Sensitivity of Private Space Station Profitability to Market Demand and Use of Space Resources.

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Introduction: The International Space Station (ISS) started operations in 1998 and has since housed over 200 humans in Low Earth Orbit (LEO). A recent testimony by the Inspector General of the National Aeronautics and Space Administration (NASA) argued that operational costs for continuing ISS operations is more then half of NASA's annual budget for human spaceflight and extension beyond 2024 will bring with it significant increase to safety due to aging hardware[1]. The government is now calling on private industry to take the reins of the space-station market.

In 2017, the Science and Technology Policy Institute (STPI), part of the Institute for Defense Analyses released a report regarding the profitability of private space stations[2]. This work concluded that a space station intending to act commercially, would most likely not be successful at obtaining profits in the market by 2025. These findings were highly sensitive to the cost of launch in determining annual cost of the station as it requires regular resupply missions.

Analysis of the various estimates used in the STPI report reveal that upwards of 40% of the annual cost could be reduced through use of space resources. In the current study, alternative possibilities are explored by leveraging near-term and proposed in-space resource markets. In particular, processed lunar water can fill the needs of propulsion propellants, oxygen to breath, water to drink and water to use. Recently, a group from government, industry and academia came together to produce a comprehensive report on the prospects of lunar propellant production[3]. This report includes trade studies and industry plans which can be directly applied in studying resource costs for a private space station. In addition to uses of water, lunar or asteroid regolith and rocks provide silica and metal ores which can offset raw material needs for the station. The current work builds on the STPI study by using results from the space resources community and a new open-source analysis tool in order to explore and quantify the risks, benefits and scale effects of using space resources to increase the profitability of private space stations.

Background: The Committee for Expansion into Key Space Industries (CENKI) was founded in 2016 by a group of graduate engineering students from the University of Colorado with the mission *to assemble the community and technical resources to stimulate the development of a thriving space economy*[1]. Over the last 3 years, CENKI has put out original student research from a diverse set of perspectives ranging from economics and business to engineering and policy[4,5].

As a flagship project, CENKI has developed and vetted a tool for studying complex space-economic-systems, known as the Space Economic Simulator (SES)[6,7]. This open-source code is being developed to handle any combination of deterministic and probabilistic modeling related to the costs and revenues of many services or resources. In this way, any number of individually known uncertainties can be incorporated seamlessly with model components that may be fully certain or simply not as important to model to high fidelity. It is the hope that CENKI's research efforts culminate in an online database of SES "player" modules that can be used in a plug-and-play fashion to perform any type of analysis for space business, policy recommendations or academic exploration. With this capability, we hope a standard SES study will become a trusted answer to the question, "How can one quantify the profitability and potential risk of a future commercial venture or overall space economy?"

To continue toward CENKI goals, the present work takes on the topic of commercial space stations and the transition from the ISS. As noted in the introduction, a recently completed study on private stations was performed by STPI. This provides an excellent baseline from which to build SES player modules. These modules are simulated in a virtual marketplace many times to realize the full spread of possibilities. Specifically, our focus is on the cost for the station which can be reduced through use of space resources. How the benefit of these resources scales with the demand for station is used as a driving input.

Research Methods: In the current study, the basic revenue estimating relationships (RER) defined in the STPI study are used in order to quantify profitability of a specific scenario. Each scenario will be defined by a varying number of worker and customer astronauts which in turn defines the size of the station, driving the overall cost for the station owners. Additionally, the amount of consumables and repair needs which can be acquired at a reduced rate from in-space resources are used as the main tuning knob of the study. In order to accomplish this, the cost estimating relationships (CER) are generalized to a function of inhabitants and augmented with cost reductions for getting resources from space.

[1] www.cenki.space

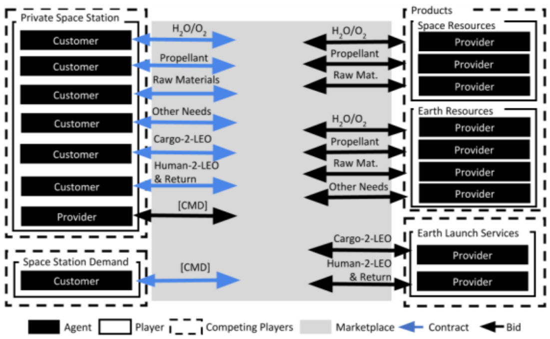

Figure 1. Simulation schematic.

