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Establishing a framework for studying the emerging cislunar economy

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ABSTRACT

Recent developments from the New Space industry have seen the appearance of a number of new companies interested in the creation of a self-sustained economy in cislunar space. Industries such as asteroid mining, Moon mining, and on-orbit manufacturing require the existence of a developed economy in space for the business cases to close in the long term, without the need to have the government as a permanent anchor customer. However, most studies and business plans do not consider the global picture of the cislunar economy, and only work with Earth-based activities when evaluating possible customers and competition. This work aims to set the framework for the study of the cislunar economy as a whole by identifying the market verticals that will form the basis of the economic activities in cislunar space, focusing on activities that create value in space for space. The prospective cislunar market verticals are identified based on a comprehensive review of current space activities and of proposed future business cases. This framework can be expanded in the future with evaluations of market sizes and relationships between verticals to inform business plans and investment decisions. The study was performed during the first two months in the summer of 2016 as part of the author's internship at NASA's Space Portal Office to complete the International Space University Master of Space Studies.

1. Introduction

Cislunar space, commonly defined as the region of space containing the Earth and the Moon, is being the target of much of the commercial New Space development. Many existing companies are aiming to include the Moon in the human economic sphere of influence, currently limited to geostationary orbit. These companies include in their business plans activities that go from Moon mining and delivery services (Astrobotic, Moon Express) to a transportation system to support 1000 people working in space (ULA Cislunar 1000 [1]). Others are trying to expand the economic sphere even further to include near-Earth asteroids, with plans for asteroid mining (Deep Space Industries (DSI), Planetary Resources).

It is a general expectation in the space community that the cislunar economy will develop in the next 10–20 years, but there is no clear picture of how it will be structured. Most market research and technical studies focus on activities that bring value back to Earth, or just study a single activity in space (i.e. asteroid mining) without considering the effect of other possible markets. However, a self-sustaining cislunar economy will be based on activities that create value in space for space, and will include activities on both the Moon and near-Earth asteroids. This project aims to perform a comprehensive study of the potential commercial markets of the cislunar economy, determining the market verticals, the relationships between them, and the current status of the industry. This will provide a picture of how the mature cislunar economy will look like, and how we may reach that maturity. Market verticals are chosen as the unit of study because they can be considered niches independent from each other. This allows for a preliminary classification of the economic activities in independent groups, and then the mutual relationships can be studied to understand the economy as a whole. To this end, a market is defined as a demand for a service or a product, and a market vertical is defined as a group of companies that serve each other's specialized needs, focusing on a single niche.

This project is meant to set the basis for future studies of the cislunar economy. By identifying the market verticals and the current status of the industry, a framework for the study of the cislunar economy is defined, and a first estimation of the evolution of the cislunar economy can be created. This roadmap and framework can be used in future market studies to inform business plans and investment opportunities. To this end, the study begins by identifying production and distribution activities that will emerge in cislunar space, based on the current status of the New and Old Space industries, and focusing on activities that create value in space for space. These activities are then grouped into market verticals based on their products and customers, and finally the verticals are classified according to their impact on the cislunar economy as a whole, based on their mutual direct relationships.

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Abbreviations

BEO	Beyond Earth Orbit
DSI	Deep Space Industries
EML1/2	Earth-Moon Lagrange Point 1/2
LEO	Low Earth Orbit
NSG	NewSpace Global
TRL	Technology Readiness Level
ULA	United Launch Alliance

2. Overview of the space industry

Future cislunar markets will evolve from the current status of the space industry, so a proper understanding of current and emerging space activities is needed to understand the evolution of the space economy. A review of current space activities, dominated by the so called Old Space, can be found in the Space Report, published yearly by the Space Foundation. On the other hand, emerging space markets are usually classified in the eight different verticals of NewSpace Global.

2.1. Current space activities

The Space Report 2016 divides current global space activity in three major sectors: commercial products and services, commercial infrastructure and support industries, and government space activities. Together, they represent an industry with combined size of $322.9B in 2015 [2]. These sectors are mostly formed by well-established and mature companies that operate in sectors with high value but low growth, the *traditional space* (also Old Space) [3], with some notable exceptions in sectors such as Earth observation and launch providers. Table 1 summarizes the industry sizes and the divisions present in the Space Report.

The largest segment of current space activities, Commercial products and services, generated $126.3B in revenues in 2015, about 51% of the revenues from all commercial activities. The huge majority of it is generated by telecommunication services (direct-to-home TV, satellite communications, and satellite radio), and the rest is due to the emerging Earth Observation industry (agriculture monitoring, weather data through GPS radio occultation, etc.). The other half of the commercial activities, Commercial infrastructure and support industries, includes ground stations and equipment, commercial satellite manufacturing and launch providers, insurance premiums, suborbital flights, and R&D activities. The largest part of it is the ground stations and equipment segment ($110.5B), mainly due to the market for global navigation satellite systems ground equipment, which adds up to $83.3B.

Finally, government space budgets complete the rest of the industry, with a total budget of $76.5B worldwide. Government activities cover a wide range of applications, from communications, surveillance and weather forecasting to human spaceflight, and ISS operations (for the ISS partners), and education. The majority of the spending comes from the US government with a total spending of $44.6B in space activities. Of this, 93% corresponds to the Department of Defense ($23.6B) and NASA ($18B), with the rest split among at least seven other agencies. The rest of the sector's budget ($31.9B) comes from non-US military spending ($10.6B), a range of space agencies (ESA, CNSA, Roscosmos, JAXA, CNES, DLR, etc.), and other national budgets and international organizations such as EUMETSAT.

Table 1
Segments and size of the current space industry [2].

