AIAA2008-7791
Economic Interaction Modeling for a Space Economy *

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This paper continues work towards defining an accelerated transition sequence from the mission-dominated space enterprise of today into a self-sustaining space-based economy. The basic question is how to incorporate the effects of the interactions between businesses which will occur in a developed economy into the planning for each enterprise. A sequence defined in previous work is refined by incorporating published cost models and recent developments. Methods for economic analysis of interactions are related to aspects of the space economy. Qualitative analysis of input-output relationships shows mechanisms for business growth. Interactions with the reboost, refueling and orbit transfer vehicle enterprises are considered.

I. Introduction

Growing interest in commercial activities in space will lead eventually to an extensive space-based economy. This evolution may take the meandering path along which the large cities of Earth developed. In 1998, roughly forty years after the first artificial earth satellite was put in orbit, commercial space expenditures exceeded government/military expenditures. The growth of commercial activity beyond Earth continues to be one of extreme competition and attrition.

Our approach is to consider a fully developed space-based economy as the final steady-state outcome, and consider how to get there from the present situation. The basic question driving our research is how to catalyze the present rate of evolution by incorporating logical predictions of what markets, products and services will exist, and what interactions will develop between them.

We stipulate at the outset that we are not tying the research to any single current program, but do incorporate accepted mainstream data where possible. Thus this remains an unabashedly "academic" exercise, albeit one which we hope will be useful to planners.

I.A. Background

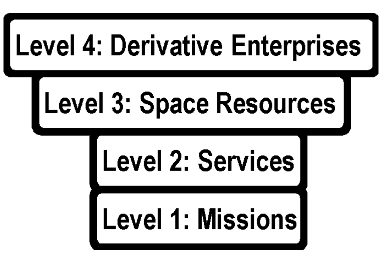

Figure 1. Four-level Space Economy Evolution

In Ref. **?** and Ref. **?** we considered the issues involved in generating a flourishing space economy, noting that opportunities developed at the interfaces between existing projects to provide common resources and services. We postulated that by combining the business plans of two or more well-chosen 'space commercialization' concepts, the market projections of both the concepts could be greatly improved, their costs and risks slashed, and hence their return on investment improved. We laid out a suggested a global Consortium structure for large infrastructure projects, that would facilitate the financing, insurance and possible solutions to the security concerns, and technology transfer barriers. We suggested that this path might even provide a fortuitous and logical solution to the impasse about ownership of extraterrestrial resources. The 4-level natural evolution of a space economy shown in figure 1 from Ref. **?** is as follows:

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Level 1: Missions. Launch vehicles, lunar exploration, military recon, STS, ISS, Hubble telescope, deep space science, weather sensing, GEO television, telephone / internet, remote sensing, GPS, GLONASS, Galileo, LEO science missions, sounding rockets, suborbital tourism.

Level 2: Interactive Services. Orbit reboost packages, refueling, repair, orbit transfer vehicles, orbit-on-demand common cargo vehicles, tethers, new earth-based enterprises.

Level 3: Extraterrestrial resource exploitation. Lunar oxygen, solar power station, lunar mining, metal parts, radiation shielding production, lunar landing and launch facility, lunar orbit transit station, Mars / Asteroidal cyclers.

Level 4: Derivative Enterprises. 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.

Our 2006 paper[?]set the short-term objectives of looking at the first steps that are needed to develop the Level Two enterprises, considering interactions. We explored the idea that if these developments were incorporated, there could be a tangible short-term benefit. We showed how there could be an order of magnitude reduction of the cost of access to GEO for equivalent value. The two short-term objectives were largely met in Ref. **?**, though the work there is revisited and refined here, two years later.

