In-Space Manufacturing - 2022 Industry Survey and Commercial Landscape

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Abstract

New in-space economy fields are emerging. Microgravity research for in-space manufacturing (ISM) has been active for decades but continuous production of profitable products is still a very nascent industry. Numerous commercial space stations, free-flying platforms and small re-entry capsules have been announced in the last years with the goal to expand the field. Factories in Space (www.factoriesinspace.com) is the largest public database of commercial entities in the in-space economy and microgravity manufacturing fields.

In-Space Manufacturing (ISM) divides into 3 high-level destinations. First is ISM for space, which involves activities related to in-orbit construction that will remain for use in space. Second is ISM for Earth, which includes new materials and products that have better properties when made in microgravity and which are sent back to Earth. Third is ISM on surfaces like on the Moon, Mars and asteroids. In parallel to them, various enabling and supporting service providers already exist or are being developed in the areas of transportation, orbital platforms, microgravity access, space utilities, space mining and more.

First part of the paper defines what in-space manufacturing entails and establishes classification to group the commercial entities. Literature review was performed to assist with the taxonomy. After filtering the database, the key players were listed to create an overview and survey of the supply chain.

Second part of the work brought statistical insight of which types of companies are or aim to become active in the emerging in-space manufacturing fields. All 117 in-space manufacturing activities were categorized into: advanced materials, biotechnology, large structures, microfabrication, novelty & luxury goods, pure substances or space food. Within the classifications, comparisons were made between popularity, destinations, status, first launch years, geographical distribution and funding where available.

The are no actively recurring commercial in-space production activities yet. Many products have been demonstrated but not repeated or scaled up. Biggest challenge for in-space manufacturing is finding the potentially profitable goods or materials or overcoming the chicken-and-egg problem of large investment requirements and then catering to small or non-existing markets.

New profitable and sustainable economic activities in space have the potential to speed up space technology development and the rate of activities, which would also greatly benefit human and robotic space exploration thanks to multi-use systems. To authors' knowledge, such industry surveys of commercial in-space manufacturing activities have not been published before.

Keywords: in-space manufacturing, in-space economy, ISM, ISAM, ISRU

1. INTRODUCTION

Factories in Space has tracked new in-space economy entities since 2018. There are over 500 entries as of September 2022, likely making it the largest public database. The initial target was microgravity applications and services but scope was expanded when a large quantity of overlapping in-space economy companies started to be announced.[1]

In-space economy means generating revenue in space using assets in orbit or beyond Earth. In-space economy is the new extraterrestrial space industries.[2] Sometimes called as space-based economy and in narrower definitions on-orbit economy, space-for-space economy and it also encompasses cislunar economy. New in-space economy includes space stations, commercial landers, space infrastructure, in-space manufacturing and much more.[1]

For in-space economy to thrive, new value creation and revenue sources beyond Earth will be required. In-space manufacturing could become one of the largest industries in space and also one of the biggest customers to other in-space economy fields.[3]

In-Space Manufacturing (ISM) is a subset of in-space economy. In-Space Manufacturing is the transformation of raw or recycled materials into components, products, or infrastructure in space.[4]

More definitions and overlapping fields such as ISAM and ISRU can be found in the section 4. Wider space community may be starting to coalesce around the term ISAM[5] and then ISM is still a definable subset.

Literature review was performed and studies about commercial entities within in-space manufacturing seem to be sparse. There is a large quantity of publications about the microgravity benefits, promising applications, economic studies and experiments[6–10] but overviews and broader classification definitions have not been found.

N. Yaakoubi published a study in 2022 on "Emerging Opportunities and Threats in the In-Space Manufacturing Industry for Earth-return-products".[11] listing many of the commercial entities. M. T. Moraguez has written many works related to in-space manufacturing and explored cost studies for promising applications including on-demand spares manufacturing, large structure manufacturing, and planetary surface infrastructure manufacturing.[12,13] Butow et al. summarized state of the space industrial base in 2020, which included many ISM fields.[14] IDA's Corbit et al. studied global trends in on-orbit servicing, assembly and manufacturing.[15]

"In-Space Manufacturing and Resources Earth and Planetary Exploration Applications" book was published in July 2022 and has sections on Space Medicine & Human Health, Space Biology, Space Chemistry, Space Mining, Space Farming & Food, Advanced Materials and Space Construction.[16] "3D Printing in Space" book was released in 2014.[17]

R. Skomorohov et al. wrote a comprehensive literature review and study in "In-orbit Spacecraft Manufacturing: Near-Term Business Cases".[18] A. E. Trujillo et al. published "Feasibility Analysis of Commercial In-Space Manufacturing Applications" and studied antenna reflector manufacture, solar panel manufacture and spare parts manufacture.[19] D. Sivolella released a book "Space Mining and Manufacturing: Off-world Resources and Revolutionary Engineering Techniques" in 2019.[20] B. J. Stoor published a research report titled "In-Space Manufacturing: A Roadmap to the Future" in April 2018, which described current efforts in in-space manufacturing and in-space servicing as the stepping stone to ISM due to technology overlap.[21]

The following are extended version of the supporting macro trends for in-space manufacturing:[1]

- Decreasing launch costs. Now about 2-3 times less according to P. Lionnet[22] but potentially 10-100 times lower in the future, e.g. Starship.
- Commercial space services and infrastructure.
- Commercial space stations and modules.
- Commercial crew and cargo programs.
- Small re-entry capsules.
- Additive manufacturing in space.
- Artemis program and planned return to Moon.
- Space utility companies.
- ISRU and space resources advancements.
- Increasing momentum for space settlements.
- Pollution and climate change on Earth.
- NewSpace iterative mindsets and affinity for bolder risks, also from long-term investors.

This study focuses on commercial entities in the in-space manufacturing field. First part of the paper establishes classification for the commercial entities. Second part presents statistical overview of the 117 surveyed in-space manufacturing entities.

2. BENEFITS OF IN-SPACE MANUFACTURING

Much has been written about the physical, scientific and economic benefits of in-space manufacturing.[23–25] Here are only a few examples:

- Microgravity effects due to gravity-induced phenomena such as as convection, segregation, buoyancy, and sedimentation.[26]
- Ultra-vacuum, especially when using a wake shield facility.[27]
- Containerless processing, for very high temperatures or to avoid nucleation.[26]
- Decoupling from rocket launch limitations such as mass, volume (rocket fairing), vibrations and structural loads.[28]
- Not having to survive in terrestrial gravity.
- Use of recycled or space mined resources to lower costs.[13]
- On-demand manufacturing for long journeys.
- Possibility to launch bulk material[18,29] and manufacture in-situ. To maximize rocket capabilities or for example use non-rocket space-launch solutions such as SpinLaunch with very high accelerations.

NASA has a website on in-space manufacturing, where it is stated that "The ability to perform In-Space Manufacturing provides a solution towards sustainable, flexible missions (in-transit and on-surface) through on-demand fabrication, repair, and recycling capabilities for critical systems, habitats, and mission logistics and maintenance. These capabilities provide tangible cost savings due to reducing launch mass, as well as significant risk reduction due to decreasing dependence on spares and/or over-designing systems for reliability. ISM consists of an integrated task portfolio which culminates in the development of manufacturing and recycling systems and processes that will enable on-demand production of a wide array of parts and components."[30]

There are also significant downsides and challenges of in-space manufacturing, which explains why it is not yet commonplace.

In the future, in-space manufacturing has also the potential to replace terrestrial production on Earth to preserve life and nature on Earth, as Gerard O'Neil envisioned: "...nearly all our industrial activity could be moved away from Earth's fragile biosphere within less than a century from now."[11]

3. SHORT HISTORY OF IN-SPACE MANUFACTURING

Here follows a non-exhaustive chronological overview of some of the first historical steps and latest advances and companies in the in-space manufacturing fields. Expanded from the previous work.[1]

Early days The New York Times published an article "Manufacturing in Space No Longer So Far-Out" but the year was 1970. Some of the areas under investigation were: glass preparation; industrial microbiological applications in zero gravity or a vaccine satellite program; industrial chemistry; processing of electronic crystals; boron filament manufacture; weightless containerless melting and solidification of potential new metal and ceramic products; spherical forming and composite casting; and the production and separation of industrially useful isotopes. Interviewed believed that by 1985 the first products developed in space will be on the market.[31]

Many space manufacturing experiments were performed on Skylab in 1973. First Space Manufacturing Conference was in 1977. The early 1980s was the first age of in-space manufacturing with many studies published for profitable materials as part of beginning Space Shuttle flights and for future usage of the planned Freedom Space Station.[32–38]

Microgravity Research Associates was founded in 1979 for the purpose of engaging in materials processing in space. It planned to grow crystals in space, starting with gallium arsenide. The high-quality gallium arsenide crystals could be used to make chips that would be much faster than silicon chips.[39]

