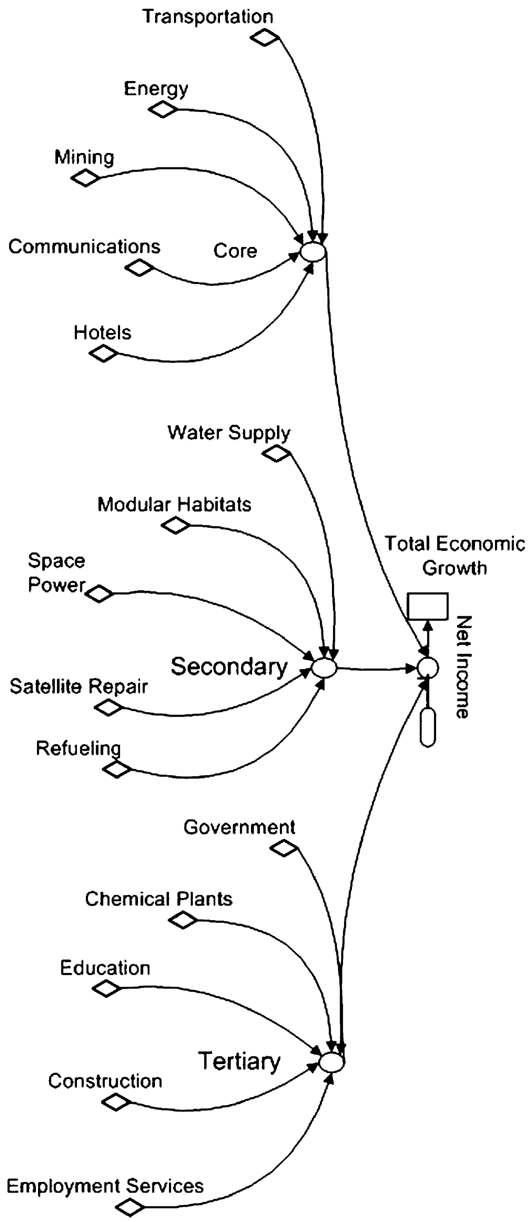

Fig. 2. A section of the overall economy model.

3.3. Pricing

The market analyzed is not at a competitive size, so an oligopolistic structure is a valid assumption. Pricing can be visualized as follows. In an unorganized economy with free market pricing, a consortium that seeks services of a given kind will likely draw schemes for market domination and price gouging. Government regulation or deregulation alone cannot provide both the incentives and the controls needed for orderly growth. Much of today's "high-tech" was generated in the course of Government contracts that covered much of the technical risk, and promised the huge bonus of a large government production contract. In the space infrastructure business, this approach would lead to prohibitive costs.

A second approach is that extraterrestrial businesses would set prices just below the level of Earth-origin services delivered at the same extraterrestrial point. Again, this would generate little cost savings. It would not generate new extraterrestrial enterprises because the cost would be too high to make the overall infrastructure development feasible.

A third pricing option is a "mutual-survival pricing" scheme, established by discussion between the consortium and its participants. Here the benefits of interactions and mutual support would be taken into account up front, and the risk reduced through the governmental assurances of the Consortium, enabling all players to develop pricing that would be far lower than either of the above two options. Such bilateral arrangements are not new in the space marketplace.

Initial participants who agree to such a scheme would have the incentive of near-monopolistic protection—with alternatives in place (with agreed pricing) that could develop into competition if one player fails to deliver. Beyond an agreed protected term, the market would open to newcomers, with reduced risk and in-place infrastructure, experience and market acceptance. At this point, further price declines are to be expected. For those industries that have the option to purchase inputs from multiple suppliers, the interaction model becomes somewhat more complicated. An optimization model can determine the best supplier.

3.4. Cost structures/economic forecasting techniques

Although the individual costs for each process vary in reality, a uniform cost structure has been implemented. For each project, costs associated with facility construction, transportation and launch insurance are considered as startup costs; material costs (if applicable), managerial costs, insurance and a depreciation statistic are built into the functional cost category. The startup costs are summed in the initial period, which results in a net negative income for several periods. Income is calculated by measuring the revenue based on quantity demanded multiplied by the price per quantity. Once the project total cost (PTC) and the project revenue (PR) are tabulated, the initial investment requirements are explored. Utilizing the internal rate of return (IRR) and the weighted average cost of capital (WACC) [25], a value for the initial investment is determined.

The IRR that an industry should receive per process is set at 20%. Though large for typical investments, this is the bounded norm for most current space ventures because of the high risk. The evolution of the IRR is not analyzed in this model, but anticipated results should prove to be more positive due to lower returns required by investors as the risks come down.