II. Postulated Sequence of Initial Development

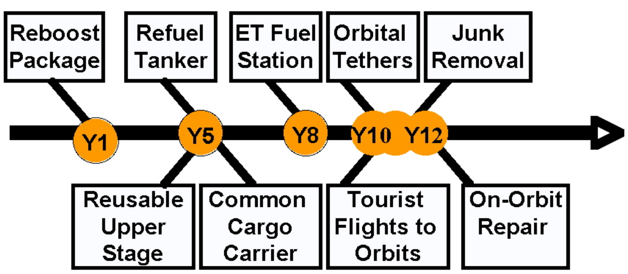

Figure 2. Postulated sequence of the first few Level Two enterprises

To make the connection to todayÕs realities, figure 2 lays out a sequence, refined from Ref. **?** focusing on how Level Two Interactive Services might grow. The process depends on two key assumptions which derive from previous work . The first is that there is an acceptable level of certainty that all business elements in the process will start operation on a common timetable. The second is that competition and mutual interaction will keep reducing costs over time, while allowing windows of attractive profitability and market security. These assumptions enable synchronization and scheduling of market demand, price reductions, and technical feasibility. Ref. **?** grounds these assumptions in the logic for a multinational / global entity organized and empowered to enable and sustain this progression through planning, coordination, and some backing to obtain capital at sustainable costs. Ref. **?** laid out the sequence at a very simple level, to explore the process by which a plan for the rapid growth of a Space-based Economy can be developed.

II.A. Scope and Objectives

The objectives of this paper are:

1. To refine the economics calculation and update the technical data behind the examples considered in Ref. **?**.

2. To consider the issues in developing a model for interactions between businesses, along the general pattern of the demonstrations of Ref. **?**.

III. Part 1: Refinement of Previous Results

III.A. Developments in the past two years

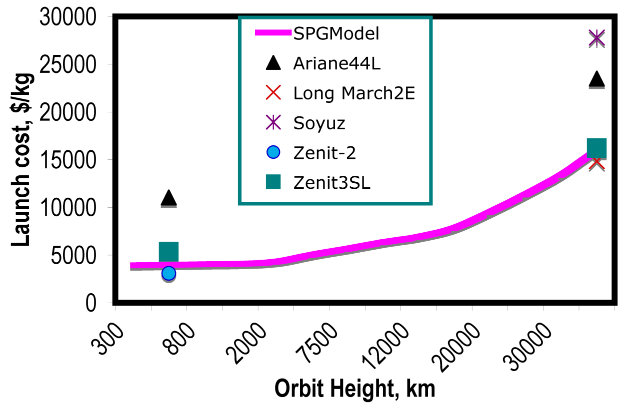

Figure 3. Launch cost data model based on Futron 2000 data

The European company GEORING[?] plans to combine fuel storage and on-orbit servicing. They aim to reduce operational costs of satellite servicing, reasoning that reducing costs by 1 percent should increase demand by 5 percent. Reynerson[?] describes their Spacecraft Modular Architecture Design (SMAD) Concept which uses an on-orbit-servicing vehicle to replenish or replace spacecraft components. The Dutch/Swedish SMART-OLEV[?] Orbit Life Extension Vehicle uses a Space tug with multiple roles. The tug uses continuous-thrust propulsion (presumably ion thrusters) for orbit transfers. Its business case describes a market of 140 spacecraft needing re-boost, in addition to orbit slot transfers, and rescue missions for craft that may have lost their attitude control. It is designed to dock and undock upto five times, and projects a 12-year life extension for GEO satellites at less than 30 percent of the cost of a new satellite. The DARPA Responsive Space initiative has led to several concepts involving reboost, refueling and other on-orbit servicing **?**, **?**,,[?].[?] The idea that on-orbit servicing (OOS) will have effects that propagate through the whole architecture and economic decision-making is accepted, for instance, in the survey by Tatsch, Fitz-Coy and Gladun.[?]

In this paper the following refinements have been made to the results presented in Ref. **?**:

Cost figures have been referred to the NASA-USAF Cost Model (NAFCOM)[?] as published on the internet with an interactive applet. This offers the Spacecraft Level Cost Model, where craft dry mass and the size of the production run are correlated with development and production costs, assuming a Wright learning percentage of 85, or a 15 percent cost reduction with each doubling of quantity. This is a conservative estimating tool, since it is based on historical data, mostly with small-production run systems. However, these costs are much lower than what we had postulated in our first-cut estimates in Ref. **?**.

