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In-orbit Spacecraft Manufacturing: Near-Term Business Cases Individual Project Report

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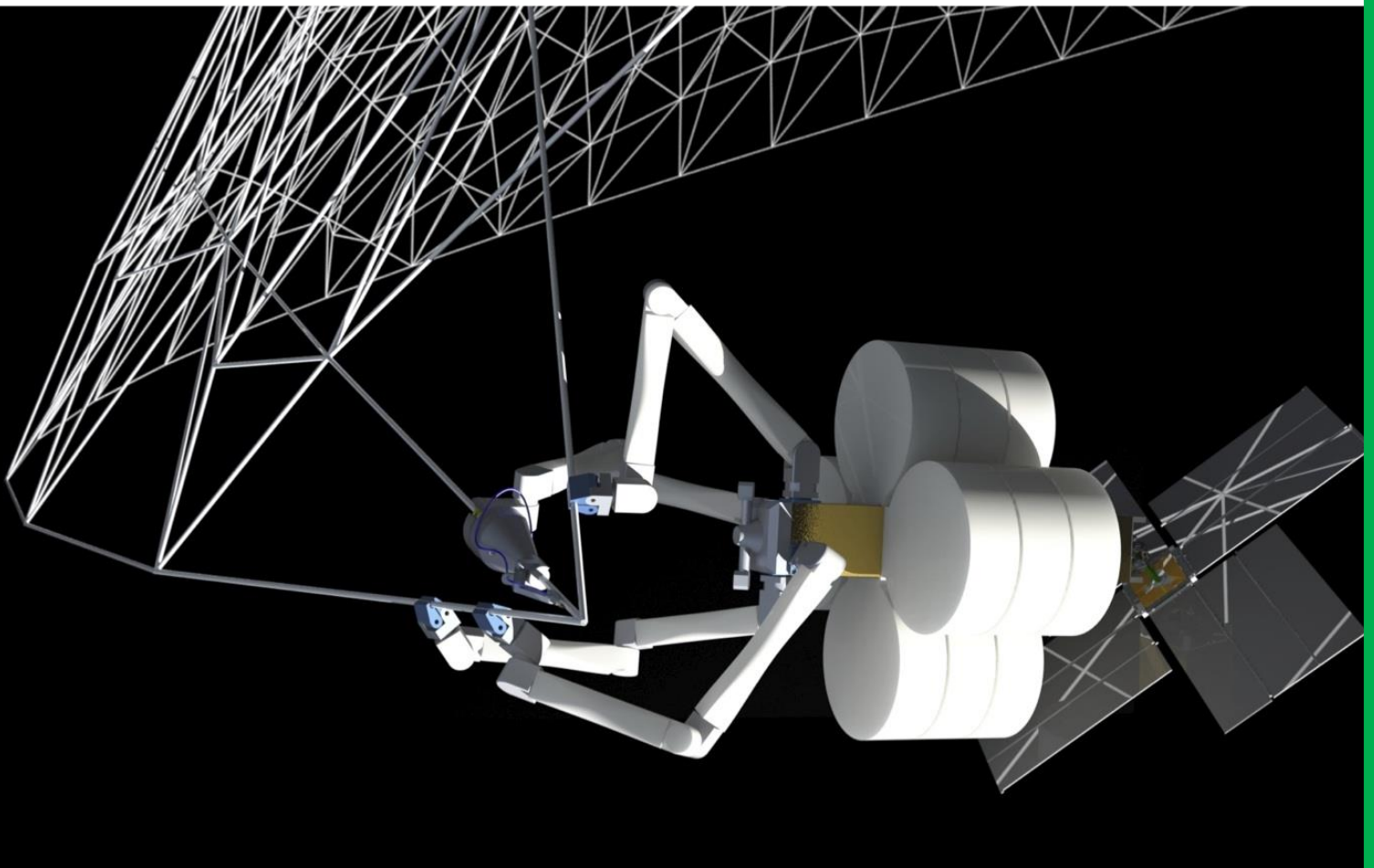
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In-orbit Spacecraft Manufacturing: Near-Term Business Cases