Civilian Space Policy and Applications report from 1982 discusses many relevant opportunities for commercialization of space technology and discussed Materials Processing in Space for unique materials.[26] C. Rood quoted in 1982 that we will likely see products of space industrialization by the end of the decade and that according to a 1979 study by Science Applications, materials processing in space should yield gross revenues of $80 billion by 2010.[40]

W. R. Wilcox wrote in 1982 that someday we may produce speciality materials in space for use here on Earth. For the moment, however, we are not certain that such processes can be profitable, or what those materials should be.[41] D. Osborne wrote in 1985 that the weightless environment of space, in which valuable new commodities can be manufactured more efficiently than on Earth, may be the next economic frontier for American companies and went on to describe possible commercial applications, active companies at the time, and necessary infrastructure like space stations.[42]

"By mid-1989, more than half of the 50 largest U.S. industrial corporations were participating in one or more of NASA's programs for stimulating commercial space research. Some are interested in the potential of orbital space as a unique place to conduct research and develop new or improved processes for manufacturing commercial products. Some are pioneering private development of commercially marketable space research facilities."[26]

"During the 1980's, there was a lot of enthusiasm for materials processing in space. A lot of it was driven by a popular book called The Third Industrial Revolution, written by engineer G. Harry Stine. Stine believed that access to the space environment, including weightlessness, vacuum, and radiation, would revolutionize manufacturing."[43]

In 1985, NASA and the National Bureau of Standards put on sale the first products made in space for commercial use. The products are tiny, perfectly spherical latex beads, each 1/2500th of an inch in diameter. They were manufactured in weightlessness for use as microscopic yardsticks in a variety of scientific and commercial tasks, such as calibrating equipment. A small vial containing 30 million of the beads costs $384; 29 of the vials were delivered to purchasers this week.[43–46] Related to this, Particle Technology, Inc., was the first private enterprise to have sold a product manufactured in space.[42]

J. H. Goodrich et al. discussed in 1987 how The Center for Space Policy forecasts that, if given a suitable environment for development, by the year 2000 space industries could be producing $27 billion annually in pharmaceuticals to battle cancer and $3.1B in gallium arsenide semiconductors for electronics, and $11.5B of pure optical glass. Scientists foresee the manufacture of these products on space stations and on free-flying platforms with compartments leased by industry. Manufacturing would be done by robots.[47] J. H. Goodrich et al. wrote about pharmaceutical production in space in 1989.[48]

Commercial Space Transport Study Final Report published in 1994 has a large section and appendix about space manufacturing including future vision and promising applications.[49]

None of those forecasts came true. For decades since, only research seems to have continued without any notable company or commercial product announcements.

"But even before the destruction of the Challenger, the future of space manufacturing was uncertain. Despite numerous experiments in producing drugs, growing semiconductor crystals and creating metallic alloys, no American companies have moved beyond exploratory manufacturing operations in space."[26]

After 2010 ACME Advanced Materials was founded in 2014 to develop and produce unique materials in a microgravity. Then they announced the first production of superior Silicon Carbide wafers. After raising funding of €400,000 in 2015, they seem to have become dormant around 2018.

Optical fibre ZBLAN was started to be publicly touted as the first profitable product made in space in about 2016-2017.[50–52] One of the first studies about ZBLAN manufacturing in microgravity was released in 1995.[53] News already in 1998 estimated ZBLAN commercial potential at $2.5 billion.[54] NASA's has awarded optical fiber related contracts to FOMS, Physical Optics Corporation, Apsidal and DSTAR starting from 2016.[55–58] Made in Space launched internally funded ZBLAN demonstration missions in 2017 and 2019.[59,60] FOMS reported high-quality production on ISS in 2019.[61] Flawless Photonics is developing ZBLAN production system in Luxembourg.[62] After all the news, progress seems slower than expected in the recent years and Made In Space is focusing elsewhere[63] but lack of news could also be because of secrecy.[1]

There are many commercial services on the ISS to perform experiments, demonstrate payloads and potentially in-space manufacturing processes. For example, Nanoracks Nanolab, Space Applications Services ICE Cubes, Airbus Bartolomeo, Space Tango CubeLab, yuri and many more upcoming.

Varda Space was founded in 2020 and is developing reusable satellites with re-entry capability for in-space manufacturing and other services.[64] Space Forge, founded in 2020, is working on re-usable ForgeStar satellites with return-to-Earth capability for microgravity on demand.[65] Inversion Space,[66] Outpost,[67] In Orbit Aerospace,[68] The Exploration Company[69] and others are also working on small re-entry capsules. ESA's Space Rider reusable spaceplane will serve similar purpose and is offering slots to fly payloads starting from 2023.[70]

Made in Space (now Redwire), founded in 2010, has been testing large-scale in-space assembly and construction technologies and additive manufacturing. They launched first 3D printer to ISS in 2014.[71] In 2019, NASA awarded $73.7M for Archinaut One to manufacture 10-meter beams and unfurl solar arrays.[72] Redwire announced the first commercial sale of in-space produced optical crystals in June 2022 and estimated the approximate value at $2 million per kilogram. It was manufactured in Redwire's Industrial Crystallization Facility onboard the International Space Station (ISS). Redwire also said this transaction marks the first time that a space-enabled materials product has been sold on Earth.[73] Depending on definitions, there was the latex beads example from the 1980s that was instead the first likely commercial product manufactured in space as described earlier.

In February 2022, The Center for the Advancement of Science in Space (CASIS), manager of the International Space Station (ISS) National Laboratory, made a research announcement soliciting flight projects for in-space production applications seeking applied research and development projects leveraging the ISS National Lab within the areas of advanced or exotic materials production and associated technologies. Flight investigations should demonstrate space-based manufacturing and production activities that: enable new business growth and capital investment, represent scalable and sustainable market opportunities, produce reoccurring value with the potential to generate demand for and revenue from access to space.[74]

SOLARIS is a proposed preparatory programme for Space-Based Solar Power by the European Space Agency and it would also improve the state-of-art in many in-space manufacturing fields such as robotic in-space assembly.[75]

In August 2022, the Federal Communications Commission of the USA opened a proceeding on the economic potential and policy questions related to servicing, assembly, and manufacturing taking place beyond the Earth's atmosphere. It will examine the opportunities and challenges of space missions like inspecting and repairing in-orbit spacecraft, capturing and removing debris, and transforming materials through manufacturing while in space.[76]

4. CLASSIFICATION

One goal of this paper is to establish taxonomy or classification for the commercial entities in in-space manufacturing to be able to group them.

The following classification is preliminary and author expects it to improve greatly thanks to feedback, independent iterations, and over the upcoming years as the new space-based industries become more established.

One approach to defining what is in-space manufacturing is to view it in the context of a manufacturing value chain as illustrated on Figure 1. For a company to be included in the study, there should be a manufacturing activity happening beyond Earth. This manufacturing activity in space can either be planned for the future, cancelled, or in some cases be a very promising technology itself. There should also be a specific announced item that will be made in space. Production or fabrication of goods in microgravity usually results in some measurable physical or chemical changes. Ideally, there will also be a commercial intent to scale up the manufacturing as markets develop.

Figure 2 illustrates the in-space manufacturing ecosystem, methods, process and partially duplicates the value chain description.

4.1 In-Space Manufacturing Taxonomy

In-Space Manufacturing (ISM) is a process involving the fabrication, assembly, and/or integration of goods outside the Earth's atmosphere.[11,18] Alternatively, In-Space Manufacturing is the transformation of raw or recycled materials into components, products, or infrastructure in space.[4] The manufacturing can happen by humans or be automated. As the list can be endless, priority has been given to existing or near-term planned activities.