Launch costs are related to the survey published by Futron[?] for pre-2001 launchers. Here we do use the low end of the prices, on the argument that competition is bringing the price down. Futron cites comments from western industry officials that launch prices have come down by 30 percent in 2000-2003, so this is a valid choice. Launch costs to LEO and GTO differ by as much as a factor of 3, which is more than can be explained by physical criteria such as orbit energy or launch mass ratio. The best explanation for the increased cost is the increased complexity and risk associated with achieving precise orbits at higher overall energy levels, usually involving first firing of another set of high-Isp engines. The launch cost variation is shown in Figure 3. Again, this results in much lower costs than what we had used in Ref. **?**. Given the total investment, the annual mission operating cost is estimated by going back to NAFCOM.

III.B. Reboost Package Enterprise

Our own generic model of the re-boost package is not intended to reflect any of the above specific projects, but to use parameters that are logical. The reboost package is sized at 200kg dry mass and 500kg total launch mass. This is smaller than the SMART-OLEV and other On-orbit service vehicles; however we believe that this is the right mass range for a single-purpose vehicle that will be taken to GTO by a launch vehicle. The type of propulsion is not specified, but efficient electric propulsion solutions are being proven.[?] For larger GEO spacecraft, combining multiple boost packages may be preferable to designing special larger boost packages.

We look at the Reboost Package business two ways. Such enterprises usually start as part of military programs that cover the development cost. Thus it would be realistic to start the NPV projection at a stage when development has already been accomplished and production is set to start. In this case, we found that the reboost enterprise could break even in about 16 to 17 years, even with an Internal Rate of Return of 20 percent (risk is mostly mitigated with government funding), and a nominal revenue of just 1.6M dollars per GEO satellite per year that it operates with a boost package. Given that the average communication satellite generates something on the order of 40M dollars in revenue per year of successful operation, this is a very attractive price. A 10-year lifetime extension is assumed for each satellite with a package attached.

A production run of 100 satellites is assumed, with 85 percent on the Wright learning curve. No efficiency of scale is included in the mission operations cost of 0.287M dollars per package per year, although this function is expected to be combined with the mission operations of the basic spacecraft. This situation is not very different from what we projected in Ref. **?**

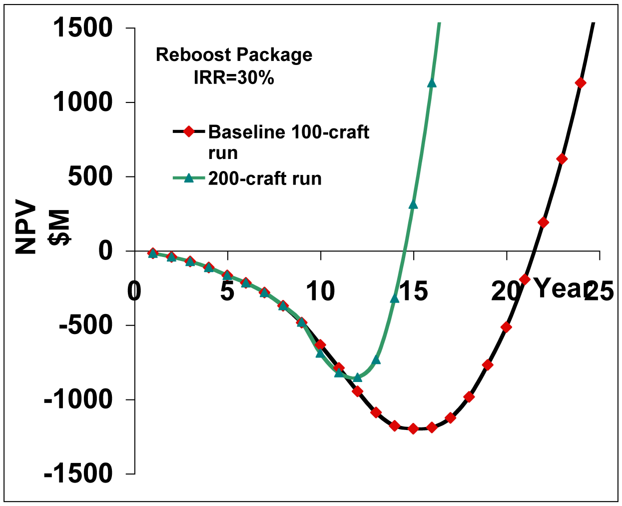

Figure 4. NPV of the Reboost Package enterprise

We now develop a different commercial baseline, just to level the playing field for comparison of enterprises. The development cost is estimated at 71M dollars using the NAFCOM spacecraft level cost model. Although the NAFCOM generally gives higher estimates than what DARPA might pay today, in the case of a small and low-mass craft the estimate is comparable with what a two-phase DARPA project might fund. A five-year development period is assumed, with a 30 percent IRR expectation, since the risk is now fully to be borne by the investors. First launch is to occur in Year 6. Now the revenue per satellite per year has to be on the order of 10M dollars to reach breakeven. This result is used as the baseline in figure 4.