Sector	Segment	Size
Commercial space products	Direct-to-home TV	$97.8B
	Satellite communications	$21.5B
	Satellite radio	$4.6B
	Earth observation	$2.47B
	Total	$126.3B
Commercial infrastructure and support industries	Ground stations and equipment	$110.5B
	Commercial satellite manufacturing	$6.05B
	Commercial launch industry	$2.6B
	Support & suborbital activities	$0.9B
	Total	$120.1B
Government budgets	US military budget	$23.6B
	Non-US military budget	$10.6B
	US civil budget	$21.0B
	Non-US civil budget	$21.37B
	Total	$76.5B
Total size of current space activities		$322.9B

2.2. Emerging space activities

The bulk of current space activities are part of *traditional space* (also known as *Old Space*): highly structured companies focused on established lines of business, often with the government, and established in sectors with high value but low sales and growth [3]. In contrast to this, the New Space industry is leading a number of emerging space activities that are leveraging new technologies and entrepreneurial philosophies to open up new markets in the space sector. Arguably the best classification of the New Space markets is the one done by NewSpace Global (NSG) and their eight market verticals. The verticals are: Spacecraft; Launch vehicle providers; Human spaceflight; Microgravity research; Spaceland; Space resources; and Space-Based energy. These eight verticals partially overlap with current space activities, but also extend them into future ones. Fig. 1 shows the eight verticals in potential chronological order, with the existing markets on the left, and the prospective markets on the right, as classified by NSG.

1 Spacecraft: The *Spacecraft* vertical includes spacecraft design and development, as well as spacecraft services (essentially communications and Earth observation) [5]. Most of these activities are already established markets and part of *Old Space*. The New Space industry is especially active in the development and use of nano and microsatellites (mainly CubeSats), where 70% of the launches over the next two years will be of commercial nature. These satellites are traditionally dedicated to technology development and Earth observation (47% and 37% of the spacecraft respectively), but this will shift to a majority of Earth observation spacecraft (73% of total) in the following years [6].
2 Launch vehicle providers: Commercial launch providers have existed since the creation of Arianespace in 1980, but current New Space activities are changing the market with lower launch prices, higher number of flights (launch rate), and reusable rockets. This change is being led by SpaceX, whose Falcon 9 has brought launch prices to low Earth orbit (LEO) down to an about 2800 $/kg and has already successfully recovered several of their boosters after an orbital launch [7,8]. New Space is also addressing the demand for small satellite launchers, which is expected to grow steadily in the following years. A number of companies such as Rocket Lab and Virgin Galactic are developing launch vehicles to serve this new market [6].
3 Human spaceflight: The *Human spaceflight* vertical includes orbital and suborbital crewed trips. No commercial entity has flown their own astronauts so far, but companies such as Virgin Galactic and Blue Origin have announced suborbital crewed flights for tourism and research starting 2017 [9,10], and Space Adventures has already taken 7 tourists to ISS in Russian rockets. Beyond suborbital, commercial orbital spaceflight is expected to take off in the following years, when the participants of NASA's Commercial Crew Program start flying (expected in 2017) [11].

Fig. 1. NSG 8 verticals of New Space, from existing (left) to farther into the future (right) [4].

4 Microgravity research: *Microgravity research* covers any R&D activities that take advantage of the microgravity environment of space to study effects that become predominant when gravity is removed, such as surface tension and capillary forces. These effects are mostly present in materials and life sciences, where microgravity has already allowed many discoveries. Commercial microgravity research could lead to new materials and microchips, and advances in biotech, and medical devices and applications [12]. Some companies such as Acme Advanced Materials and Zero Gravity Solutions have already started to work on products derived from microgravity research.

5 Spaceland: The term *Spaceland* refers to the different spaceports that are being built to house the commercial launches brought in by New Space companies, for example Spaceport America and Spaceport Colorado. Even though some of them are already operational, no commercial flights have taken place in any of them as of date. Moreover, *Spaceland* also includes commercial orbital space stations, such as the ones proposed by Bigelow Aerospace or Axiom Space. Commercial orbital stations are expected to start operations before 2020 [13,14].

6 In-space services: The 6th vertical includes a broad range of activities from mission operations and support to satellite servicing: station keeping, refueling, repositioning, anomaly resolution, debris mitigation, etc. [5]. Some companies such as Effective Space Solutions are working on developing satellite-servicing spacecraft [15]. Others, such as Altius Space Machines, are working on hardware for cryogenic refueling [16]. However, these markets are still some years away, as evidenced by their position in the verticals list.

7 Space resources: Further into the future, space-derived resources will form the 7th vertical of New Space. Space resources include materials extracted from the Moon or near-Earth asteroids. The most important resource will be water for propellant and consumables, followed structural metals and semiconductors. Near-Earth asteroids can also provide a good source of platinum-group metals, which could be sold back on Earth for a profit [17]. There are some companies whose business plan includes extracting resources from space-based sources [18–20], but all the plans call for the first materials to be extracted and delivered to cislunar space in the 5–10 year timeframe.

8 Space-Based energy: Finally, the last New Space vertical is *Space energy*. This usually refers to space-based solar power, i.e. beaming solar-based power from orbiting platforms back to Earth. This technique is technically feasible at present, but the current economics of space do not allow for profitable business plans [21]. Space energy would in principle be economically interesting once launch and manufacturing costs become low enough, or by using space resources. However, some companies have emerged with the intention of starting the space-based solar power industry in the near future [22].

With this structure, NewSpace Global sets the scene of where the current New Space industry is and where it is headed, creating a comprehensive picture of current and planned activities.