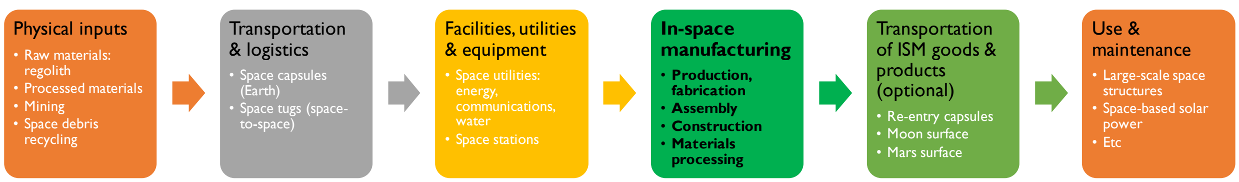

Figure 1: Value Chain Analysis of In-Space Manufacturing

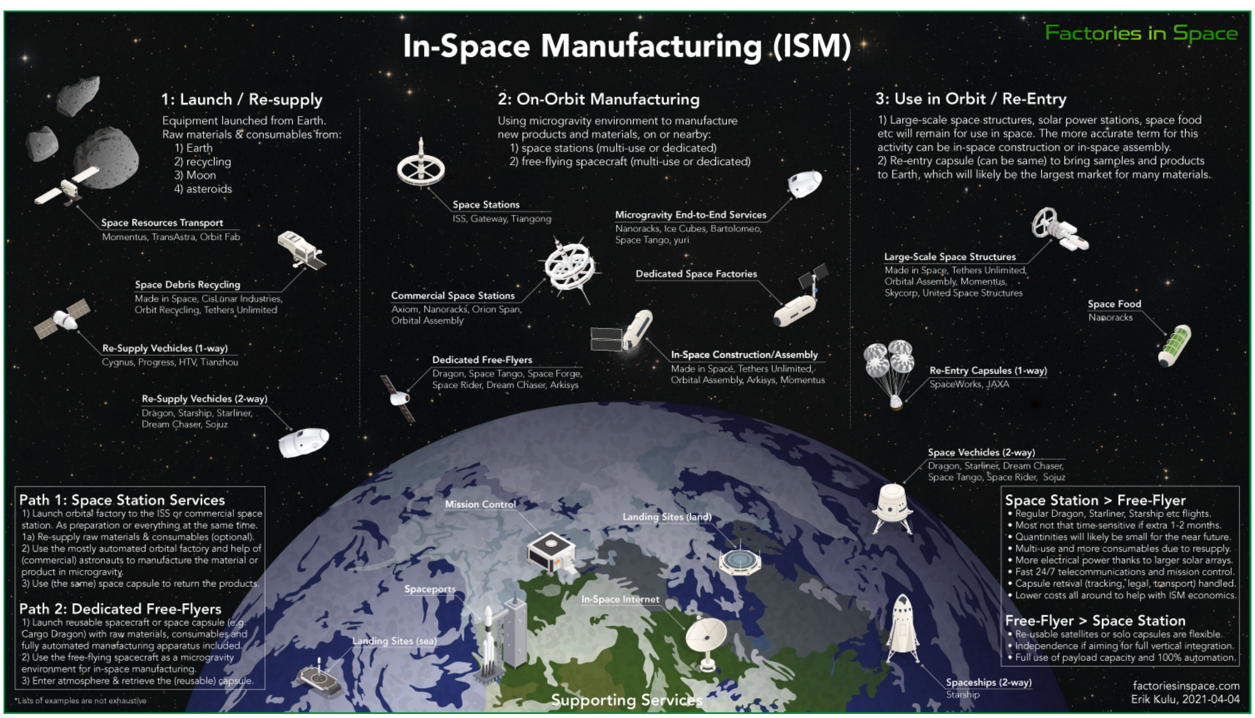

Figure 2: In-Space Manufacturing

Manufacturing is considered to be an activity that involves at least one of the following three components: fabrication, assembly, and integration. Those are described as follows:[18]

- Fabrication: The process of producing basic spacecraft or spacecraft subsystem components through 3D printing or traditional industrial methods such as welding, cutting, bending, etc.;[18] For example, 3D printing solar panels.[19]
- Assembly: Combining fabricated or pre-fabricated components into subsystems or entire spacecraft or direct complex 3D printing;[18] For example, joining the 3D printed solar panel with a stock of solar cells and wiring to form a functioning solar array.[19]
- Integration: Bringing together subsystems into one system and ensuring that the subsystems function together as such, including software; also includes potential processes associated with activities before or after upgrades, deliberate disintegration, and re-integration of subsystems into a spacecraft.[18] For example, integration could include installing the solar array onto a waiting spacecraft and incorporating it with its power system.[19]

Here are some alternative definitions for in-space manufacturing, which are worth capturing:

- Space manufacturing is the production of tangible goods beyond Earth.[77]
- Space manufacturing involves the production of manufactured goods in an environment outside a planetary atmosphere.[78] In economics, goods are items that satisfy human wants and provide utility. A common distinction is made between goods which are transferable, and services, which are not transferable.[79] Commercial goods are tangible products that are manufactured and then made available for supply to be used in an industry of commerce. Commercial goods could be tractors, commercial vehicles, mobile structures, plane, and even roofing materials. Commercial and personal goods as categories are very broad and cover almost everything a person sees from the time they wake up in their home, on their commute to work to their arrival at the workplace.[79] Commodities may be used as a synonym for economic goods but often refer to marketable raw materials and primary products.[79]
- Space manufacturing is the processing of materials in space to take advantage of the unique characteristics of space. For space manufacturing to become a reality, much research and development is needed to identify a wide range of opportunities, which are unique to space, technically feasible, economically feasible, and attractive to investors.[80]
- As of 2019, NASA Marshall Space Flight Center categorized manufacturing processes based on operational use scenario and the application of the parts being manufactured. In-space manufacturing is currently defined as manufacturing in an intravehicular (crew) environment. ISM takes place inside a pressurized habitat structure (ex. International Space Station) and is primarily focused on logistics reduction and on-demand manufacturing of spares.[81]
- ISM is an umbrella term for a variety of technologies, processes, and architectures which deliver a desired component or system to a spacecraft outside of the traditional Earth-launch paradigm.[19]

The following list of keywords, alternative terms, applications and fields is not exhaustive. Feedback is very welcome and author expects the terminology to evolve greatly as in-space manufacturing develops.

Synonyms of In-Space Manufacturing:

- Off-Earth Manufacturing.[82]
- Space-Based Manufacturing.[83]
- In-Orbit Manufacturing - Term "in-orbit" refers to the part of orbital space around Earth up to geostationary Earth orbit (GEO) as place of manufacture.[18]
- Orbital Manufacturing.
- Space Manufacturing.
- In-Situ Manufacturing.
- In-Space Fabrication.
- In-Space Manufacturing for Earth - In narrower definition it means making products and materials in microgravity, which cannot be made on Earth, or which are better.
- In-Space Production - Same as the narrow definition of in-space manufacturing. ISS National Lab has started to actively use this term.[84]
- Materials Processing in Space - Term used in the earlier decades of space exploration and

with that keyword many older reports and articles are findable. Materials processing in space (MPS) is the science which takes advantage of the microgravity condition found in space to produce improved materials such as pure and uniform crystals, containerless processing and new pharmaceutical products. While it is far too early for truly accurate appraisal, some published projections for the potential market value of MPS have ranged from $18 to $25 billion by the year 2000.[85]

- Microgravity Manufacturing - Alternative name for in-space manufacturing and in-space production. Parabolic flights and drop towers have been excluded.

Each entry in the database has 6 multi-selectable columns: high-level category, destination, method, field, process or technology, types of goods.

4.2 High-Level Category

The first multi-selectable column in the database is used for the top-level categorization:

1. In-Space Manufacturing (ISM)
2. In-Space Servicing, Assembly and Manufacturing (ISAM)
3. In Situ Resource Utilization (ISRU)
4. Supporting Services

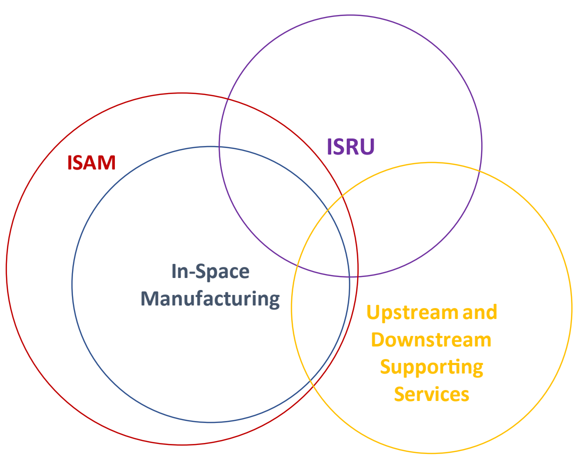

Figure 3: Venn Diagram of In-Space Manufacturing, ISAM, ISRU

Important to note that ISRU (In Situ Resource Utilization) and ISAM (In-Space Servicing, Assembly and Manufacturing have considerable commonality. Figure 3 shows the visual overlap of ISM, ISRU and ISAM. That overlap in definitions and the inevitability that some activities and companies may belong to multiple areas has been accepted.

The work here will only include entities marked with ISM but they may also belong to other categories due to overlap. Those other classifications will be explored in future works.

4.2.1 ISAM - In-space Servicing, Assembly and Manufacturing

The In-space Servicing, Assembly and Manufacturing (ISAM) National Strategy released in April 2022 defines that "ISAM is a suite of capabilities, which are used on-orbit, on the surface of celestial bodies, and in transit between these regimes. ISAM capabilities enable specific activities, in the areas of[4]

- servicing — the in-space inspection, life extension, repair, or alteration of a spacecraft after its initial launch, which includes but is not limited to: visually acquire, rendezvous and/or proximity operations, docking, berthing, relocation, refueling, upgrading, repositioning, undocking, unberthing, release and departure, reuse, orbit transport and transfer, and timely debris collection and removal;

- assembly — the construction of space systems in space using pre-manufactured components;

- manufacturing — the transformation of raw or recycled materials into components, products, or infrastructure in space."[4]

The wider space community is starting to coalesce around the umbrella term of ISAM. Establishing a consistent terminology and understanding of the capability set is key to aligning strategy."[5]

These ISAM capabilities may use technologies that include inter alia, robotics; sensors and software for trusted autonomy; re-entry/deorbit systems; advanced in-space computing; verification and validation; standard interfaces; propulsion systems; systems engineering tools and techniques that support spacecraft serviceability; and low-cost reusable in-space mobility, logistics, and transportation systems, as appropriate.[4]

On-orbit Servicing, Assembly, and Manufacturing (OSAM) refers to manufacturing, joining, and other processes in the external space environment.