Competition will dictate a drop in the price charged. We incorporate this as a 5 percent reduction per year, starting in Year 16 when the NPV has crossed minimum. This now shows the NPV crossing zero in Year 22, which is about 16 years after first launch as before.

IV. Part 2: Modeling of Interactions

The boost package business exists because of the market created by other businesses (military and GEO satellites that can extend useful life by having more fuel and perhaps by replacing thrusters). In the above example, a 5 percent annual drop in revenue per installed boost package is the only acknowledgement of the possibility of competition, mainly from other boost package suppliers. Other effects not accounted here are:

Negative:

1. Drop in demand for replacement GEO satellites until technological obsolescence becomes the limiter of useful life.
2. Drop in demand for boosters and Space engines.

Positive:

1. Drop in insurance costs of new satellites (currently running at upto 30 percent of cost), will increase demand. This may, however, reduce demand for boost packages in that potential customers may prefer to launch new satellites rather than revive old ones. Unless there is a launch problem consuming a large percentage of the orbit-correction fuel, the customer may not exercise options on reboost packages.
2. Most importantly, the reboost business will build confidence and experience in orbit rendezvous and 'responsive Space' on-orbit servicing, opening the engineering and the market for the refueling, salvage, repair and junk removal businesses that follow.

In Ref. **?** we demonstrated that incorporating reboost, refueling, orbital transfer vehicles and on-orbit part replacement could reduce the launch cost to GEO, measured in terms of satellite functionality, by some 90 percent. The savings came from not needing a single-use 3rd stage engine to LEO, the use of low-cost launchers to get the 3rd stage fuel to orbit separately, the drop in risk due to the possibility of reboost, refueling and access to repair, and eliminating the need for 17-year reliability on all satellite components, and the need for several redundant systems.

If there were a way to incorporate the benefits of other enterprises into business planning (as is routinely done in earth-based businesses), costs and risk would come down so much that new businesses would proliferate much faster. The policy issues here involving international collaboration, anti-trust rules and world trade rules, are beyond the scope of this paper, but follow the thread started in Ref. ?. Here we take an initial look at economics theory applicable to these issues.

IV.A. Linkages

The interactions among well chosen space enterprises can create synergies and cost savings that arise from various sources such as economies of scale, changes in demand and supply of key intermediate inputs, and backward and forward linkage effects in the space economy. Economies of scale arise when the average cost is declining over a relatively large range of output. Increased demand for particular inputs that are commonly used by a set of enterprises could also result in scale economies at the level of the intermediate input suppliers, leading to lower cost of inputs. The initial base of enterprises can lead to the development of ancillary and supporting industries through backward linkages (for example, development of input suppliers) or forwarding linkages (for example, retailing of products) in the space economy. Interactions can also have negative impacts on certain current space related industries as for example, new technologies are developed to offer better services and solutions.

We review the related economics literature to present a better understanding of the theoretical underpinnings of our approach. We draw upon several strands of literature, namely impact studies, agglomeration effects (clusters), backward and forward linkage effects, internal and external scale economies and PorterÕs theory of competitive advantage to understand co-location decisions, inter-sectoral interactions and their impact on the cost and profitability of these businesses. We also look at the examples of some industries such as the automobile industry where the development of industry clusters has had a significant impact on the development of the industry.

IV.B. Economies of Scale

We begin by defining internal and external economies of scale. Economies of scale arise where production is more efficient at larger levels of output. So for example if we double all inputs, the output will increase by more than double. This implies that in an industry where there are economies of scale, the cost per unit decreases as output increases. Ref. ? discusses the kind of production increase needed to experience scale economies.