Individual Project Report

International Space University

Ruslan Skomorohov
MSS 2016



ISU Individual Project Advisor:
Prof. Chris Welch



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ABSTRACT

The recent developments in space commercialization and the entry of new private entities of various size has re-opened the question of in-space manufacturing. This report examines the viability of a broad set of initial use cases for in-orbit manufacturing around the Earth in particular, involving technologies with a time horizon of 3-5 years. These include large aperture spacecraft or components, components for traditional satellites, standards-based components and nano-satellites such as cubesats, and serial production commercial satellite use cases among others. The definition of manufacturing used extends to any activity involving some or all of three main parts of the value chain including fabrication, assembly, and integration. It also covers cases where testing, deployment, maintenance, repair, upgrades, recycling, and re-deployment have significant inclusion related to the mentioned areas. Pre-fabrication and 3D printing of components in orbit are considered across a number of sub-systems, including solar panels, support structures and truss elements, communication antennae, mirrors, radiation panels and other thermal components, propulsion and fuel elements, and standardized electronics, among others. A classification, evaluation, and selection methodology is provided. The initial broad set of use cases is analyzed and filtered based on factors such as technical feasibility, technology readiness level, potential market, costs, trade-offs and alternatives, and long term use case sustainability. The resulting short list is treated to a preliminary high-level business case analysis and existing project case studies are examined. Lastly, recommendations on the prospects for further investigation are provided.

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The front cover is using an image the courtesy of Tethers Unlimited and displays SpiderFab™, an in-orbit manufacturing facility.

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ABBREVIATIONS

ADCS	Attitude Determination and Control Subsystem
AIAA	American Institute of Aeronautics and Astronautics
AM	Additive Manufacturing
AMF	Additive Manufacturing Facility
ASCE	American Society of Civil Engineers
Comms	Communications
DRL	Demand Readiness Level
ERL	Economic Readiness Level
ESA	European Space Agency
GEO	Geostationary Earth Orbit
GSO	Geosynchronous Orbit
GTO	Geosynchronous Transfer Orbit
HEO	Highly Elliptical Orbit
I4IS	Institute for Interstellar Studies
IAC	International Astronautical Congress
iBOSS	Intelligent Building Blocks for On-Orbit Satellite Servicing
ISS	International Space Station
ISU	International Space University
LEO	Low Earth Orbit
Mech.	Mechanisms
MEO	Medium Earth Orbit
MSS	Master of Space Studies
MVP	Minimum Viable Product
NASA	National Aeronautics and Space Administration
OBDH	On-Board Data Handling
S/C	Spacecraft
SETI	Search for Extraterrestrial Intelligence
SWOT	Strengths, Weaknesses, Opportunities, and Threats
TRL	Technology Readiness Level
TTC	Telemetry, Tracking, Command
UK	United Kingdom
US	United States
USA	Unites States of America

1. INTRODUCTION

This report explores in-orbit spacecraft manufacturing and potential near-term business case considerations. It is the result of an individual project part of the International Space University (ISU) Master of Space Studies (MSS) program. In order to introduce the work behind it, the motivation is discussed, followed by the project scope and focus along with the structure of the report. The target audience of the report and the importance of the outcomes are detailed as well.

1.1 Motivation

Recent developments in commercial space have opened the doors for new private entities as well as established companies or governments to pursue new opportunities in the wider spacecraft industry. This includes new use cases along the spacecraft lifecycle, including in-orbit activities. In addition, new developments in Earth-bound and space robotics combined with innovation in 3D printing and additive manufacturing have enabled new capabilities. Companies such as Made In Space, Inc. have collaborated with the National Aeronautics and Space Administration (NASA) to deploy and test 3D printers on the International Space Station (ISS) and proposed concepts focusing on manufacturing in space and in-orbit in particular (Molitch-Hou, 2016). The company's recently announced other initiative, Archinaut is robotic 3D printer focusing on large structures (Made In Space, 2016). This was preceded by Tethers Unlimited's study of similar concept – SpiderFab (Hoyt, et al., 2013a). A relatively different approach is undertaken by the Phoenix program of DARPA, which also uses advanced robotics, but is focusing on modular satellite architectures and improved geostationary satellite usefulness, lifespan, and reliability (DARPA, 2016). The common characteristics addressed by all of those concepts are related to new broader industry needs related to launch and test costs, volume and mass restrictions arising from planned and envisioned large aperture spacecraft, or standards-driven restriction such as those for cubesats. Additional motivation for the focus of the report is the rising number of satellite constellations planned by a variety of companies such as Skybox (Terra Bella/Google), SpaceX, OneWeb, Digital Globe, and Planet (Bradshaw, 2015), or Spire and BlackSky Global (Dillow, 2015), as well as increased capacity by traditional satellite entities.