Processes are for example used to fabricate larger than launch payload faring structures, assemble these structures, and to perform repair/servicing.[81]

Quoting from State of the Space Industrial Base report released in August 2022: "Coming to Terms with In-Space Servicing Assembly and Manufacturing (ISAM) - Many terms have been applied to this capability area, including NASA's On-Orbit Servicing Assembly and Manufacturing (OSAM), the broader Space Access, Mobility, and Logistics (SAML) initiative, the USSF's Space Mobility and Logistics (SML), and others, describing the broad array of technologies and missions required to support a robust and sustainable economy and presence in space.[5]

4.2.2 ISRU - In Situ Resource Utilization

In Situ Resource Utilization (ISRU) refers to extraction and use of raw materials found in situ on planetary surfaces for manufacturing or sustained habitation.[81] Alternatively, any hardware or operation that harnesses and utilizes 'in-situ' resources to create products and services for robotic and human exploration.[86] Encompasses exploration, mine planning, mineral processing, metallurgy and sale of off-Earth resources.[87]

Space Resources is a broad term, which deals with the prospecting, mining, beneficiation, processing, ISRU and recycling of natural or artificial resources in space, including Moon and asteroids.[88]

4.2.3 Supporting Services

Example downstream and upstream supporting services for in-space manufacturing:[1]

- Space Stations & Habitats
- Space Resources / Space Mining / ISRU
- Space Utilities
- Spaceships, Re-Entry Capsules & Landers
- In-Space Transportation
- Surface Transportation
- Microgravity & ISS Flight Service - End-to-end service providers to access microgravity environment, which can be facilities on the ISS and upcoming space stations, or dedicated free-flyer spacecraft.

4.3 ISM Destinations & Targets

ISM divides into 3 large areas by destinations, targets or locations:

1. **Earth** - In-space manufactured goods and products intended to be brought back to Earth for sale and use in terrestrial markets. Sometimes called space-for-Earth, Earth-return, return-to-Earth ISM applications. The value-added in-space processing must outweigh the cost of transportation and the use of a space factory.[11,89]
2. **Space** - In-space manufactured goods, building materials and infrastructure, which will remain in space. Also called space-for-space.
3. **Surface** - also known as Surface Manufacturing or Surface Construction.[90] Space manufactured goods, building materials and infrastructure which will be taken to the surfaces of planetary bodies like Moon, Mars or asteroids or where the manufacturing activity happens on the surface.

"A major programmatic risk for any Earth-return ISM application is the emergence of a lower cost, ground-based technique to fabricate a product with performance equal to that of the ISM product. An ideal product for Earth-return ISM is one where it can only be made in microgravity and the business case closes considering launch costs, manufacturing costs, and sale price. As of 2018, no large-scale commercial operation for Earth-return ISM has proven successful."[13] The situation is the same in 2022.

M. Moraguez gathers ISM-for-Earth applications under Earth-Return Systems, which is the fabrication of products that require some unique aspect of the space environment, i.e. microgravity or ultra-vacuum.[13] The goods and technologies can be very different thus here they warrant separate categories.

M. Moraguez collects ISM-for-surface applications under Planetary Surface Systems, which is fabrication of components using locally available raw material, either through in-situ resource utilization (ISRU) or recycling of on-board components.[13] It is likely that much manufacturing on planetary surfaces will also happen using (partially) transported raw materials and again many manufacturing technologies would be shared with space-for-space applications thus a different categorization has been created.

4.4 ISM Methods

In practice, the are 2 main methods or approaches of where to perform in-space manufacturing: dedicated spacecraft vs space stations.

1. Dedicated free-flying spacecraft - including small reusable satellites with re-entry capability.
2. Space stations - including the ISS and upcoming commercial space stations.
3. Suborbital flights - some microgravity manufacturing can happen during short flights but it is not expected to become a primary method.

Not included in this study:

- Parabolic flights
- Drop towers
- Ground-based microgravity simulators

The International Space Station (ISS) and other space stations are likely more cost-efficient, because of the existing transportation chains and a lower fixed pricing. As of 2021, the cost to transport one kilogram of cargo up to the ISS (upmass) is $20,000 and the cost to bring 1 kg down is $40,000, while one hour of crew member time is $130,000.[91]

D. F. Robertson wrote about backhauling novelty items to Earth on returning capsules as a potential way to make new space businesses happen as inspired from the trucking industry.[92]

Some microgravity manufacturing may also be possible on suborbital flights and parabolic flights but the latter has been excluded due to very limited time in microgravity.

4.5 ISM Fields and Categories

The following are the primary categories of in-space manufacturing in alphabetical order. They are based on existing or near-term activities as per database and are not meant to be the final classification for long-term.

1. **Advanced Materials**
2. **Biotechnology**
3. **Large Structures**
4. **Microfabrication**
5. **Novelty & Luxury Goods**
6. **Pure Substances**
7. **Space Food**

This list is expected to significantly expand in the coming decades. Some possibilities may include:

1. Vehicles - rovers, drones, re-entry capsules, space tugs, etc.
2. Spare Parts & Tools, etc.
3. Household Items - furniture, etc.

4.5.1 Advanced Materials

Advanced materials made in microgravity have also been called unique materials or exotic materials. They may include ZBLAN[?] and other exotic glasses, superalloys,[16] optical crystals,[73] thin-films,[16] semiconductors,[16] bulk metallic glass and many more.

4.5.2 Biotechnology

Biotechnology field collects applications like biomedical,[16] medicine, stem cells,[16] tissue engineering,[16] 3D bioprinting,[16] organ growth (human organs),[93] pharmaceuticals.[16] and many more.

4.5.3 Large Structures

Large-scale structures will ultimately enable and lead to the construction of unprecedented space structures and platforms.[94] All related to building for space.[93] It can include booms, building materials, additive manufacturing, infrastructure, megastructures, additive construction,[16] in-space construction,[16] in-space assembly, space-based solar power, space stations and many more.

M. Moraguez separates ISM applications of Structurally Optimized Systems (Fabrication of lightweight structures optimized for in-space loads) and Larger-than-Launchable Systems (Fabrication of large structures that no longer need to fit inside launch vehicle fairings)[13] but the commonality is they are both large structures and have shared manufacturing technologies.

4.5.4 Microfabrication

Orbital microfabrication field includes goods such as semiconductors, solar cells, ultra-thin coatings and many more, which are microfabrication concepts or processes. Microfabrication is a more general term because the manufacturing activity may also happen on planetary surfaces.

4.5.5 Novelty & Luxury Goods

Luxury and novelty goods such as jewellery, art, wine, coffee, beer have started to see increased traction as space-flown goods.

Looking back centuries ago to how silk trade and spice trade got started and what long-term impact they had to global economy, then luxury goods made in space could similarly help to kickstart in-space economy. More practical and industrial goods would follow later once science develops and technology readiness increases.

4.5.6 Pure Substances

Previously called raw materials, pure substances such as water, oxygen, hydrogen, propellants, metals can also be a result of in-space manufacturing. Recycling is here too.

These fields are more commonly defined as ISRU, which can fall under the definition of ISM as "fabrication" of raw material stock from mined or extracted resources.[19] Other authors have often chosen to exclude it and it is a separate category to enable it.[19]

M. Moraguez had an application of Recycling Orbital Debris as Feedstock - Recover components and feedstock from defunct spacecraft for use as an alternative to launched mass.[13]

4.5.7 Space Food

Space food will be a large industry to supply fresh food to workers, settlers and tourists, both in-space and on Moon, Mars and beyond.[1] Other relevant keywords or synonyms are space agriculture, space farming, deep space food, hydroponics, aquaponics etc.

NASA and Canadian Space Agency have been running Deep Space Food Challenge searching for new solutions to feed astronauts in future missions and it is currently in Phase 2.[95]

There is potentially a considerable overlap with vertical farming technologies and benefits on Earth and terrestrial revenues may help with the economic sustainability of companies until more people are staying and working in space.

4.6 ISM Processes or Technologies

The following list of example ISM processes and technologies is not exhaustive. Many of these can produce different types of goods in various ISM fields.