The WACC is an added forecasting statistic that determines the minimal value of the capital financed by assessing the cost of debt and the interest on the external capital provided. The equity and the debt associated with the capital are dependent on the PR and the PTC, respectively.

4. Results

Results from two example processes within the full economy model are presented here. The results of interactions and risk variability on the NPV are presented.

4.1. NPV: hotel business

Fig. 3 shows an example of how the NPV for a hotel business in space changes with time, for three different cases. Case 1 is an isolated entity. Case 2 is where the transportation cost goes down because of the increasing success of the orbital tourism industry. This is the

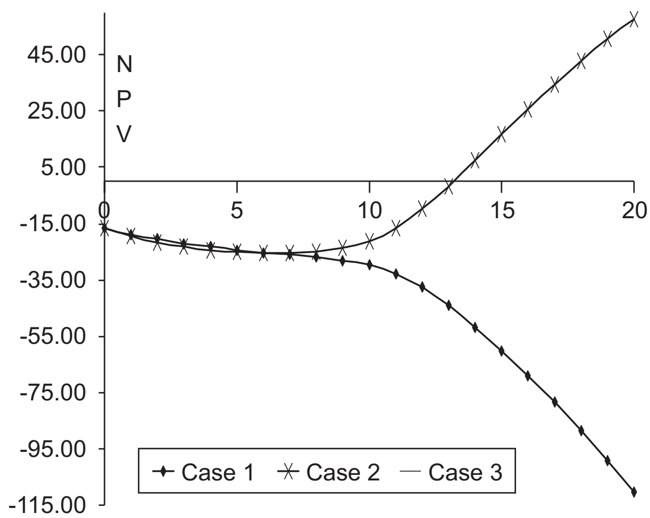

Fig. 3. Space hotel net present value.

dominant interaction effect for this illustration. Case 3 is where the business sees a decreasing insurance cost due to the presence of other infrastructure, specifically, the success of the tourism industry.

In the analysis, the price to stay in the hotel is set to be an independent variable as well as the internal rate of return (IRR = 20%). Before calculating the NPV several other variables were determined:

- Annual operational cost is the variable cost based on demand function and it is fixed at 10% of the total cost of construction. Depreciation period is set to be 25 years.
- Space hotel Startup costs are equivalent to material costs of construction.
- Hotel demand is based on the price of the hotel stay. It is estimated using a project price elasticity of demand.
- After obtaining the demand values, revenue can be easily calculated by the following equations:
- $\text{Revenue} = \text{demand} * \text{price}$,
- $$\text{Total cost} = \text{fixed material cost} + \Sigma\text{operational costs} - \Sigma\text{revenue},$$
- $\text{Net income} = \Sigma\text{net revenue} - \Sigma\text{interest payments}$,

  where interest payments are based on IRR.

Once these variables and relationships between them are determined, NPV can be calculated by using the NPV function in STELLA. In this case, the input is equal to revenue—operational costs. The rate is IRR fixed at 20%. The initial value is the invested capital which consists of the total cost for employees, supply and insurance.

$$\text{Invested\_Capital} = \text{init(TCC)} + (\text{TC\_for\_People} + \text{TC\_for\_Supply} + \text{Fixed\_Costs}) \times \text{Insurance\_Variability}.$$

Thus, NPV for the Space hotel becomes NPV ((Revenue − Operational_Costs), SH_IRR, (−1∗SH_Invested_Capital)).

4.2. Interaction theory results

The Case 1 graph in Fig. 3 shows increasingly negative NPV for 20 years. The reason is that the demand function is based loosely on interaction theory due to the requirement that a large number of people will be interested in staying in the hotel as the price decreases.

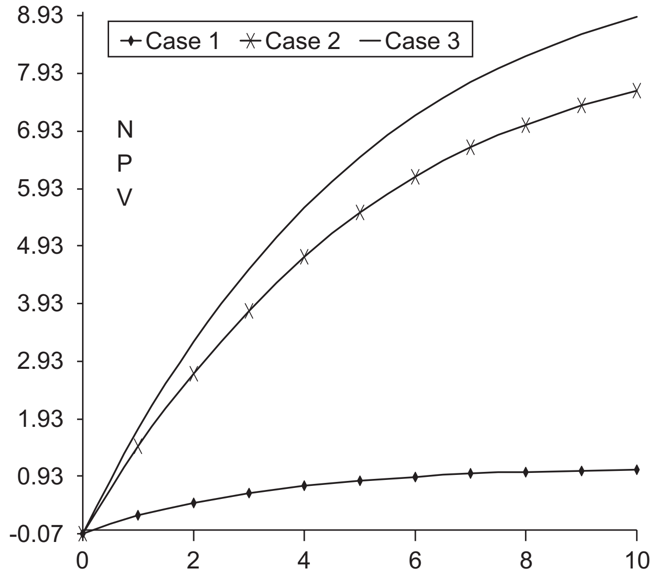

Fig. 4. Lunar steel production net present value in $trillions.