IV.C. Clusters

The literature on industry clusters studies in part how membership of an industry cluster impacts the competitiveness of its member firms.[?] Ref. ? define clusters as "networks of production of strongly interdependent firms (including specialized suppliers) linked to each other in a value-adding production chain. In some cases clusters also encompass strategic alliances with universities, research institutes, knowledge intensive business services, bridging institutions (brokers, consultants) and customers."Ref. ? identifies factors influencing cluster formation such as "buyer-supplier relationships, or common technologies, common buyers or distribution channels, or common labor pools. Ref. ? defines "business clusters" as a "geographically bounded concentration of similar, related, or complementary businesses, with active channels for business transactions, communications and dialogue, that share specialized infrastructure, labor markets and services, and that are faced with common opportunities and threats."

Hence, the basic idea is that the viability of a firm is enhanced by the nature of the cluster of related and supporting industries such as suppliers of capital good, specialized labor, intermediate inputs, repair services, research and development, distribution, etc. We draw upon the literature to understand the factors influencing cluster competitiveness, the dynamics of the interactions among firms in the cluster, and how these interactions help increase the viability and profitability of the firms in the cluster. Among the early approaches to industry location /cluster are studies by Weber and Marshall. Ref. ? used agglomeration economies or cost savings arising from spatial concentration of firms to explain agglomeration or clustering of firms. Hoover focused on externalities related to proximity among business enterprises (localization economies), rather than urbanization economies or advantages associated with proximity to urban areas. Ref. ? focused on external scale economies or cost savings that arise as the industry grows in size, irrespective of the size of the size of the individual firms. In the context of co-location, they are economies or spillovers that arise because of proximity due to co-location of firms in an industry. Marshall also discusses other benefits of concentrated industrial districts, arising from a large, skilled/specialized labor pool, greater specialization of labor and increased knowledge spillovers and diffusion.

Bergman and Feser[?] review the literature on industry clusters. Their review indicates that for example, while,[?],[?] focuses on agglomeration economies, labor pooling, and knowledge spillovers,[?] studies the link between innovation and clustering.[?] have identified three major drivers of industry clustering: 1) strategic business opportunities derived from specific kinds of interfirm alliances ; 2) traditional regional factor market advantages (labor pools and localized knowledge spillovers and 3) the role of non-business institutions such as universities, colleges, trade unions, and associations. They also discuss firm rivalry, just-in-time trends, niche marketing, and civic capacity. Their review also lists other advantages of proximity between firms such as increased market power through brokered buying and selling, the better availability and use of specialized repair facilities, shared infrastructure, reduced risk and uncertainty for aspiring entrepreneurs, better information and tailored infrastructure.[?]

Ref. **?** studied 100 industries in 10 nations to understand why some nations succeed and others fail in international competition. He tried to explain why a nation is successful in a particular industry: for ex, Switzerland in precision instruments and pharmaceuticals. He presented his famous 'diamond' which described four factors influencing the environment in which local firms compete and that enhance or impede competitive advantage. These four factors, namely firm strategy, structure and rivalry, demand conditions, factor conditions, and related and supporting industries all influence each other and determine the industries in which a country develops competitive PorterÕs analysis suggests the investment in advanced factors of production by related and supporting industries creates spillover benefits (availability of higher quality inputs at internationally competitive prices), helping to make the firm internationally competitive. Hill[?] explains that "one consequence of this process is that successful industries within a country tend to be grouped into clusters of related industries". Such clusters are important, because valuable knowledge can flow between firms within a geographic cluster, benefitting all within that cluster.

Bergman and Feser[?] cite two examples of cooperation among co-located firms. The examples are from.[?] The joint location choices of Japanese manufacturers and their suppliers for JIT reasons is one example. They also identify collaboration economies and the resultant ability to identify niche markets and new specialized products as another reason for the formation of industry clusters. Another example is the concentration of most of the US rubber industry in Akron, Ohio.[?] Many related and supporting industries such as rubber chemical producers, synthetic rubber companies, and manufacturing of rubber processing machinery have production facilities, laboratories or representatives there. Michael PorterÕs study cited the cluster in the German textile and apparel sector including high quality cotton, wool and synthetic fibers, sewing machine needles, and a wide range of textile machinery.[?]