2.3. *Value in space for Earth*

Current and emerging space activities have one thing in common: they create value in space for Earth. The current space industry is dominated by space services (communications, Earth observation) and the infrastructure to support them (ground stations, launch providers, etc.). New Space is attempting to open new markets, but most of them either bring value back to Earth (microgravity research, Earth observation) or support these activities (human spaceflight, Spaceland). Even those verticals that can create value in space for space, namely space resources and in-space services, only consider creating value for space in the long term, with most short term plans serving the existing space-for-Earth industry.

Given that the total of today's human economic activity takes place on Earth, space activities are forced to create value in space for Earth. However, a self-sustaining economy in space will require activities that create value in space for space. Launch costs (at least about 1700 $/kg with the future Falcon Heavy) limit the amount of mass that can be placed in orbit in an affordable manner, which in turn limits how much one can bring from Earth to the cislunar economy. Moreover, the strict requirements imposed by launch call for spacecraft built in space and operated exclusively in space, instead of having to also go through launch and/or reentry (the so called "impedance matching" [23–25]). It makes sense then that a self-sustaining space economy will create most of its value in space.

This transition from space-for-Earth to space-for-space value also makes sense as part of a progressive expansion of the human economic sphere into space: creating value in space for Earth serves as a middle step between purely Earth-based activities and purely space-based activities. Creating value for Earth allows companies to monetize their technology development and activities and reduces risk in what would otherwise be a long-term investment (15–20 years). It also establishes a possible initial customer for space-for-space activities. These will define the market verticals that will be the core of the economic system, and studying their evolution and mutual interactions will inform business decisions on the development of the industry. The next section identifies these space-for-space activities and the associated market verticals, and proposes a possible roadmap for their evolution.

3. Extension to cislunar space

New Space activities serve as a transition point between an Earth-based economy and a space-based one. Creating value in space for Earth can provide a way to monetize investments in technology development, create new markets, and reduce risks in the long-term commitments that traditionally characterize the space sector. The NSG verticals can then serve as the basis for identifying these space-based markets. The question is how the current New Space verticals will transition into the cislunar verticals, that is, which future cislunar markets can be created with the current New Space activities.

Table 2
Extension of NSG verticals to cislunar space.

NSG vertical	NSG description	Extension to cislunar (value in space for space)
1. Spacecraft	Satellite manufacturing and services (communications, remote sensing)	On-orbit manufacturing, space data relays, navigation and positioning
2. Launch vehicle providers	Orbital and suborbital launchers	Lunar landers, space tugs.
3. Human spaceflight	Suborbital tourism, high altitude balloons	Crew capsules, crew landers, orbital and lunar tourism
4. Microgravity research	Microgravity research and providers	Asteroid prospecting, planetary science, radioastronomy, biology
5. Spaceland	Spaceports and Bigelow stations	Cislunar stations (EML1/2) (way stations, repair stations, etc.) lunar base, propellant depots
6. In-space services	Satellite servicing (station keeping, refueling, retiring), anomaly resolution	On-orbit repair, retrofit, debris removal and reclaim
7. Space resources	Moon and asteroid mining	Asteroid and lunar mining: water, metals, semiconductors
8. Space-Based energy	Space-based solar power to Earth	Space-based solar power to Moon and beamed power

3.1. Value in space for space

Table 2 shows how the NSG verticals can be extended to cislunar space. This table is based on a comprehensive review of the existing literature and public business plans, and finding analogies for current and emerging space activities that create value in space for space. The extension of each vertical is based on similarities of the technologies required, the available markets, and the activities typical of each vertical. For example, scientific activities were considered an extension of the microgravity research vertical (4th), while transportation markets were considered an extension of launch providers (2nd).

Each New Space vertical can spur a number of activities based on its technology and market, but the cislunar activities derived from a single vertical can be part of different verticals themselves. For example, the 2nd vertical *Launch vehicle providers* can create markets for lunar landers and propellant depots, which would be distinct verticals in the cislunar economy, since they serve completely different markets. The rest of the section reviews how each New Space vertical could develop into cislunar space.

1 Spacecraft: Spacecraft manufacturing and assembly is one of the key activities that could be moved to space. Manufacturing spacecraft in space would decouple satellite platforms from launch requirements, allowing spacecraft too big to be launched inside a fairing, or too weak to sustain launch stresses. Initial manufacturing would be limited to the most simple components, such as antennas, trusses, and fuel tanks, and it would eventually include manufacturing of all components but the most complex ones, such as microcontrollers, as more materials become available [26]. The most prominent company in on-orbit manufacturing is Made in Space, which is aiming to develop full on-orbit manufacturing capabilities [27]. However, it is currently focusing on ISS servicing (where they operate a 3D printer), and microgravity manufacturing for Earth use [28].
On the other hand, services such as communications can be readily used for cislunar activities, as data relay systems similar to the Tracking and Data Relay Satellite. These systems could transition later on into a complete space-based internet network connecting cislunar facilities with each other and Earth. Companies such as Kepler Communications are already planning relay satellite constellations, with the final goal of creating the space internet [29]. Other companies such as SpaceX and OneWeb are aiming to create space-based internet for Earth [30,31], but the network could in principle be adapted for space-to-space use.
Other services that could be extended from use on Earth to use on cislunar space would be navigation and positioning, either in orbit or on the lunar surface. Current spacecraft that operate outside the GPS orbits have to rely on their own instrumentation and on the Deep Space Network for navigation, and navigation on the Moon is limited to relative optical positioning [32]. Routine commercial operations in cislunar space could potentially benefit from a navigation and positioning system as did the Earth-based industry.