This large volume of people will only come if new transportation systems are created.

Cases 2 and 3 verify the true interaction theory by demonstrating the usefulness of acknowledging the interactions. NPV in both cases turns positive after about 13 years and increases rapidly to almost positive 60 billion dollars by the 20th year in business. Cases 2 and 3 include the effect on transportation system prices. The current price of a human ticket to LEO is approximately $10K/kg. The current price of material to LEO is around $2.2K/kg. As these prices come down, the true variable cost will drop drastically. The interactions with other companies, especially those supplying the space hotel, are defined by the elasticity of interaction—essentially a price elasticity of supply. As more suppliers are available, prices drop due to competition (though oligarchial). Thus, prices drop due to all of these interactions and the investment turns out to be very profitable.

In Fig. 4, we examine a more straightforward example of interactions, in this case the production of steel on the Moon. Various processes for such industry have been considered in the literature [26]. In this case, we assume that the transportation cost for materials from Earth remains constant over time. In the first case, there is no interaction. In Case 2, the water by-product is sold to other entities, covering essentially all of the transportation cost of hydrogen and carbon from Earth. In Case 3, in addition, the demand for steel goes up as a result of the reduced cost of water—and results in a decrease of the per unit cost of producing steel, given the fixed facility and startup cost.

The dollar numbers in the steel example are immense, and some explanation is in order. The demand for steel from various projects in a full economy, with lunar bases and lunar electromagnetic launchers, amounts to several thousands of tons each year; however, the cost per ton is still considered to be over $1M/MT for lunar production (this is much lower than the $6M/MT minimum value expected for delivery from the Earth to the Moon). Until that cost can be brought down through interactions with other industries, it is doubtful that steel manufacture will really take off. On the other hand, with guaranteed markets for the water by-product and perhaps for the excavated regolith and ore by-products, the cost of steel production can come down, as energy costs come down. These remain to be modeled. Here NPV will come down with steel costs, but the probability of success will greatly improve.

5. PART 2: policy for a space economy

An interesting perspective on economic features to be expected at the later stages of advanced extraterrestrial civilization is given by Hanson [27] who assumes a random development and a Darwinian process. This scenario, reminiscent of the American movie "Independence Day", should sufficiently motivate people to consider more organized and thoughtful means of developing a space economy.

5.1. Opportunity in common imperative

One significant recent shift in security concerns is from purely national and international concerns about proliferation of technology for weapons of mass destruction, to concerns about sabotage and terrorism involving non-state actors. This has caused the addition of a thick layer of security precautions, requiring vetting at the individual level, quite apart from national criteria such as citizenship. This is an opportunity to rethink the whole concept of security regulations involving space technology. Briefly put, the need for personal vetting renders much of the prior regulations superfluous.

In Ref. [2] various models of international collaboration were surveyed. The ESA model was seen to have relevant lessons for a future International Space Infrastructure Consortium (ISIC). The ESA evolved into a regional intergovernmental organization, mandated to develop and implement long-term policy and programs. The agency recommends objectives for national space policies and coordinates them with other organizations. The budget is funded through contributions from member states. The national space agencies of the partner nations maintain their own autonomy and separate their military facilities from their civilian ones, keeping their ESA project participation linked to the civil program. The relationship with national programs is cited as the most difficult aspect, not surprisingly.

An ISIC may be modeled partly on the ESA structure. Certainly, the detailed structure must be modified from today's voluntary national "contribution" to the ESA budget, to permit strong commercial "pull" from the top, while accommodating differences in national priorities. Several partner nations may see it as a national priority to participate in such programs that bring technology employment and facilities to their countries, regardless of the immediate profit. This motivation is expected to apply in the case of space infrastructure as well. Meanwhile the ESA model of separating the Consortium projects from the civil and military programs allows technology leader nations to maintain their advantages in items that are not shared with the Consortium. Within ISIC's activities, technology and human interactions could be based on reciprocal agreements.

ISIC could then provide the overall framework for private entrepreneurship. This framework must have a common baseline of infrastructure. It must have access to information and opportunities to compete on a level playing field in providing products and services. ISIC may provide initial 10-year (or other suitable startup period) market guarantees. With the technological capabilities of large system integration and simulation mentioned before, the size and variety of the markets for the overall project can be used to kick-start several derivative business ideas. Once these are fitted into an interlinked supplier-market web in order to alleviate risk and costs, many alternative paths will open up for each step of the major infrastructure projects.