Moreover, there is a clear trend of increased interest in terms of publications. After the initial First Wave of the broader in-space manufacturing spur in the 1970s and 1980s, there is a renaissance Second Wave with the advent of the various new technologies discussed earlier that started in the late 1990s and is even more pronounced in the recent few years. A variety journal articles, books, reports, and other academic and industry publications encountered over the course of this study is summarized in Fig. 1-1. It excludes news articles and similar sources prone to hype cycles. Although it uses a broader domain incorporating in-orbit manufacturing and adjacent topics along the technology and business dimensions and it presents a non-statistically strict data, it showcases a clear trend.

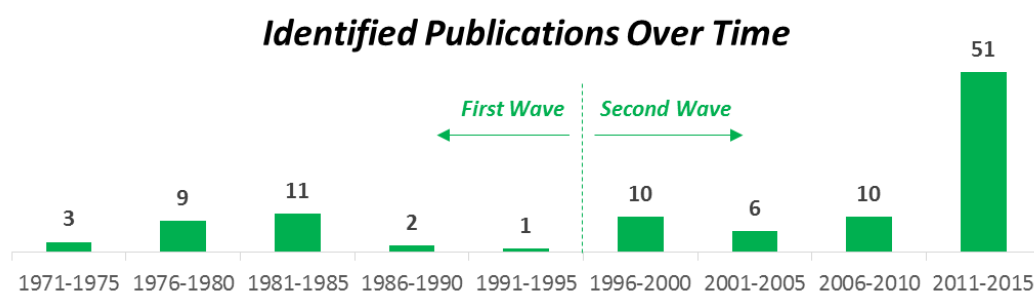


Figure 1-1: Publications in the broader in-orbit manufacturing and related topics domain over time

The connection of these developments with the next step in creating a space economy is very strong and a main reason why the individual project topic was proposed to ISU by the Institute for Interstellar Studies (I4IS). Machines building parts of or entire other machines, also known as von Neumann machines, is a building block towards moving civilization to space. Along with impacts on manufacturing of systems in space such as laser infrastructure, antennas for search for extraterrestrial intelligence (SETI), and others are paving the way towards future interstellar travel.

1.2 Project Scope and Report Structure

If in-space manufacturing will flourish at some point that could provide the technological basis for the infrastructure required for interstellar travel as such an infrastructure is mandatory. Therefore, as an immediate step towards that rather long term goal, this report is focused on near-term use case and business case analyses. It aims at identifying and examining selected business cases for in-space manufacturing of spacecraft that are feasible within the near-term future. For the purposes of this study, there are a number of definitions and constraints assumed, focusing the work and providing the project scope.

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:

- **Fabrication:** The process of producing basic spacecraft or spacecraft subsystem components through 3D printing or traditional industrial methods such as welding, cutting, bending, etc.;
- **Assembly:** Combining fabricated or pre-fabricated components into subsystems or entire spacecraft or direct complex 3D printing;
- **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;

The scope of the report limits manufacturing to parts of or entire spacecraft, but also allows to incorporate additional elements of a spacecraft's lifecycle to be integral parts of a use case. Further, the term "in-orbit" refers to the part of orbital space around Earth up to geostationary Earth orbit (GEO) as place of manufacture. "Near-term" in the title of the report refers to timeframes related to technology that will be available in 3-5 years. Business cases are important in the context of profitable use cases and in-orbit spacecraft manufacturing. This is a constraint in terms of viability of a use case as a profitable business venture. Mass production of materials or processing of asteroid or Lunar-mined resources can be considered manufacturing and are excluded although they can be viewed as manufacturing industry when compared to Earth-bound analogues. Other topics out of the main scope of the report include manufacturing by humans, which is only briefly discussed but generally left out which is justified due to astronaut costs and added complexity and burden on the business case (including dependence on space agencies in the near term future). In addition, any legal, policy and organizational or management aspects are also outside of the intended focus of the report as technology maturity and high-level business viability are precursors for those to be considered.