1. Additive Manufacturing
2. In-Space Assembly
3. Containerless Processing
4. Solidification
5. Recycling
6. Ultra-Thin Coatings

Example technologies not included in this study:

- Asteroid mining and lunar mining, unless there is an in-situ manufacturing component.
- Not all NASA-funded additive manufacturing technologies have been included. There preferably should be an announced commercial intent to do the manufacturing activity in space.

4.7 ISM Types of Goods & Outputs

Example types of goods or end-products (non-exhaustive) that could be manufactured in space are:

1. ZBLAN
2. Human Organs
3. Human Implants
4. Carbon Nanotubes
5. Semiconductors
6. Latex Spheres
7. Spare Parts
8. Building Materials
9. Solar Cells, Solar Arrays
10. Space-Based Solar Power Stations
11. Large Space Telescopes
12. Particle Colliders/Accelerators

Example goods not included in this study:

- Space-flown goods. Purely space-flown items are not included. Nevertheless, long-term microgravity environment can itself have an effect and for example ageing process can be considered as manufacturing on Earth.
- Bottled wine - 12 bottles of wine were sent to space by Space Cargo Unlimited, brought back to Earth after 1 year, and one of them was expected to sell for $1 million at an auction.[96]
- Space beer made from space-flown yeast or hops.

5. 2022 ECOSYSTEM OVERVIEW

Here follows the overview of the 117 entries included in this new in-space manufacturing survey of commercial space entities.

5.1 Advanced Materials

Table 1 lists the entities in the unique materials field. About 7 of them are or have worked on ZBLAN.

Table 1: In-Space Manufacturing Companies for Advanced Materials

Name	Destination	ISM Field	ISM Goods	Status	Founded
ACME (A2M)	Earth	Advanced Materials	Silicon Carbide Wafers	Dormant	2014
Apsidal	Earth	Advanced Materials	ZBLAN, Optical Fibers, Glass	Development	2019
DSTAR Communications	Space	Advanced Materials	ZBLAN, Solar arrays	Development	2019
Faraday Technologies	Space	Advanced Materials	Covetic materials	Development	1991
Flawless Photonics	Earth	Advanced Materials	ZBLAN	Development	2017
FOMS	Earth	Advanced Materials	ZBLAN	Demonstrated	2015
Made In Space (Redwire)	Earth	Advanced Materials	ZBLAN, Optical Crystal	Demonstrated	2010
Mercury Systems (POC)	Earth	Advanced Materials	ZBLAN	Development	1985
Microgravity Research Associates	Earth	Advanced Materials	Microchips	Dormant	1979
MoonFibre	Surface	Advanced Materials	Composites, Thermal Insulation, Filter	Development	2019
Space Forge	Earth	Advanced Materials	Microchips, TBD	Development	2019
Varda Space Industries	Earth	Advanced Materials	TBD	Development	2020

5.2 Biotechnology

Table 2 lists the commercial entities under the biotechnology field.

Table 2: In-Space Manufacturing Companies for Biotechnology

Name	Target	ISM Field	ISM Goods	Status	Founded
3D Bioprinting Solutions	Earth	Biotechnology	Human organs, Bone tissue, TBD	Demonstrated	2013
Allevi	Space	Biotechnology	TBD	Dormant	2014
Blue Horizon	Earth	Biotechnology	Soil	Development	2021
Cedars-Sinai	Earth	Biotechnology	Stem cells	Development	1902
Greiner Bio-One	Space	Biotechnology	Cell Cultures	Development	1868
LambdaVision	Earth	Biotechnology	Retinal implant	Development	2009
Merck Research Labs	Earth	Biotechnology	Pharmaceutics	Demonstrated	2004
Nortis	Space	Biotechnology	Organ-on-chip,Tissue-on-chip	Development	2011
nScrypt	Earth	Biotechnology	Implants	Development	2002
Space BD	Earth	Biotechnology	Pharmaceutics	Demonstrated	2017
Space Origami	Earth	Biotechnology	Crystals	Early stage	2018
SpacePharma	Earth	Biotechnology	Pharmaceutics	Demonstrated	2012
Techshot (Redwire)	Earth	Biotechnology	Human organs, Bioprinting, TBD	Demonstrated	1989

5.3 Novelty & Luxury Goods

Table 3 lists commercial entities under the novelty & luxury fields.

Table 3: In-Space Manufacturing Companies for Novelty & Luxury Goods

Name	Destination	ISM Field	ISM Goods	Status	Founded
Sapporo	Earth	Novelty & Luxury Goods	Beer	Demonstrated	1876
Space Craft Beer	Earth	Novelty & Luxury Goods	Beer	Development	2021
Space Roasters	Earth	Novelty & Luxury Goods	Coffee	Dormant	2018

5.4 Space Food

Table 4 lists the commercial entities listed under the space food field.

Table 4: In-Space Manufacturing Companies for Space Food

Name	Destination	ISM Field	ISM Goods	Status	Founded
Air Protein	Space	Space Food	Protein food	Development	2019
Aleph Farms	Space	Space Food	Lab-grown meat	Demonstrated	2017
Alginity	Space	Space Food	Food, Oxygen	Dormant	2018
Argotec	Space	Space Food	Coffee	Demonstrated	2008
Bake In Space	Space	Space Food	Bread	Dormant	2017
BeeHex	Space	Space Food	Pizza	Dormant	2016
Budweiser	Surface	Space Food	Beer	Development	1876
CemVita Factory	Space	Space Food	Nutrients, Pharmaceutics, Food	Development	2017
Deep Space Ecology	Surface	Space Food	Food	Early stage	2016
Dewey	Earth	Space Food	Hemp	Development	2018
DoubleTree by Hilton	Space	Space Food	Cookie	Launched	1969
Eden Grow Systems	Space	Space Food	Food	Development	2017
Explaneta Space	Space	Space Food	Food, Art	Dormant	2019
GreenOnyx	Space	Space Food	Food	Development	2013
Interstellar Lab	Surface	Space Food	Surface Habitats	Development	2019
Orbital Farm	Space	Space Food	Food	Early stage	2018
Redwire	Earth	Space Food	TBD	Development	2020
Sierra Space	Space	Space Food	Food	Development	1963
Solar Foods	Space	Space Food	Protein food	Development	2017
Space Zab	Space	Space Food	Food, Pharmaceutics	Development	2017
StarLab Oasis	Space	Space Food	Food	Development	2021
Zero G Kitchen	Space	Space Food	Food	Demonstrated	2018

5.5 Pure Substances

Table 5 lists commercial entities under the pure substances applications.

Table 5: In-Space Manufacturing Companies for Pure Substances

Name	Target	ISM Field	ISM Goods	Status	Founded
Airbus	Surface	Pure Substances	Oxygen, Metals	Development	1970
Braskem	Space	Pure Substances	Plastic feed stock	Demonstrated	2002
CisLunar Industries	Space	Pure Substances	Metals	Development	2017
Diatomic Space	Surface	Pure Substances	Oxygen, Water, Propellant	Early stage	2022
Eta Space	Surface	Pure Substances	Hydrogen, Oxygen	Early stage	2019
Exoterra	Space	Pure Substances	Hydrogen, Oxygen	Development	2011
Final Frontier Design	Surface	Pure Substances	Water	Development	2010
Helios	Surface	Pure Substances	Oxygen, Metals	Development	2018
L'Garde	Surface	Pure Substances	Oxygen	Development	1971
Lunar Water Supply Company	Surface	Pure Substances	Water	Early stage	2020
Northrop Grumman	Space	Pure Substances	Metals	Development	1994
OxEon Energy	Surface	Pure Substances	Ice, Hydrogen, Oxygen	Development	2017
Pioneer Astronautics	Surface	Pure Substances	Iron, Silicon	Development	1996
Regolithix	Surface	Pure Substances	Oxygen	Early stage	2021
Shackleton Energy	Surface	Pure Substances	Water	Dormant	2007
Skyhaven	Surface	Pure Substances	Hydrogen, Methane	Development	2017
Skyre	Surface	Pure Substances	Hydrogen, Oxygen	Development	2007
Solar System Resources Corp	Space	Pure Substances	Helium-3	Early stage	2020
Space Industries	Surface	Pure Substances	Helium-3, Water	Development	2018
Space Mining Technologies	Surface	Pure Substances	Water, Oxygen, Hydrogen	Early stage	2017
Takasago	Surface	Pure Substances	Water, Oxygen	Development	1923
Terraxis	Space	Pure Substances	Water, Metals	Early stage	2020

5.6 *Microfabrication*

Table 6 lists the commercial entities under the microfabrication field.

Table 6: In-Space Manufacturing Companies for Microfabrication

Name	Target	ISM Field	ISM Goods	Status	Founded
Astrobotic	Surface	Microfabrication	Solar cells, Solar arrays	Development	2008
Luxenus Space	Space	Microfabrication	Solar cells	Early stage	2022
Maana Electric	Surface	Microfabrication	Solar cells, Solar arrays	Development	2017
Nebula Interplanetary Systems	Earth	Microfabrication	Microchips	Early stage	2021
Redwire	Earth	Microfabrication	Semiconductors	Development	2020

5.7 *Large Structures*

Table 7 lists commercial entities under the large structures and in-space construction fields.