Figure 1 represents the general scenario which is simulated using the SES. Each player module represents either an individual financial entity, like the private space station, or a lumped representation of an entire industry sector, like the launch and resource markets.

Each player has a custom set of internal logic which can take any form of RER and CER as well as business strategies such as schedule and contract negotiation tactics. Thus, the STPI study assumptions are simply converted into SES player logic so that the cost of resupply and repairs, as well as the number of inhabitants, can be varied while including all model uncertainties. In the past, simulations consisted of multi-year scenarios where launch schedules were varied to compare each strategies return-on-investment[7]. In the current work, a single year of the research space station is analyzed to better quantify the effect of space resources and crew member demand (CMD) on the annual cost of a private space station.

A SES player module can have either one or many provider and customer agents. These agents interact in the virtual marketplace in order to bid-on or select-bids on service or product contracts. For example, the launch industry has a provider agent which bids on customer proposals for the needed service of launching mass to LEO from Earth(see Fig.1). If the launch player was the focus of the study, or part of a more complex overall simulation, it could also have various customer agents which offer contract opportunities to outsourced launch vehicle components or services. Having multiple players which provide the same product or service creates competition in the marketplace. The customer makes the final decision based on internal logic of which bid to choose. The bidding process can go back and forth any number of times based on the bid-casting and bid-choosing logic. For the current work, choices were made after a single round of bidding. Each player model considered in this study will now be described.

Earth Resources is a lumped-market player that represents all products purchased on Earth and launched to the station. In order to focus this study on the products which can be sourced from space, "Other Needs" is considered a catch-all for any annual cost which cannot be offset from non-earth based providers.

Space Resources is similar to the Earth resources player except it only includes products derived from water or regolith. Discounted prices for space resources are varied from 0% to 50% in terms of $/kg of product delivered to the station. To put this in perspective, the collaborative ISRU study considered a cost reduction of 25% ($3,000 from $4,000) for lunar sourced relative to Earth sourced propellant in LEO[3].

Launch Services is a third lumped-market player which uses aggregate market data to represent the spread of possible launch cost and launch failure probabilities. In the current study, insurance is not modeled. A launch failure represents a loss for the pivate space station. This hits on a rather complex aspect of market forecasting that we do not attempt capture, namely the human reaction to launch or on-orbit failures. In the current work, the station demand model does not adjust relative to events in the market.

Demand for Passengers is the largest unknown in the possible commercial space station market. Following the assumptions of the STPI study, only stations which have humans working or visiting are considered. This constraint allows for the direct coupling of station volume and mass to that of the number of inhabitants which in turn is then directly coupled to the driving demand and resulting revenue. As the input to this trade, annual CMD is varied from 2-48 CM/yr.

Private Space Station is modeled as a complex player representing a single commercial entity operating a for-profit business in space. The company must purchase a number of products to meet the CMD. Some can be acquired from space resource providers at a discounted rate while others must come from the expensive gravity well of Earth. Launches from Earth to the station in LEO must also be purchased. In the event of a launch failure, the revenues are not recouped and thus the modeled profitability is decreased.

Conclusions: Extending the STPI study by modeling players with market-agents provides the community with quantified sensitivities of a commercial operation's profitability to space station demand. In the end, a clear benefit can be seen across all scenarios considered when it comes to use of space resources to offset the high cost of transporting mass from Earth.

References: [1] Martin, P. K. (2018) *NASA Office of the Inspector General* [2] Crane, K. W. et al. (2017) *Science, Technology and Policy Institute*. [3] Kornuta, D. et al. (2018) *Commercial Lunar Propellant Architecure*. [4] Bennet, T. et al. (2016) *AIAA Space*, 5308. [5] Gemer, A. (2017) *SRR & PTMSS*, 1679. [6] Bennet, T. et al. (2018) *IEEE Aerospace Conf.*, 2020. [7] Bennet, T. et al. (2018) *IEEE Aerospace Conf.*, 2344.