2 Launch vehicle providers: The launch vehicle market would translate in cislunar space into transportation services in space, i.e. space tugs and lunar cargo landers. Essentially, the equivalent to launch providers would be delivering payload to and from any location in cislunar space. The similarities in the technology and operations are obvious: technology used in rocket launchers and, more recently, reusable boosters can be used in lunar landers, and the second stages could be adapted to act as space tugs. This is precisely what United Launch Alliance (ULA) is working on, with the Advanced Cryogenic Evolved Stage (ACES) upper stage and XEUS lunar lander, a modified ACES [1]. This would not be limited to current launch providers though, other companies such as Moon Express and Astrobotic, as well as the other Google Lunar XPrize competitors, are developing lunar landers without working on Earth launchers [18,33].

3 Human spaceflight: Commercial human spaceflight in cislunar space would include everything from crew capsules for orbital operations to crewed lunar landers. This would cover markets such as orbital and lunar tourism, as well as crewed lunar landings for governments and lunar base operations. Some companies are already developing crewed capsules that can operate all around cislunar space, such as SpaceX's Crew Dragon or Boeing's Starliner [34,35], and ULA's XEUS lander could accommodate crew [1].

4 Microgravity research: Microgravity research can be done in LEO, but some scientific activities can be extended to the complete cislunar space. Lunar bases would enable radioastronomy activities form the far side, away from Earth's noise, as well as planetary science activities on the surface. Affordable access to the lunar surface would also benefit activities in exobiology research, as well as enable some biological research that would require the complete isolation of the Moon's environment, due to intrinsic risks for example. On the other hand, planetary science can be extended outside cislunar space to other planets, asteroids, and comets. Companies such as Deep Space Industries and Planetary Resources are developing asteroid prospecting spacecraft with commercial components, potentially creating a market for interplanetary satellites, and scientific payloads.

5 Spaceland: The markets contained within the *Spaceland* vertical are bound to become nodes for the movement of people, and maybe cargo, between Earth and orbit. Spaceports and commercial orbital stations could act as staging points between launchers and cislunar spacecraft for impedance matching [25]. In cislunar space, stations have been proposed at different orbits: LEO, Earth-Moon Lagrange points 1 (EML1) or 2 (EML2), highly-elliptical orbits between geostationary orbit and EML1, lunar distant retrograde orbits, etc. However, they would all offer similar services, such as propellant resupply, spacecraft repair, or staging for beyond Earth orbit (BEO) missions or for missions returning from interplanetary space. Initially, stations would vary on specific purpose and structure between crewed modules such as Bigelow's BA-330 [13] and propellant depots [36], but stations in key staging points such as EML1 might eventually offer all the different services. Several companies consider cislunar stations part of their business plans, such as Bigelow Aerospace, Axiom Space, or Shackleton Energy, and others are working on

technology for cryogenic propellant transfer and storage, such as Altius Space Machines [13,14,16,37].
Another key node in the transportation network will be lunar surface bases, which will serve as a node between lunar resources cislunar space, as well as host crewed activities such as tourism and research. Bigelow has been working for some years on a module for planetary bases [13], and several companies plan to extract lunar resources for use in cislunar space, which would require the development of base infrastructure on the surface.

6 In-space services: In-space services already would create value in space for space in their current conception, but the existence of the other cislunar markets would allow an extension of the scope and services available. Services currently envisioned such as anomaly resolution, and satellite refueling, station-keeping, and retiring could be made cheaper, and would enjoy a wider customer base as activity in the cislunar region increases. Otherwise, on-orbit manufacturing could enable affordable orbital repair and retrofit, and combined with space tugs and propellant depots could enable active debris removal for reclaim and recycling. Crewed cislunar stations could allow astronauts to service satellites in person, and components could be recycled and reused for new spacecraft, potentially reducing launch mass for some missions.

7 Space resources: The space-derived resource that would create most value in space would be water as propellant and consumable, as current space mining companies are targeting. After propellant, the most available and usable resource will be structural metals, be it titanium or aluminum from the Moon or ferrous metals from asteroids. Finally, semiconductors make third place on the list for their use in production of solar panels. Other compounds and elements, for example for the production of plastics, are also present, but their lower abundance and interest might not make them affordable until later stages of the development of the economy [17]. Asteroid mining companies are targeting water initially, but Deep Space Industries also plans to set up a complete manufacturing infrastructure [20]. On contrast, current Moon mining companies seem to focus only on water as propellant, arguably due to the increased propellant needs for export from the Moon compared to asteroid materials.
The constraint on the markets to create value in space eliminates the use of some asteroid resources such as platinum-group metals from the list, though these would be produced as byproducts of metal mining activities, and would increase the revenue of the asteroid mining companies.

8 Space-Based energy: Focusing space energy on space-for-space value limits its application to beamed power to spacecraft and space-based solar power for the lunar surface. Beamed power to the lunar surface would allow operations during the 14-day-long nights away from the Poles, and might serve as a proving ground for technology for Earth applications. On the other hand, beamed power to spacecraft has been proposed as a way for efficient propulsion, allowing spacecraft that do not carry heavy and expensive power supply systems for their propulsion. Beamed power technologies are still in their infancy, and not so many companies are working on them, even less so for space-only applications.

3.2. Cislunar market verticals

In order to understand how the different activities and markets will influence each other, it is interesting to classify them according to market verticals. As defined in Section 1, a market vertical refers to a group of companies that serve each other's specialized needs, focusing on a single niche. Knowing the different niches that will form within the economy would simplify analysis of market sizes and interactions, and provide a more comprehensive global view of the cislunar economy to inform business decisions. The cislunar activities shown in Table 2 will form the basic activities of the cislunar economy. Among them are all the activities that will determine what to produce and how, thus defining the economy. However, they do not align with the verticals from current New Space. They can be divided in 11 verticals: water mining, metal mining, on-orbit manufacturing, in-space transportation, cislunar stations, lunar landers, lunar bases, advanced orbital services, satellite services, off-Earth science, and beamed power.