5.2. Linking economic and policy models

Eilingsfeld and Schaetzler [28] have pointed out that most models for space tourism appear to assume a low (6%) annual cost of money—a figure that is unrealistic for private ventures that must obtain venture capital funding rather than low-cost long-term loans. They have shown that using realistic costs of money discourages such business plans, as they are not seen to be viable even over a 50-year successful record of operation (see Fig. 3 as well). This is a long-standing problem in the spacecraft industry, as pointed out by Simonoff [29]. Debt financing is vastly preferred to venture capital; however, lenders are deterred by the high risk and lack of useful collateral. It is true of space projects that hardware from one cancelled or failed project is rarely available or useful to another project.

The Consortium model provides two answers to this problem. Firstly, in such a model, long-term government or government-backed financing would be available—either directly provided by the participating nations or underwritten by the Consortium through a combination of private and public funds. Secondly, the presence of the Consortium and infrastructure vastly reduces risk to the lender, reducing insurance and loan costs. Thus, the model provides a consistent economic and policy solution.

The Consortium can in principle set up cooperative pricing arrangements, though in practice there is a grave danger that a powerful bureaucracy will instead drive all costs up and destroy the purpose of the whole enterprise. Examples of pricing arrangements involving nations include the agreement between the People's Republic of China and the US to limit launches on PRC launchers for a set period.

A final point is to consider the most frequently cited obstacle to extraterrestrial resource exploitation—the Moon Treaty stipulation that private entities will not be able to claim property rights, or a right to exclusive use of real property for any useful length of time. Strong feelings on this topic are reflected, and cited, for instance, in Wasser [30] who proposed legislation—a "U.S. Land Claims Recognition Law" to allow private property rights for extraterrestrial resources, but to maintain free access to all on a "Space Line" which would transport passengers from all nations to this new frontier. It is imperative to develop an acceptable protocol for property/resource exploitation rights.

Previous efforts to consider such protocols were conducted in the UN. Thus the "common heritage" and "preserve for all humankind" concepts took precedence, but the UN left the Moon Treaty in a state that is plainly unworkable for the technological entrepreneur. The Seabed Treaty and the Law of the Sea are also seen to be under stress as the technology of seabed resource exploitation advances, along with the global ability to monitor environmental stresses. This may provide the impetus to reconsider the interests of national sovereignty, common heritage and private ownership/exploitation rights against the accompanying responsibilities and liabilities.

5.3. Multinational entities

The Consortium can break through this obstacle. It can insist that ventures for resource exploitation be multinational public corporations, open to investors from all member nations, with limits on maximum stock ownership to prevent concentration in any one nation. We submit that such a scheme addresses the basic objection of nations to the idea of resources being dominated by other nations. Thus it offers a way to get agreement to license such multinational entities to exploit extraterrestrial resources with long-term leases and exclusive-use rights that make their business plans viable.

6. Discussion

What is presented here is a small example of a portion of what must become a comprehensive quantitative model. Substantial obstacles still remain.

(a) Cost estimation techniques for space endeavor are today based on historical empirical data. To a first approximation, these are based on first-time development cost of launchers and satellites of increasing size and power. Such methods will fail to project cost efficiencies of large-scale production, standardization and global sourcing. Hence modeling must account for detailed technology. Unfortunately, there are few models of other cost or pricing in the space industry so far.

(b) The issue of up-front interaction of business plans is a touchy one, raising concerns about the need for secrecy in business strategizing. Hence, initial models must be based at least in part on hypothetical "reference businesses" in each category that are based on today's proven but less efficient technologies and methods. Beyond this, only a Consortium empowered to issue Requests for Proposals (RFPs) can demand detailed business plans, and safeguard their secret aspects. To the present authors, this no doubt takes a large leap of faith based on our limited experience with how corporate legal departments work and think—they are paid to safeguard the company's interests rather than take risks. Determined direction from top-level executives has always been needed to induce better results.

(c) Policy discussions on space have to date been dominated by governments, with little room for large-scale commercial collaboration.

7. Conclusions

We start by reiterating the primary conclusion of Ref. [2]:

(1) Global cooperation is key to building the infrastructure for a space economy.

In addition, we have now shown that:

(2) Interaction between projects brings down the cost and dramatically improves the NPV of space business ideas. A corollary, yet to be shown quantitatively for a large enough economy sample, is that as the number of participating, collaborating entities goes up, the overall project cost, and specifically the public funding needed, can be shown to go down.
(3) Models exist for dealing with the security and economic barriers between participants.
(4) A Consortium model enables entrepreneurs to obtain long-term stable funding at rates typical of long-term government loans.
(5) The Consortium model, with a requirement that extraterrestrial resource exploitation enterprises be multinational publicly owned ventures, opens the way to a new Space Treaty that allows limited property rights.

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