In order to fulfill its goals, the report beyond this introduction is structured in several distinct sections:

- **Review of related work** explores existing literature on the topic of in-orbit spacecraft manufacturing use cases, evaluation methodologies applicable to technology feasibility or maturity and business model viability, as well as related and auxiliary literature to support various parts of the methodology and analysis.

- **Methodology** introduces the approach used in the devise of the categorization and evaluation methods, and the analysis of use cases for viability as business cases.
- **Analysis and Results** presents the analysis performed to create a landscape of all use cases, identify a short list of use cases for in-space manufacturing of space systems potentially viable within a five-year timeframe, perform further technology readiness analysis on short-listed use cases, explore at a high level the business case viability, and devise a concept-of-operations of an in-orbit spacecraft manufacturing facility and run a preliminary cost-benefit analysis on it.
- **Performance to Plan Discussion** examines the project in the context of the initial plan – what went well and where the difficulties were as well as any major adjustments or changes.
- **Conclusions and Recommendations** summarizes the report across chapters and provides recommendations related to results of the project and suggests further steps and research.

This structure conforms to the guidelines provided by ISU for the purposes of the individual project's final report within the context of the MSS program's associated module.

1.3 Target Audience and Importance of Outcomes

This report targets several groups as an audience. First, space agencies interested in using the frameworks and having a landscape of what could be left to be driven by private capital or where support is needed, etc. Second, aspiring entrepreneurs looking to decide where to focus efforts. Third, investors such as angel and venture capital funds that make investment decisions related to in-orbit spacecraft manufacturing business opportunities. Fourth, engineers who want to focus their efforts on areas with better industry prospects. Fifth, space scholars and enthusiasts who are interested in the field, for example, ISU faculty and students.

There are three important outcomes of the report that need to be pointed out. The first is the extensive literature review and summary, which has not been detected anywhere else in literature during the work involved in the report. It is a key outcome of the report and provides a fresh view of important gaps and direction of further research necessary even beyond what is undertaken further in the report itself. The collection of references is unique in terms of comprehensiveness and focus on the broader in-orbit manufacturing topic along with some adjacent topic sources. The second is the proposed method for use case mapping, categorization, and filtering to get to a prioritized list of potential business cases, which provides a systematic approach and basis for further analysis covering both technology and business aspects related to in-orbit manufacturing. The third is the set of selected business cases requiring further analysis and the minimum viable product (MVP) concept of operations based on them as well as the case studies that are put through the evaluation methodology and discussed at a high level. Any of these outcomes could have proprietary or undisclosed governmental equivalent analyses, but those are not available to the general public and academia, and none have been revealed throughout the research over the course of the project.

2. REVIEW OF RELATED WORK

This literature review examines existing work related to technology and business dimensions of in-orbit spacecraft manufacturing and the broader space sector. It starts with a review of assessment methodologies and overview studies related, or potentially applicable to space manufacturing, concepts. Then a comprehensive search for literature and sources of use cases or concepts was performed. These were reviewed through the lens of technology versus business analysis depth using a categorization created for the purposes of this report. Beyond that, there are a number of additional topics covered in this review due to the need to assess directly or indirectly related areas. These include robotics and telepresence, astrodynamics, launch industry, Earth-bound spacecraft manufacturing, as well as material science, asteroid and Lunar mining, and deployment mechanisms and other potential alternatives to in-orbit manufacturing.

The review was done by a comprehensive search across publically available sources and always allowed for a certain margin in terms of relevance since it was part of the process of further defining the scope of this report. Some additional biases arise from the easily available archives of conferences and journals as the time of publishing progresses due to the nature of the Internet. For example, the publications in Figure 1-1, which are restricted to exclude online articles and mentions, still might have a time-based bias. Therefore, a sensitivity on various sources was done and showed a similar trend. The two “waves” of interest in the broader in-space manufacturing are clearly identifiable and are used to segregate newer from older literature in section 2.2.