1 Water mining: Water will be the most valuable resource in space mining, since it can be used as either monopropellant or LOx/LH_2 bipropellant, as well as consumable, radiation shielding, and in other applications such as cooling liquid. Due to its value, water could be derived profitably from two sources: asteroids and the Moon. Water from the Moon and asteroids would compete in the market for propellant and consumables in cislunar space: the added costs in terms of propellant for lunar water would act as a trade-off for increased availability and accessibility of the Moon compared to asteroids. This trade-off, added to the current uncertainty in the final price points, makes it unclear which source of water will prevail. This is reflected in the fact that there are companies aiming for water from both asteroids (DSI, Planetary Resources, TransAstra) and the Moon (Moon Express). Moreover, it makes sense to combine both lunar and asteroid water in the same vertical, since they would be addressing the same customer base, and delivering to the same stations in cislunar space, thus forming an industry niche.

2 Metal mining: Metals are the other raw material that could readily be used in space with current technologies. The most immediate on-orbit manufacturing activities will require structural metals for antennas, trusses and other structures, and semiconductors for solar panels. These materials would mostly be derived from asteroids, where their abundance and low propellant costs would make them affordable. The Moon might also provide a source of metals for orbital activities, but their propellant costs might limit their use to the lunar surface. Metals extracted from the Moon will also be different than those derived from asteroids: asteroids are richer in ferrous metals (iron, nickel), while the Moon has a higher abundance of titanium. This difference could mean that the vertical would eventually be divided in two, depending on the metal and its use, but early use and extraction mechanisms would be similar enough to group all the metals in the same niche.

3 On-orbit manufacturing: On-orbit manufacturing would not be limited to manufacturing components from raw materials, but also include on-orbit integration and assembly. As mentioned before, the first components that will be manufactured in orbit will be structural components such as trusses and other simple elements (e.g. antennas), and simple mechanisms (reactions wheels, gimbals, etc.). Eventually, manufacturing would include more complex components such as solar panels and engines, but most of the complex elements (microchips for example) would still be manufactured on Earth. Spacecraft could be assembled in orbit with components brought from Earth, or combined with components manufactured in orbit. Orbital assembly techniques might also be used in the construction of bigger spacecraft such as stations and interplanetary vehicles.

4 In-space transportation: Propellant depots and tug services would form the vertical of in-space transportation. As mentioned before, using space tugs to deliver spacecraft to their operational orbit would allow higher launch masses, since the spacecraft would only have to be launched to LEO. Space tugs could deliver satellites, station components, crew capsules, and other payloads to their operational orbits, creating a market with a wide customer base. However, reusable space tugs would require on-orbit refueling opportunities. This is best done with orbital propellant depots, which in a mature cislunar economy would be supplied with propellant from the Moon or asteroids. Early operations could be done with propellant supplied from Earth, if launch costs allow it, or with a distributed launch scheme similar to ULA's [38].
Alternatively, electric propulsion tugs might be used to deliver spacecraft without time-sensitive payloads. These tugs could be

supplied with propellant from Earth, and could be spun off for space debris removal or spacecraft retiring.

5 Cislunar stations: Cislunar stations would make up the nodes of transportation of goods and people in cislunar space. Stations in key places in cislunar space such as LEO, or EML1 and EML2 would act as staging points between launchers, lunar landers, space tugs, and interplanetary spacecraft (impedance matching), and act as hubs for the movement of goods such as propellants and human consumables. This niche would cover activities such as orbital hotels, microgravity research, way stations for BEO missions, and repair stations for satellites. While some stations would include propellant depots, these could be completely automated and serve mostly space tugs, justifying their placement in a separate vertical.

6 Lunar landers: Lunar landers would complete the cislunar transportation network, connecting the Moon's surface with the different cislunar stations. Cargo landers would address markets such as surface payload delivery for scientific missions (Astrobotic's offer) and lunar base support (resupply, component delivery, etc.). Advanced landers with take-off capabilities would also export resources such as propellant from the Moon, as envisioned for example in the Evolvable Lunar Architecture [39]. Crewed landers could be used both in short-stay sorties to the lunar surface for scientific missions or tourism, and to transport crew to and from the lunar outpost.

7 Lunar base: Given the cost of deploying infrastructure on the Moon, lunar surface activities would most likely be coordinated from a common base. This would eventually lead to the establishment of a permanently crewed lunar outpost. This base would provide support for resource extraction and scientific activities, and eventually house commercial passengers (e.g. tourists). Activities would include infrastructure deployment and construction, allocation of crew resources and life support, crewed support for all surface activities, and lunar tourism.

8 Advanced orbital services: On-orbit servicing markets would be extended to include on-orbit repair and retrofit, refueling, and debris removal and reclaim. The availability of cheap propellant in orbit would make on-orbit refueling affordable, and components manufactured in orbit could be used for retrofitting and repair of satellites. These services would also benefit from the experience with on-orbit assembly, potentially using similar techniques. Finally, the need for raw materials in orbit for manufacturing could potentially create a market for the recycling of orbital debris, reducing the cost of active debris removal.

These services are grouped together because they could be completed by the same kind of vehicle: an autonomous or semi-autonomous vehicle with the ability to dock with cooperative and/or non-cooperative targets, and perform operations with them. This creates a niche for this kind of spacecraft that could be exploited by the same company. This vertical is currently being developed by companies such as Orbital ATK, Effective Space Solutions, and Space Logistics.