Table 7: In-Space Manufacturing Companies for Large Structures

Name	Destination	ISM Field	ISM Goods	Status	Founded
ABM Space	Space	Large Structures	Solar sail	Early stage	2011
AI Spacefactory	Surface	Large Structures	Surface Habitats	Development	2017
Anisoprint	Space	Large Structures	Spare Parts, TBD	Development	2015
Astreia	Surface	Large Structures	Surface Habitats	Development	2019
Astroport (XArc)	Surface	Large Structures	Building Materials, Bricks	Development	2020
Automated Dynamics	Space	Large Structures	Boom	Development	1984
Awake Aerospace	Space	Large Structures	Space Station	Concept	2020
Blue Origin	Space	Large Structures	Building Materials, Alloys	Development	2000
Blueshift (Outward)	Surface	Large Structures	Building Materials	Development	2017
Hassell Studio	Surface	Large Structures	Surface Habitats	Concept	1938
ICON	Surface	Large Structures	Surface Habitats	Development	2016
Eagle Technology	Space	Large Structures	Antennas	Development	1998
Kilncore	Surface	Large Structures	Thermal tiles	Early stage	2020
LavaHive	Surface	Large Structures	Surface Habitats	Concept	2015
Luna Innovations	Surface	Large Structures	Building Materials	Early stage	1990
Lunar Resources	Earth	Large Structures	Solar arrays, ZBLAN	Early stage	2018
Made In Space (Redwire)	Space	Large Structures	Boom	Demonstrated	2010
Magna Parva	Space	Large Structures	Boom	Dormant	2005
Mainstream Engineering	Space	Large Structures	Thermal tiles	Development	1986
Nanoracks	Space	Large Structures	Milling, Cutting, Welding	Demonstrated	2009
OffWorld	Surface	Large Structures	Structures, Infrastructure	Development	2016
OHB	Space	Large Structures	Boom, Spare Parts	Development	1958
Optomec	Space	Large Structures	Spare Parts	Development	1982
Orbital Assembly	Space	Large Structures	Space Station	Early stage	2018
Orbital Composites	Space	Large Structures	Solar arrays, Antennas	Development	2018
Orbital Matter	Earth	Large Structures	Boom	Early stage	2022
Orbit Recycling	Space	Large Structures	Building Materials	Early stage	2018
Planetoid Mines Company	Surface	Large Structures	Boom, Landing Pad	Early stage	2009
Raven Space Systems	Space	Large Structures	Re-entry Capsule	Early stage	2020
Relativity Space	Surface	Large Structures	Surface Habitats	Development	2016
Rhea Space Activity	Space	Large Structures	Mirrors	Development	2018
Skycorp	Space	Large Structures	Space Tug	Early stage	1998
Sperospace	Surface	Large Structures	Metals, Structures	Early stage	2019
Tethers Unlimited	Space	Large Structures	Boom, Antenna, Array	Development	1994
TGV Rockets	Space	Large Structures	Spare Parts	Development	1998
ThinkOrbital	Space	Large Structures	Space Station	Development	2021
Ultra Tech Machinery	Space	Large Structures	Spare Parts	Development	1986
United Space Structures	Space	Large Structures	Surface Habitats	Early stage	2009
ZeCoat Corp	Space	Large Structures	Mirrors	Development	2011

6. 2022 STATISTICAL OVERVIEW

Here follow a statistical overview of which types of companies are or aim to become active in the emerging in-space manufacturing fields.

6.1 Market Survey Criteria

This survey criteria resulted in the 117 entries:

- Belongs to in-space manufacturing, as defined in Section 4.
- A planned manufacturing activity taking place beyond Earth and an intent to produce specific goods. Thus some ISRU, assembly and other in-space economy fields are not included.
- Potential ISM technologies or supporting services without announced commercial goods have been nominally excluded.
- Commercial entities or at minimum offering commercial services to the public markets.

6.2 Destinations

Figure 4 shows the destinations, targets or locations of new in-space manufactured products as defined in Section 4.3. Most goods or constructions are planned to remain in space, followed by the surfaces of Moon or Mars, and the least amount of companies is aiming to return ISM products to Earth. This is interesting, because existing, near-term, and larger markets are thought to be on Earth and that has partially started a wave of small re-entry capsule and microgravity facilities startups for example.

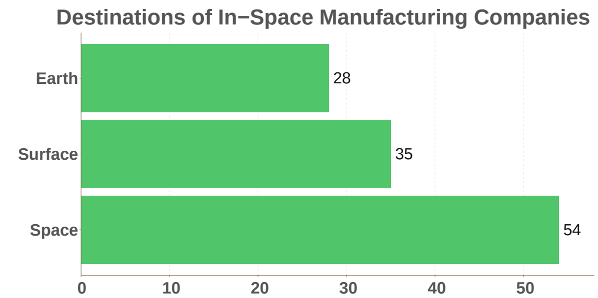

Figure 4: Targets of In-Space Manufactured Goods

6.3 Destinations with Categories

Figure 5 shows the destinations together with in-space manufacturing fields as defined in Section 4.5. Products intended to be flown back to Earth are dominated by advanced materials and biotechnology applications followed by novelty & luxury goods. The largest ISM category, where the produce will remain in space, is space food and large-scale structures but otherwise very varied. For surface ISM, the manufacturing will also happen on the same planetary surface in most cases but it is still considered "in-space" or beyond-Earth manufacturing. Surface ISM applications are also very mixed thanks to better access to and processing of raw resources but a large new category is the production of water, oxygen, metals and other pure substances.

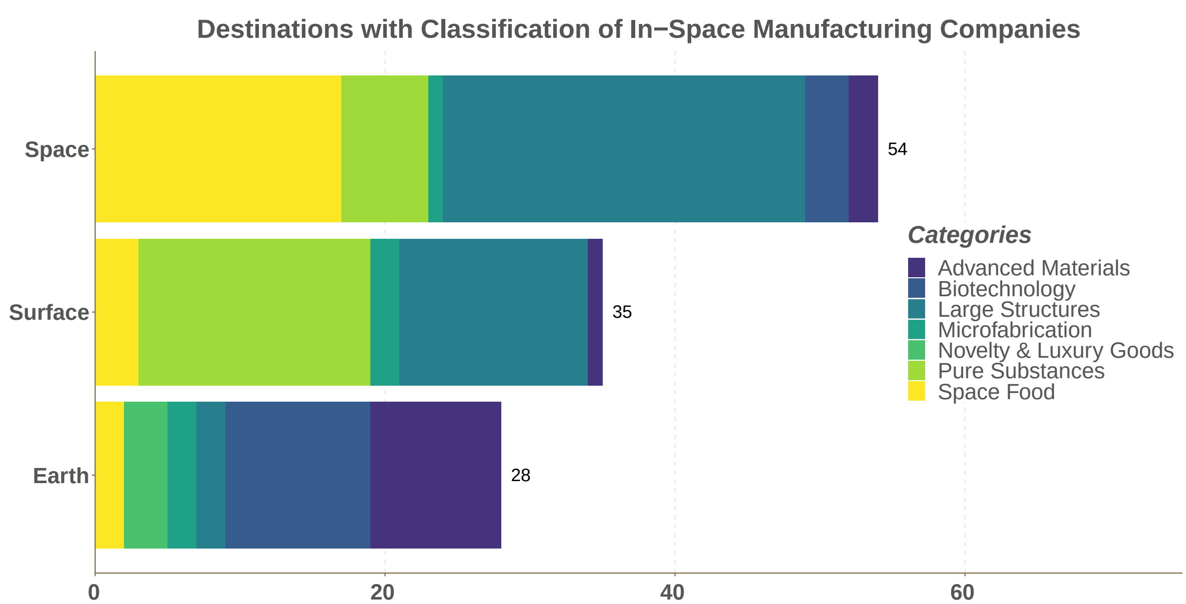

Figure 5: Destinations with ISM Fields for In-Space Manufacturing Companies

6.4 Classifications or Fields

Figure 6 shows the classification of in-space manufacturing companies as defined in Section 4. Generally, there is only one primary category per company but for example Redwire has been included multiple times. Thus the 117 entries are not strictly separate companies but separate ISM activities. Large structures is the most popular field followed by space food, pure substances, biotechnology and only then advanced materials for Earth.