2.1 Technology and Business Methodology and Overview Studies

The initial focus of the literature review was to find methodologies of classification and evaluation of business and technology aspects of in-orbit spacecraft manufacturing or applicable to it, then cataloguing a number of use cases and evaluating them as business cases. In the course of the review though, it became evident that there is no single methodology or overview that covers in-orbit manufacturing at the depth needed. Table 1-1 displays a number of studies ranging from evaluation methodologies and assessments to technology- or business-focused overviews. Nevertheless, none of them cover the three key components, which is a significant gap in the literature. The report became more focused on developing in-orbit spacecraft manufacturing classification and evaluation methodologies, which are a core outcome. The technology and business domains so far are very broad to allow for possible methodologies to be incorporated, such as the Demand Readiness Level (DRL) proposed by Paun (2011) and ones related to the business side. A few studies do have coverage of more than one domain and an applicable in-orbit manufacturing focus, but fail to be comprehensive.

Van der Veen (2011) examines and appraises a number of technology evaluation methods for applicability to the space sector in the context of technology investments. Some of these include Delphi, decision trees, S-Curve extrapolation, analogy- and patent analysis among others. The methods are assessed for potential to be used as a technology investment decision tool, but are a high level general set to be applied to the broader space sector, not specifically for in-orbit manufacturing.

Bekey (2002) is primarily focused on reviewing advanced spacecraft concepts and provides high level rules on evaluating the business aspects of manufacturing them in space, but is focused mostly on technology ideas, feasibility, and analysis. Similarly, within its workshop on 3D printing in space, Technische Universität München (2011) keeps a strict focus on the additive manufacturing topic and does not have commentary on business viability aspects. Puteax (2015) and Leung & Serra (2014) have the opposite issue in which the technical aspects are discussed only lightly.

Table 2-1: Assessment methodology or overview studies related or applicable to the space sector

Author(s), Year	Focus			Study Details
	Techno-logy	Busi-ness	In-orbit S/C Mfg.	
Adams, 1974	✓	✗	✗	Discusses assumptions about materials to be processed but focusses on the processes and processing involved related to the fabrication and manufacturing in space
Cliff, 1981	✓	✗	✗	Borrows from other industries to setup a system architecture which could perform automated design, fabrication, and repair of complex systems configured to be analyzable mathematically
Frosch, 1983	✓	✗	✗	Proposes hybrid systems which use one person to control large numbers of semi-intelligent machines and suggests applying some of these techniques to space
Crawford, et al., 1996	✗	✓	✗	Cost estimation of space science missions and overview of previous success of the methodology
Potter, et al., 1997	✓	✗	✗	Argues that teleoperational methods being developed for terrestrial surgery are extendable to space-based activities and describes teleoperation strategies to handle these different tasks
Bekey, 2002	✓	✓	✓	Examines feasibility and reviews a broad set of advanced space concept and discusses methods on assessing technology trade-offs and high level value proposition and economic aspects
Veen, 2011	✓	✓	✗	Appraisal technology evaluation methods for applicability to the space sector in the context of technology investments, e.g. Delphi, decision trees, S-Curve extrapolation, and others
Paun, 2011	✗	✓	✗	Introduces the concept of Demand Readiness Level (DRL), which relates to the degree of maturity for the expression of a need by a customer on a given market
Dent & Pettit, 2011	✗	✓	✗	Introduces a mechanism for assessing market readiness, which provides a complementary perspective on innovation and technological development
Technische Universität München, 2011	✓	✗	✓	Provides categorization of concepts focused on 3D printing with in-space manufacturing focus including principles, techniques, processes, and applications
Kapoglou, 2013	✓	✗	✓	Investigates processes involved in exploiting 3D printing to enable manufacturing capability on the ISS; methodologies used for space-based and earth-based technologies;
Leung & Serra, 2014	✓	✓	✗	A cross-platform study of feasibility of a dedicated launch service for micro- and small satellites in terms of project cost and other key factors, such as launch schedule and orbit selection.
Puteaux, 2015	✓	✓	✗	Review of the factors and the evolution of space entrepreneurship within "New Space" and assesses a number of applications and concepts relevant to early investors
Cozmuta, 2015	✗	✓	✗	Introduces Economic Readiness Level (ERL) and a model that leads to path-ways for infusion of private capital and sustainable commercial microgravity LEO-Earth economy