9 Satellite services: The production and distribution network will create opportunities for a number of space-for-space services. These will include initially data relays to support activities in the far side of the Moon or interplanetary spacecraft, and navigation and positioning services, either for spacecraft or for lunar surface operations. Data relay services would later evolve into a complete in-space internet, providing high-bandwidth connectivity to lunar outposts and the different crewed cislunar stations. These services will be the extension of current satellite services for Earth applications, but eventually more services that are currently not envisioned may appear. Currently there is at least one company publicly working on space data relays, Kepler Communications, but other companies working on space internet for Earth, such as SpaceX or OneWeb, could adapt their technologies to space-for-space applications.

10 Off-Earth science: Scientific activities in planetary science would benefit from the presence of cislunar infrastructure and could provide a spin-off opportunity for other technologies. Spacecraft sent to asteroids could be adapted for purely scientific purposes, and rovers and crewed landers could be employed in scientific missions. These vehicles could be adapted from their original purposes and sold or leased to agencies and research institutions, creating a small market for planetary science research. The same could be done the opposite way, scientific instrumentation could be adapted for commercial purposes in asteroid and lunar mining. This has been done already with commercial Earth observation, which currently uses sensors that were developed for scientific spacecraft.

Other activities in off-Earth science would include scientific research that would benefit from being away from Earth. For example, radioastronomical observations from the far side of the Moon would be free from Earth's noise, and the isolated environment of the Moon could enable some biology research that might be too dangerous to be carried out on Earth. Activities in research installations off-Earth would create a market similar to the operation of the research stations in Antarctica, i.e. they would be based on research funding and not create a direct return, which would limit the size of the market.

11 Beamed power: Beamed power forms the final vertical of the cislunar economy. Beamed power applications include power for lunar surface support in locations away from the Poles, which have to survive the 14-day-long lunar nights, and beamed power to spacecraft, which has been proposed as propulsion method for lasers sails. Beamed power to the lunar surface could be used as a technology demonstration for Earth applications, and would enable permanent operations in the lunar surface away from the Poles without the need for nuclear reactors. Moreover, the affordability of beamed power applications on Earth is not limited by technology, but mainly by launch cost. Orbital manufacturing and assembly, as well as orbital servicing, could be enabling techniques for beamed power to become affordable. Beamed power could become common place in a mature cislunar economy.

The 11 market verticals presented in this section cover the main production and distribution activities that could emerge in the cislunar economy, given the current status of both Old and New Space. This is the first step in the goal of this project: the definition of a comprehensive picture of the cislunar economy. Once the main verticals are defined, a high level analysis can create an overview of the potential evolution of the economy. The next section shows how a preliminary roadmap of the evolution of the economy can be created based on the direct relationships between verticals.

4. Preliminary overview of the cislunar economy

Having established the verticals, a first analysis can create a roadmap for the potential evolution of the cislunar economy. This can be done by analyzing the relationships between the different verticals to establish dependencies and determine which verticals need to appear first. Table 3 shows a summary of all the verticals defined in the previous section, including the activities inside each vertical, and companies that have any of those activities in their business plans. The list of companies is based on publicly available information and is not intended to be exhaustive.

These verticals cover what goods and services would be produced and how, and establishes a network for their distribution. The verticals could thus form the basis of the future cislunar economy. Notice that all the verticals have companies currently working towards them. This shows the industry's interest in developing the cislunar economy.

The analysis of the relationships was done from a very high-level point of view, not considering technology readiness levels (TRLs) or current investments, but rather direct market needs and dependencies between verticals. This can serve to create a first-order approximation to the problem. Table 4 compiles the direct relationships between the different cislunar verticals. Each cell shows how the vertical in each row acts on the vertical in each column. The relationships were determined

Table 3
Summary of cislunar verticals with potential companies in each vertical.

Vertical	Description	Activities	Potential companies
1. Water mining	Extraction of water from asteroids or the Moon.	Propellant production, consumables, radiation shielding.	DSI, Planetary Resources, Moon Express, TransAstra
2. Metal mining	Extraction of structural metals and semiconductors from asteroids or the Moon	Manufacturing of structures, components, solar panels.	DSI, Planetary Resources, TransAstra
3. On-orbit manufacturing	Manufacturing of structures, components, and solar panels. On-orbit assembly.	Satellite manufacturing, spare parts, retrofit and repair services.	Made in Space, DSI
4. In-space transportation	Tug services, propellant depots.	Spacecraft delivery to operational orbit, refueling station.	ULA, Altius Space Machines, Shackleton Energy
5. Cislunar stations	Stations in key orbits in cislunar space (LEO, EML1/2, HEO).	Way station, orbital tourism, repair station.	Bigelow Aerospace, Axiom Space
6. Lunar landers	Crewed and cargo lunar landers.	Surface payload delivery, crew sorties, lunar base support, lunar exports.	Moon Express, Astrobotic, ULA
7. Lunar base	Central hub in lunar surface.	Infrastructure deployment and construction, surface activities support, lunar tourism.	Bigelow Aerospace
8. Advanced orbital services	Services to satellites, stations, and other spacecraft.	On-orbit refueling, repair, and retrofit, station-keeping, debris management.	Orbital ATK, Effective Space Solutions, Space Logistics
9. Satellite services	Data-based satellite services.	Data relays, navigation and positioning, space internet.	Kepler Communications
10. Off-Earth science	Off-Earth research activities and instrumentation.	Planetary science probes, prospecting instruments, astronomy, biology research.	DSI, Planetary Resources
11. Beamed power	Beamed power from an orbiting platform.	Beamed power to lunar surface, to spacecraft.	Solaren

based on a qualitative analysis of the products and activities of each vertical, considering high level requirements and architectures for each of the activities. Three types of relationships were considered:

- Enabling: the activities of the first vertical (row) are required for the activities of the second vertical (column) to be affordable or technically feasible. This is based on previous studies of the activities

Table 4
Direct relationships between verticals. Cell shows effect of row vertical on column vertical. Blank means no direct relationship.