We also examine Hirschman's idea of linkages or interdependence among productive sectors of the economy. When industries use inputs from other industries they develop backward linkages. For example the establishment of an automobile plant creates demand for the products from machinery and metal processing plants, which in turn create demand for steel and may stimulate the development of such industries. Forward linkages are developed when industries produce products that subsequently become inputs for other industries. For example successful oil drilling may lead to the development of oil refineries and petrochemical complexes.[?] Hirschman's concept of linkages is applicable to and influences the formation of clusters of related and supporting industries that in turn lead to reductions in costs.

To summarize, there are static and dynamic benefits of developing a cluster of well chosen firms that create spillovers. An important static benefit for example may be reduction in the cost of intermediate inputs that arise from reduced shipping costs because proximity to suppliers. The dynamic externalities arise because of technological advances, increased specialization of labor, knowledge creation, diffusion and spillovers and can also result in cost reductions. This provides the theoretical justification for developing a set of enterprises in space that can benefit from synergistic interactions.

V. Applying Economic Interaction Theory to A Space Based Economy

In today's space industry, most of the elements cited in the cluster concept are present. The pool of trained labor, regulations for space-qualified hardware, a very strong research, development and education base and advanced technology are all present. There are efforts to increase standardization and production run sizes in order to reduce costs. However there is a glaring difference in that common infrastructure and supporting enterprises at the interfaces between "missions" are not developing in Space, partly because there is no common forum for developing such infrastructure. This is the area where we try to visualize a difference.

In the Space industry, economies of scale have increased the value of communication satellites, by vastly increasing number of transponders per satellite. Suppliers of space-qualified hardware have grown over the decades, but the costs are still very high compared to COTS components performing equivalent functions. The economies of scale generated from experience gained through the space enterprise have on the other hand had vast impact on other terrestrial enterprises, with roughly 1 trillion of the 8 trillion dollar U.S. economy being attributed to 'spinoffs'. The reverse process, i.e., economies of scale in the commercial world coming back to slash costs of space enterprise are harder to define. Other economies are harder to achieve because of the mission-oriented nature of Level 1 enterprises. The NASA USAF Cost Model shows some unit cost benefit for systems with larger numbers of identical components, with an 85 percent learning rate assumed. The reboost package and other on-orbit servicing concepts developed for Responsive Space aim to bring such economies into the field.

	Common Services/input	Planetary	Space Station	LEO sats	MEO sats	GEO sats	Reboost packages	Fuel Tanker	OTV	Fuel Depot	Orbital Tethers	On-orbit repair	Junk Removal	Lunar Oxygen	
1.	System Design, production, insurance, mission/enterprise control	I	I	I	I	I	I	I	I	I	I	I	I	I	I
2	Communication services	I	I, O	I, O	I, O	I, O	I	I	I	I	I	I	I	I	I
3	Launch Services	I	I	I	I	I	I	I	I	I					
4	Earth-LEO ELV	I	I	I	I	I	I	I	I	I					
5	Orbit transfer engines	I		I	I	I	I	I	O		O				
6	Fuel supply				I	I	I	I	I	I	O	O		O	
7	Rendezvous capacity						I, O	I	I	I, O	O	O	O	I	I
8	Orbital reboost option	I	I	I	I	I	O	I	I	I	I, O		O	O	
9	Refueling option	I	I	I	I	I	I	I, O	I	O	I	I	I	O	I
10	Repair and salvage		I	I	I	I		I, O	I, O	I, O	I, O		I, O		

Figure 5. Input-output relationships showing the evolution of space-based business.

Implementation of such concepts to the overall space enterprise is hindered by commercial, policy and legal realities, such as ITAR, the status of international treaties on ownership of space resources, legal liabilities of accidents in space, and national/ international boundaries on funding and technology. As pointed out in Ref. 1, the European Space Agency is an excellent example of part of the structure needed for a global space consortium, involving multiple governments and national space agencies as well as industry. However, a good commercial model for long-term development of space resources needs much more development.