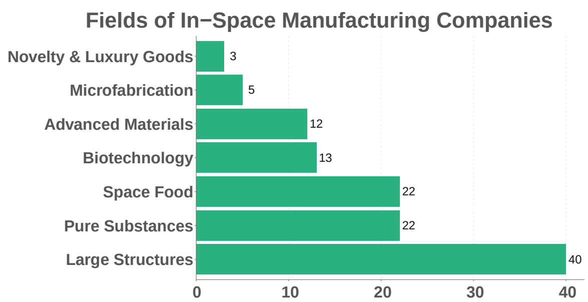

Figure 6: Categories of ISM Companies

6.5 Fields with Status

Figure 7 lists the fields of in-space manufacturing entities together with the status categories.

There are no active recurring in-space manufacturing entities making products and materials for Earth or space. Space beer from Japan is set as "Recurring/Active", because it was made from space-grown barley multiple times but not lately. Some have been demonstrated. Redwire has shown ZBLAN[60] and optical crystal fabrication in space and the latter was sold commercially.[73] FOMS has also demonstrated ZBLAN.[61] The situation should improve in the next years thanks to many small re-entry spacecraft and Axiom Space Station. It is unknown which will be the first recurring ISM goods but many more demos and small sales are likely. There still seems to be a long path for the ISM-for-Earth markets to emerge and for ISM companies to become recurring.

6.6 Founded with Classification

Figure 8 plots the founding dates of all entries in the database together with the fields. Important to note that the company founding year may not be correlated to the start of the ISM activities. Starting from 2017 and still continuing, there has been a large increase. Space food and unique materials fields stand out but other categories are present too. This timeline coincides with the first Starship announcements and successful re-usability of Falcon 9, because both are aiming to lower costs of space access, which could enable business cases of in-space manufacturing. NASA's Artemis announcement in 2019 and new funding opportunities also increased the interest, because it will be creating new markets for many in-space economy fields. While there was a decline, author forecasts that successful Starship missions to orbit, return to the Moon, and small re-entry capsules will kick off another ISM startup founding wave in about 2-3 years.[1]

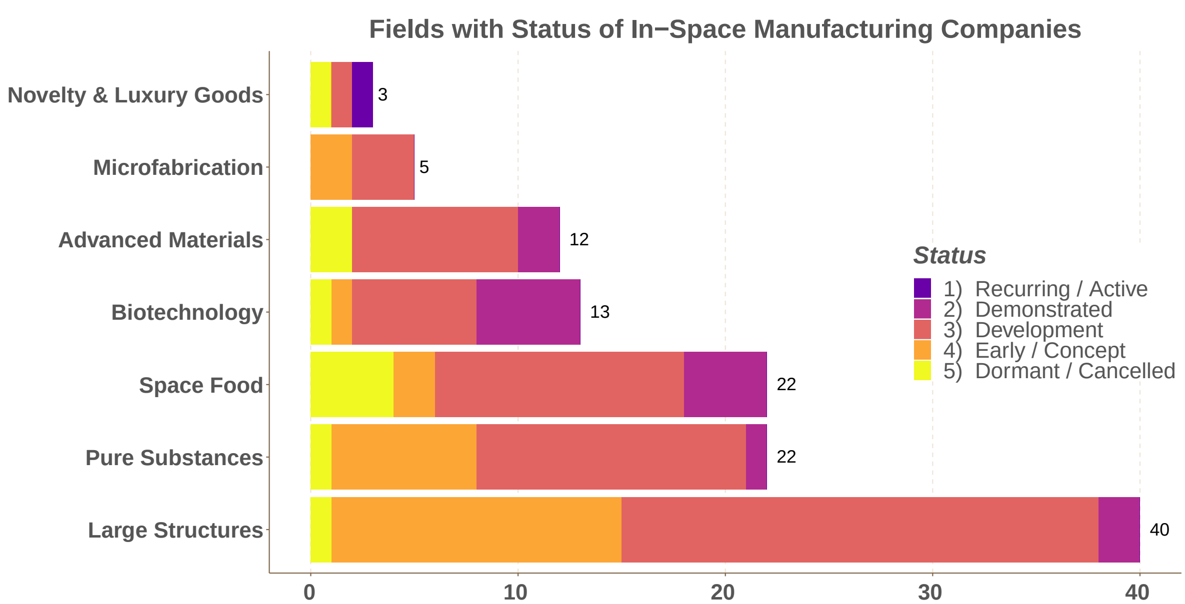

Figure 7: ISM Fields with Status for In-Space Manufacturing Companies

6.7 Funding with Classification

Figure 9 has ISM categories with funding amounts in the defined ranges. "Yes, amount TBD" often means an established company but it is unknown how much are they investing into ISM but likely a considerable amount. "Unknown" category is for companies who have not announced funding. With the latter, it is often the case that based on their activities, social media and employee count, they likely only have small amounts or no funding.

Over $1 billion in private and awarded funding have received Relativity and Sierra Space. Over $100 million in funding have to raised Made in Space (Redwire) and Aleph Farms. Between $50-100M in private funding has raised for example Varda Space Industries. Between $10-50M in funding have e.g. Space Forge, Solar Foods and Space BD. Between $5-10M in funding have for example Interstellar Lab, Maana Electric and OffWorld.

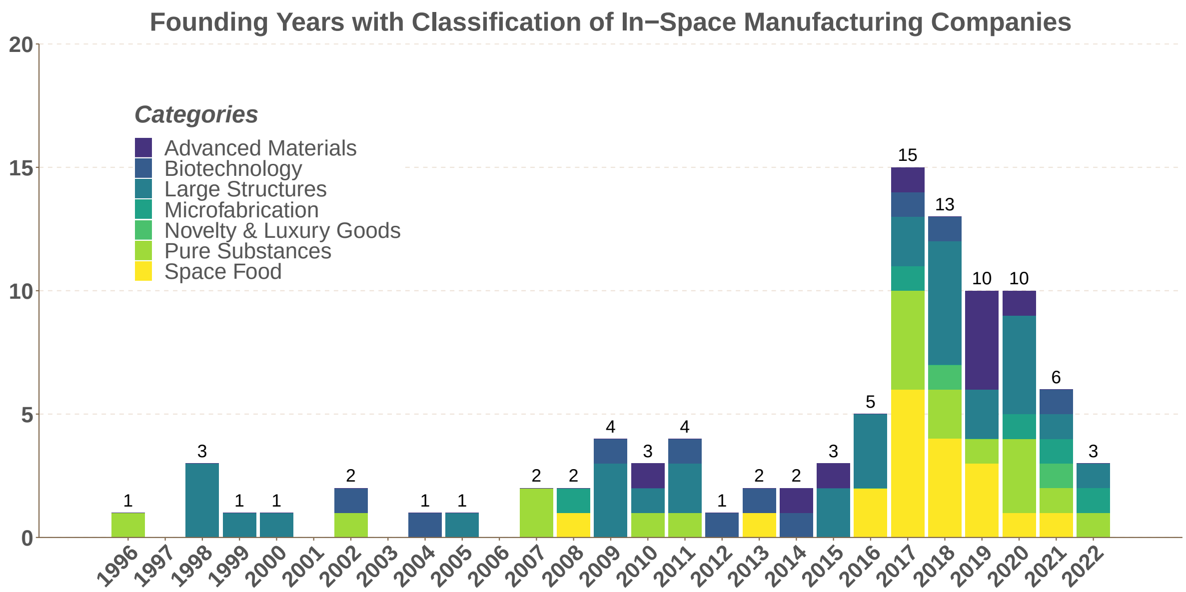

Figure 8: Founding Years with Classification for In-Space Manufacturing Entities

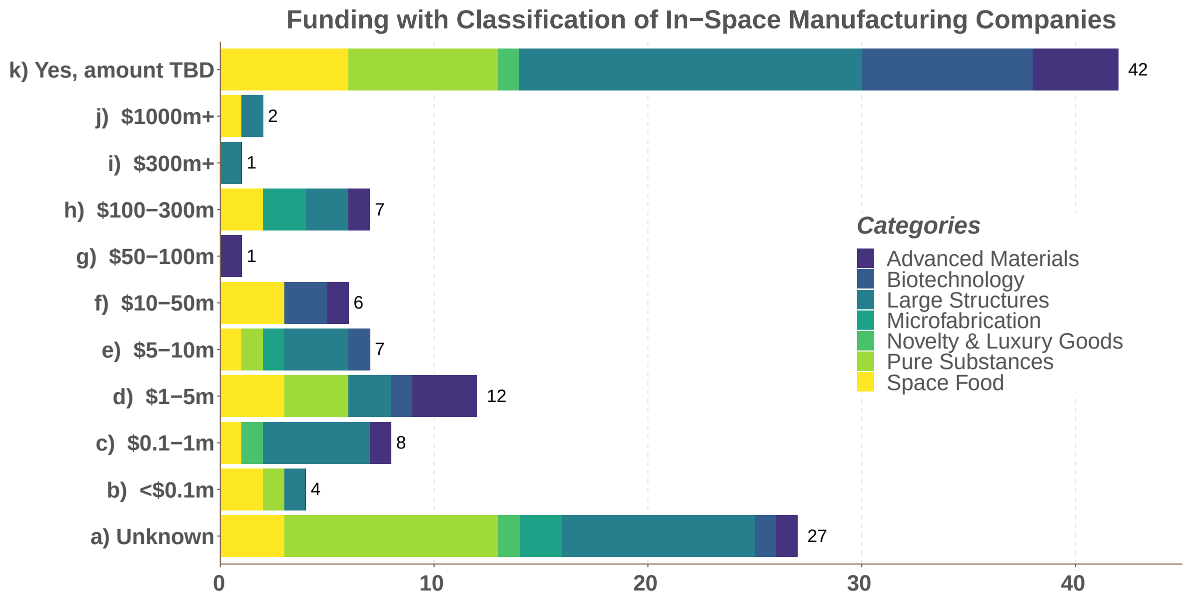

Figure 9: Funding Levels with Classifications for In-Space Manufacturing Companies