This vertical…	… acts on this vertical										
	1	2	3	4	5	6	7	8	9	10	11
1		Supports		Supports	Supports	Supports	Enables	Supports			
2	Benefits from		Supports				Supports				
3		Benefits from			Benefits from			Supports			Enables
4	Benefits from				Supports	Supports		Supports	Supports	Supports	Supports
5	Benefits from		Supports	Benefits from		Supports		Supports	Benefits from		
6	Benefits from			Benefits from	Benefits from		Enables			Supports	
7	Enabled by	Benefits from				Enabled by			Benefits from	Supports	Supports
8	Benefits from		Benefits from	Benefits from	Benefits from				Supports		Supports
9				Benefits from	Supports		Supports	Benefits from		Supports	
10				Benefits from		Benefits from	Benefits from		Benefits from		
11			Enabled by	Benefits from			Benefits from	Benefits from			

regarding technical feasibility and business cases. For example, lunar landers are obviously required to operate a lunar base, but also water mining for propellant production is generally considered enabling for affordable activities on the lunar surface [39]. Enabling was only considered if it is common agreement in the literature that the first activity enables the second. That means that some of the relationships considered as *Supporting* (see next) might turn out to be *Enabling* upon detailed examination of the business case.

- Supporting: the activities of the first vertical (row) increase the affordability of the business case of the second vertical (column). Although no in-depth analysis of the business cases was done, it is considered that the affordability is increased if an activity potentially reduces or replaces elements brought from Earth, increases the customer base, or allows improved operations or new capabilities. For example, water mining could increase the affordability of metal mining by reducing propellant mass brought form Earth to the asteroids, and metal mining could support on-orbit manufacturing by allowing new components to be produced.
- No direct relationship: there is no direct relationship between both verticals. This does not discard indirect relationships. For example, a cislunar station would not interact directly with a lunar base, but solid economic activity in the Moon's surface would benefit activities in cislunar stations through more lander traffic.

These three relationships are shown in Table 4 along with their reciprocal, i.e. if one vertical supports activities in a second one, the second benefits from activities on the first. Verticals are coded with the same number as the ones used in Table 3. The cells are color-coded for easier reading: blue for *Supporting, g*reen for *Enabling*, and light blue and light green for the respective reciprocals. Again, only direct relationships were considered.

The most noticeable result of Table 4 is the reduced number of enabling dependencies: lunar bases are enabled by water mining and lunar landers, and beamed power is enabled by on-orbit manufacturing. Otherwise, all the other relationships are supporting relationships, that is, most verticals could potentially exist on their own, but benefit from the existence of other economic activities in cislunar space.

Also noticeable is that all the verticals benefit directly from the activities of at least one other vertical. This showcases the level of interdependency that the initial cislunar economy would have, and how important it could be for all the activities to appear in similar timeframes: many of the activities from different verticals could provide a customer base for each other, increasing affordability across the board, and reducing investment risks.

Table 4 can be used to create a preliminary roadmap indicating in which order the activities of the verticals would appear in the economy. The verticals can be ordered according to how much influence they would have on the economy as a whole, which would indicate which verticals would have a higher need to be implemented earlier. It can be assumed that the verticals with the most impact on other verticals would be needed earlier, since they would reduce the cost or enable other operations. To create the ordering, the verticals can be scored for priority, based on the direct relationships from Table 4. Table 5 shows this priority scoring, giving 1 point for each *Supporting r*elationship, 2 points for each *Enabling*, −0.5 for each *Benefits from*, and −1 for each *Enabled by*. The verticals with the highest score have the highest impact on the economy as a whole, and should appear earlier in time.

Table 5 shows that Water mining and In-space transportation would be the activities with the most impact on the economy, followed by satellite services and on-orbit manufacturing. This indicates that it would be reasonable to deploy a transportation network with refueling opportunities first. Once the transportation network is in place, manufacturing and other services can begin, and more raw materials can be extracted. The final steps would be the permanent base on the lunar surface and the activities supported by it. This scoring can be used to create a priority roadmap, shown in Fig. 2.

Table 5
Priority scores for each vertical, based on direct relationships.

Vertical	Supporting	Enabling	Benefit from	Enabled by	Score
1. Water mining	5	1	0	0	7
2. Metal mining	2	0	1	0	1.5
3. On-orbit manufacturing	1	1	2	0	2
4. In-space transportation	6	0	1	0	5.5
5. Cislunar stations	3	0	3	0	1.5
6. Lunar landers	1	1	3	0	1.5
7. Lunar base	2	0	2	2	−1
8. Advanced orbital services	2	0	4	0	0
9. Satellite services	3	0	2	0	2
10. Off-Earth science	0	0	4	0	−2
11. Beamed power	0	0	3	1	−2.5

The roadmap provides a general idea of how the different verticals are likely to appear in the cislunar economy, according to first-order relationships. The spacing between the verticals reflects the differences in the priority scoring, and verticals with the same score are grouped at the same level in the roadmap. However, the roadmap has to be interpreted properly. Since the ordering is based on just direct relationships, it does not directly reflect order in time. From an economical point of view, it is more likely that the activities that enable the most other markets appear before, but technical constraints may delay the appearance of some markets. Moreover, the diverse nature of the economy means that its evolution would hardly be linear: market verticals include activities in different places in space (e.g. water mining in asteroids and the Moon), and of diverse technical nature (e.g. orbital assembly and manufacturing). Technical synergies would alter the order in which activities appear: water mining from asteroids would accelerate the beginning of metal mining from asteroids, and water mining from the Moon, lunar landers, and lunar base may develop almost simultaneously. Finally, actors that are independent of the economic needs (e.g. space agencies) may change the order in which the activities are implemented.