V.A. Input-Output relationships of Space-Related Services and Space Enterprises

Figure 5, the inputs and outputs of several space-based enterprises are considered, against a list of common services. Item 1 is essentially all the services provided from the ground now, in other words, the entire space industry except for the satellites now in orbit. Time advances to the right, as more advanced systems are created. The services transition from yellow at the top, denoting earth-based, to blue at the bottom denoting fully space-based, going through a green zone where services can come from either earth-based or space-based suppliers. If a given service (numbered items in the second column) is an input to a given enterprise (top row), then we mark 'I' in the cell. If the service is an output of the enterprise, we mark an 'O' in the cell. The table shows how the Space economy transitions from something which takes all inputs from the ground, to one where there are several outputs in Space that are of use to other space-based enterprises. It is also interesting to see that at the bottom of the table, space-based services, provided by space-based enterprises, provide inputs to several of today's earth-launched missions and services.

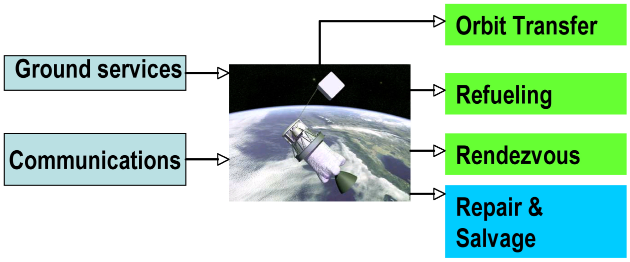

Figure 6. Schematic Representation of Input-Output Linkages of the Orbital Tether Enterprise

Let us now take one example: the case of orbital tethers, about which there is widespread public interest. Tethers are projected to become an effective means of transferring payloads (complete spacecraft or construction material, supplies etc.) from one orbit to another in space. They have been advanced as an option for LEO-GEO transfer, for capturing junk, slinging long-duration space missions out to as far as Mars, to transport cargo to and from the Moon, and for any other orbit transfer mission. Tethers, for instance may provide the breakthrough capability in launching space tourism, by connecting to what are now sub-orbital flights and sending the craft to the required orbital velocity. Concepts for propelling tethers using the earth's magnetic field have also been advanced.

The tether enterprise does not require earth launch once the system is in orbit, but can benefit from capturing mass that has already been placed in orbit to serve as counterweights that reduce the length of tether needed for a given mission. The enterprise provides a service to the launch enterprise, and may turn even suborbital launches (which can be done using aircraft that reach very reasonable supersonic speeds) into space missions. It provides services to the orbit transfer enterprise, to the fuel tanker business, to on-orbit refueling, and to orbital repair and salvage. It may also be an enabler for the lunar fuel enterprise by providing a means to transport hydrogen to the surface and oxygen away from it.

Precise calculation of the effects of each enterprise are beyond the scope of this paper, but it is easy to see that the cost projections of a tether enterprise are greatly reduced if other enterprises are present, and that in turn, the availability of tethers has a large benefit to several other enterprises. Further, as the number of enterprises increases, the market projection for the tethers also rises, so that economies of scale come into the picture.

The tether enterprise however, does not have any limit to its window of profitability as far as we can project. Other enterprises have a limited window, and the expansion of market options spells closure for such enterprises. For instance, the ground-based manufacture of 3rd stage cryogenic engines becomes unnecessary as OTVs become common and last for large numbers of transfer missions with refueling and refurbishment of nozzles, etc. The reboost package business has to transition rapidly to offer repair, refueling and re-usable OTVs instead, even if refueling is not built into future spacecraft.