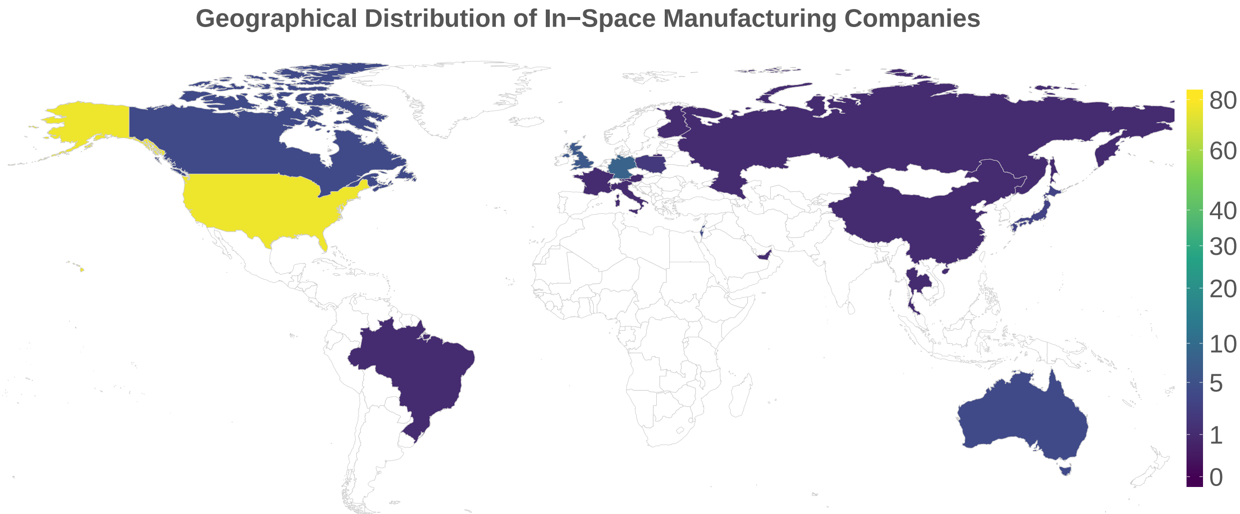

Figure 10: Map of In-Space Manufacturing Companies Headquarters

6.8 Geographical Distribution

Distribution of the in-space manufacturing companies by headquarters locations is on Figure 10.

76 of 117 are based in the United States. Followed by 8 entities registered in Germany, 6 in UK, 4 in Canada, Luxembourg and Australia but otherwise only one or two in other marked countries.

The United States is also in the first place by the quantity of commercial entities and missions flown among in-space economy companies,[1] small launchers,[97] satellite constellations[98] and nanosatellites.[99] With in-space manufacturing being one of the most leading edge and futuristic space industries, such lead and popularity is expected.

6.9 First Launches

First missions in space have been gathered on Figure 11. Knowingly cancelled and dormant companies have been marked separately. "Not announced" are companies that do not seem to have announced a year for their first ISM activities in space. The large quantity of such entities matches with the large number of idea and early stage companies, or only technology development projects.

The first launch also does not correlate to the start of a recurring commercial activity and many of these demonstrations can be scientific in nature and primarily funded by grants. The approach here is to keep the last announced year in the database until such date passes even when it becomes unrealistic. This will help to track delays in the future.

In 2015, Argotec flew espresso machine to space.[100] In 2017, SpacePharma launched their first biotechnology experiment CubeSat.[101] In 2018, Made in Space launched first ZBLAN demonstration,[59] Tethers Unlimited launched plastic recycling system[102] and 3D Bioprinting Solutions launched a bioprinter.

2019 saw the first launches for Aleph Farms, Braskem, DoubleTree by Hilton, Flawless Photonics, FOMS (Fiber Optic Manufacturing in Space),[61] Sierra Space, Techshot (Redwire) and Zero G Kitchen.

In 2022, Planetoid Mines Company[103] and Space Forge[104] should send their first hardware to space.

In 2023, Redwire is planning to launch a commercial greenhouse to space.[105] Orbital Assembly,[106] Takasago's water-splitting experiment to the Moon,[107] and Varda Space Industries[108] have also announced their missions.

In 2025, Helios plans to demonstrate oxygen and metal production on the lunar surface.[109]

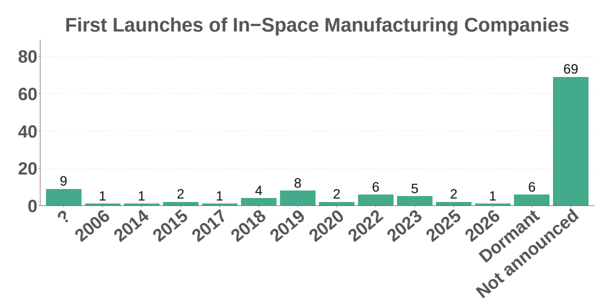

Figure 11: First Launch Years of In-Space Manufacturing Activities and Demonstrations

7. CONCLUSIONS

In-Space Manufacturing (ISM) is a process involving the fabrication, assembly, and/or integration of goods outside the Earth's atmosphere.[11, 18]

Statistical overview of 117 commercial in-space manufacturing activities has been presented. Short history, literature review and classification of in-space manufacturing fields was written.

In-space manufacturing companies have been sorted by 3 main destinations or targets for the goods: Earth, space and surfaces. Space is most popular with 54, followed 35 for surface and Earth with 28 entries.

The companies are divided into 7 categories: advanced materials, biotechnology, large structures, microfabrication, novelty & luxury goods, pure substances and space food. Most popular are space food and large-scale structures. This list will expand and change considerably when new types of goods and infrastructure will be made in space, because it is currently driven by the announced activities.

There are no recurring in-space manufacturing products or companies as of 2022. Several have performed demonstrations but no regularly active in-space production of specific goods is known. ZBLAN manufacturing in space was demonstrated by Redwire and FOMS in 2017 and 2019 but regular production has not started. Redwire announced an optical crystal in 2022 as the first sale of an in-space fabricated product. Instead, the first commercial ISM product was likely the perfectly spherical latex beads in the mid-1980s.

Finding the potentially profitable ISM goods and materials seems to be the biggest challenge for the in-space manufactured goods market destined for Earth to take off. Redwire, Varda and Voyager seem to be exploring the largest number of promising ISM areas by acquiring companies or hiring scientists and may be best positioned to discover the "killer app" for ISM-for-Earth.

There is an increasing number of service providers supporting in-space manufacturing such as Cargo Dragon, commercial ISS facilities, ESA Space Rider, and many upcoming small re-entry capsules. High-value materials worthwhile to be produced in space have been much slower to emerge. Already existing space station and transport capabilities should be lower cost when compared to accessing microgravity on dedicated spaceplanes or re-entry capsules though. Thus the emergence of so many service providers probably cannot be explained purely by market forces. It is almost like railways and large facilities are being built but then not having a great plan for their full utilization. Nevertheless, easier access to microgravity should help to spur the innovation, research and new discoveries.

The predictions from 1970s and 1980s for promising in-space manufacturing applications and markets have not come true in the preceding 40-50 years. The recent enthusiasm for ISM is likely driven by Falcon 9 reusability, Starship and return to the Moon, all lowering the cost of access to space and/or creating new demand for ISM applications.

For ISM-for-space, where the outputs will remain in space, many first demonstrations are planned in the next 2-3 years and commercial applications such as long antenna booms and ISM solar arrays should follow. This market has somewhat of a chicken-and-egg problem but government grants and awards should help to overcome it in the next years.

About in-space manufacturing on planetary surfaces, the first missions of commercial landers in the next 1-3 years should pave the wave for first commercial demonstrations and then crewed return to the Moon should see a rapidly increasing cadence of ISM activities on surfaces.

The goal is to start repeating this study biannually. Numerous improvements are planned due to many companies exploring multiple ISM fields and those activities having different status and funding. Dedicated papers exploring the supporting and enabling services for in-space manufacturing are also planned. The online-accessible database is expected to be updated multiple times per year.

Acknowledgments

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