In spite of its limitations, the roadmap can provide good insight into which activities will appear first. According to Fig. 2, Water mining and In-space transportation will appear first, and they are already on the sights of many companies. On-orbit manufacturing does not necessarily require Metal mining, which is also the expectation of Made in Space, and Satellite services are already being implemented. One could conclude then that Cislunar stations will see good market opportunities at the same time as Metal mining starts happening, and when Lunar landers exist to provide traffic for them. Advanced orbital services would require Metal mining and On-orbit manufacturing to produce components in big quantities, and Cislunar stations to assemble them. Finally, Beamed power and commercial Off-Earth science will not be available until Lunar bases are operating.

5. Future work

With the proper interpretation, the roadmap can be a starting point in understanding how the cislunar economy may develop, but it is the result of a high-level analysis of the interactions between market verticals. A refined roadmap would include a proper evaluation of technical requirements, current TRLs, and other business considerations such as market sizes, costs, and financing opportunities from entities independent from the market such as government agencies.

The first next step would be to further define each of the verticals with an analysis of technical feasibility, current TRLs, and estimated price

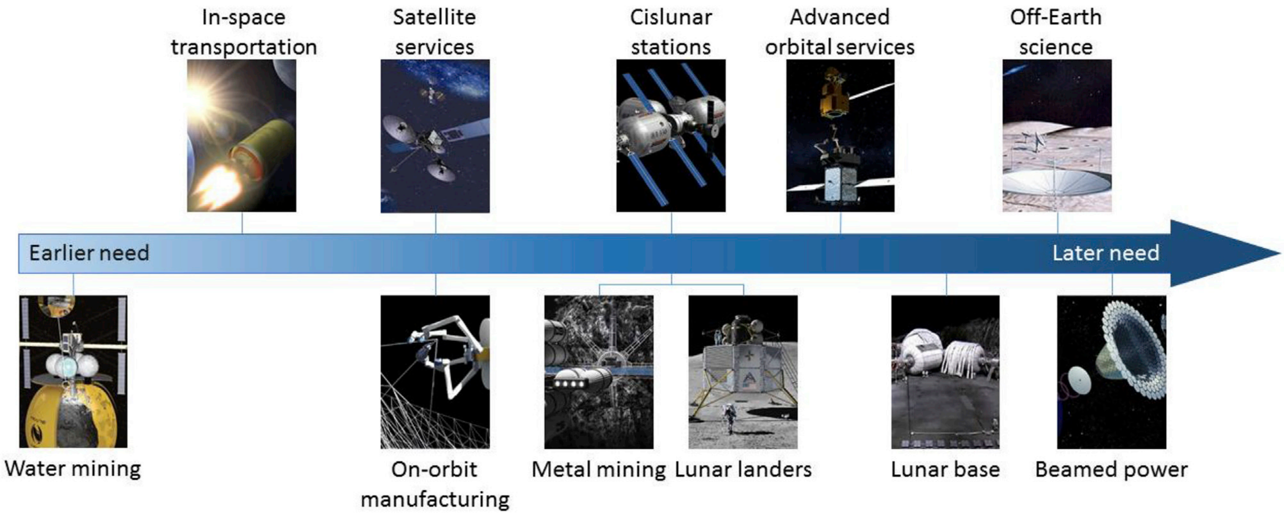

Fig. 2. Need for the activities of each vertical in the cislunar economy ordered in time.

points. The most complicated part of this will be defining the price points, since most of the technologies needed present low TRL, but defining them is critical for the study of market sizes and business plans.

Following a detailed study of each vertical from a technical point of view, market sizes and business cases can be studied in depth. Even though the verticals are defined as niches, they are heavily interconnected, and activities in any vertical would benefit from activities in others. The relationships shown in Table 4 and the roadmap in Fig. 2 can be used to study the influence on other verticals on the market sizes. In any case, most of the markets do not yet exist, and the customers and price points are not yet clear, so the best that can be done is probably an estimation in order of magnitude.

Having analyzed market sizes and TRLs, a roadmap of the actual implementation of the cislunar economy can be done, which will be able to inform business decisions and investments for the development of the economy. This roadmap would also include an analysis of the connections between the cislunar economy and Earth's economy, informing investors on how to create value while deploying the infrastructure needed for commercial activities in cislunar space.

6. Conclusions

This project aimed to establish a framework for the study of the cislunar economy as a whole. Typical business studies in commercial space activities only focus on one activity and its connection to Earth, but the interconnectivity of the future cislunar economy calls for a more global view to properly inform business decisions.

The project defined the future market verticals in cislunar space based on current space activities and New Space endeavors, aiming to classify the future cislunar commercial activities in market niches for easier study in the future. The project is completed with a preliminary overview of the cislunar economy, based on the evaluation of direct relationships between verticals, which was done from publicly available information and a qualitative evaluation of technical and business requirements. These relationships were used to create a roadmap showing which activities may appear earlier based on the needs of the economy. The resulting roadmap can provide a general idea of how the different activities in the cislunar economy may appear, but detailed study is required in order to inform business decisions. Future steps would focus on detailed technical and business analysis of each of the verticals.

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