V.B. Including Interactions in the first steps

We now return to the reboost enterprise to consider some interactions. There are:

1. The market for Reboost will be greatly affected by the impending arrival of in-space refueling technology. The market will actually rise sharply in the short term because satellite operators see benefit to extending lifetime of present operations until their satellites can be fitted with refuelable engines, and then perhaps other refurbishments can be carried out as on-orbit servicing develops. Thus we assume a rise in demand for re-boost, by 10 packages a year, starting in Year 10. The total production run is doubled, to reach 200. This reduces the average production cost by 15 percent. The effect on the NPV curve is dramatic, crossing zero now by Year 14. In the longer term, the market drops because newer satellites are built with refueling provisions. However, the sharp rise in production seems to assure a very profitable window before this occurs. This illustrates the backward linkage of the refueling business to the reboost business.

2. The forward linkage of the reboost capability to refueling may also be considered. Market acceptance and experience with rendezvous in GEO are advanced sufficiently to reduce the risk premium of the fueling business. Newer satellites will incorporate refueling, and, presumably, the capability to remove given modules and return them to LEO or Earth for servicing. This in turn will substantially reduce the reliability demands on GEO satellite components, and again, reduce costs. Operators will view GEO slots as places to park a satellite platform, carrying a suite of capabilities that is improved frequently. This in turn will have a positive effect on the demand for launches of modular components to GEO, though it will reduce the demand to launch large complete satellites to GEO. Despite the limited number of slots in GEO, there is no reason to fear that the GEO launch market or the satellite

building industry is in any danger of collapse. A market expansion is quite likely, analogous to the transition from the large computer market of the 1970s to the PC market of the 1990s.

VI. Discussion of Results

The question that most plagues space entrepreneurs is how to reduce the number of years to zero NPV at a reasonable, Internal Rate of Return (IRR) that is appropriate for the level of risk. Here interactions help in two ways. Firstly they should reduce risk by a large factor by providing support and alternative paths because of the presence of other enterprises. This was demonstrated in Ref. **?** where the effect on the cost per unit functionality of launches to GEO was considered. The presence of and reboost capability, partial repair/replacement capability, and orbit transfer engines essentially slashes GEO launch cost by 90 percent. Whether this leads to a collapse of the GEO satellite market due to lack of demand for new launches, or a rapid growth of the GEO launch market because slot owners are keen to inject new technology and gain better use of their slots, remains to be seen. Again, as seen above, the latter appears far more likely, since experience suggests that anyone who becomes complacent about the customers of communication and entertainment services, do so at extreme peril.

Including interactions will change traditional costing models drastically. At present, the experience base behind cost models is mostly of the "mission" or Level 1 enterprises. These all include large costs of redundancy, and the burden of carrying brand-new engines and fuel with the launcher for the lifetime of the mission. Although cost is related to dry mass of satellites, the correlation is partly fortuitous. Some NASA veterans have commented that the true basis for successful cost estimation (meaning for missions that go forward) is to ensure that the cost comes out no less than missions in the experience database. These methods will be overturned as interactions are modeled, and businesses such as the reboost, the OTV and the tether come into being. A major shift in cost estimation is underway, as people begin to accept the "Value Proposition" in cost estimation, as developed, for instance by Saleh,[?,?] As quantitative interaction models for a Space based economy that include these considerations are propagated, there is an opportunity to do the up-front coordination that slashes risk and accelerates the transition to Levels 2, 3 and 4.

Finally, we note that these large improvements in return on investment and risk mitigation are achieved with no assumed drop in the cost of launching a given mass from earth to orbit. Thus it shows that alternatives exist to the traditional notion that "reducing launch cost from earth" should be the overriding priority of space technology programs. A very large drop in the effective launch cost for a given enterprise can occur by going ahead with coordinated development of a suite of well-considered enterprises.

VII. Conclusions

1. The projected sequence of development is validated as new enterprises arise for reboost, refueling, repair and other on-orbit servicing, under the Responsive Space initiatives.

2. With increased development of enterprises at the interfaces between projects, the input-output relationships in the space economy shift more towards enterprises that are based in Space.

3. The theories of clustering in the economics literature appear to be applicable to the Space business, with the important difference that the infrastructure and co-location features are slow to occur.