✓ = Primary ✓ = Partial ✗ = None

Use cases and concepts in the current case are, as introduced earlier, any manufacturing activity in orbit that involves at least one of the following three: fabrication, assembly, or integration. This might be considered a departure from the typical recent association of in-space manufacturing with additive manufacturing, but the approach proposed by this report is more in-line with developed industries on Earth. For example, car manufacturers are considered part of that sector although such companies do not fabricate the basic components. In order to collect and assess the use cases, a simple literature classification system is initially introduced below. The technology depth and the business case depth are its core dimensions. Both are purposefully broken into letter categories in order to avoid false precision and interpretation of increasing “quality” and coverage of all items in “lower” categories. The only consistent directional aspect is the growth of complexity of the literature’s analysis (or “depth”) with each letter. The proposed groupings are not strict and sometimes judgement calls or forced placement had to be made for some publications. Technology Focus is categorized in six groups:

- A. Concepts (incl. standards):** Simple brief descriptions of potential technologies
- B. Design or Calculations:** Studies of use cases with specific architectures or designs, but still without any concrete engineered technology to demonstrate
- C. Developed Technology:** Sources describing some level of achieved technology within an in-orbit manufacturing or adjacent use case
- D. Technology Evaluation/Testing:** Literature covering a technology test or technology that is close to evaluation of a space-ready component, equipment, etc.
- E. Deployed Technology:** Reviews and documents of any kind that describe and report about technology already in space and used in some fashion related to a use case (even indirectly)
- F. Roadmap of Deployed Technology:** Existing technology that has been analyzed for its future development and evolution and proposed steps to move it forward

This should not be confused with Technology Readiness Level (TRL) as it is used later and has purposes related to maturity of a specific technology versus the above, which offers a literature-level classification related to use cases. Similarly, the Business Focus dimension is a set of elements that are needed for a business case to be substantiated but can be done or analyzed separately with full business case as the most complex category:

- a. No Business Focus:** In contrast to the technology focus, business would rarely not follow an existing idea or concept that has been at some level proposed by technology experts
- b. Value Proposition:** Brief or detailed view of what need, pain point or new capability the use case addresses (e.g., as short as one paragraph or a thorough analysis of value provided)
- c. Cost Estimate:** Some level of cost estimation of either how much this technology would cost to develop or what are the costs of the final product
- d. DRL:** Borrows from the Paun (2011) and Dent (2011) and is equivalent to a broader market assessment in terms of the need, the size, and/or the sentiment and trends.
- e. Competitive Analysis:** Literature that directly examines alternatives and competition related to in-orbit manufacturing, or use cases and concepts that can become such or present barriers
- f. Business Case:** A business case either at a high-level or with detailed calculation and financial backing or literature that covers multiple elements to assess the economic viability of a case

The next three subsections are organized in a way that uses this categorization to provide a structured approach to reviewing a comprehensive list of heterogeneous topics necessary to create a complete picture of the use cases and concepts universe. Beyond that, these will be key in educating the methodology and analysis in terms of a universe of terms and ideas. The first two refer back to the “wave” period analogy.

2.2.1 First Wave – Before the Mid-1990s

The First Wave of broader in-space (including in-orbit) manufacturing literature started in the mid-1970s in the context of the recent Apollo success in the US and the advent of the Space Shuttle program. Of course, a similar exuberance existed on the other side of the Iron Curtain, but less open publications exist and this literature review is limited in its scope to English language publications – an aspect that can be improved in further studies. The era was marked by grand visions of space stations, solar power station, and space settlements as evident from review below. Nevertheless, some of it still applicable as little progress has been made in the actual implementation of in-orbit industry. The literature review proceeds by combining each Technology Focus with each Business Focus category and discussing ones that have publication falling under them only if such were found.

Aa. Concepts and No Business Focus has no real entries, but is brought up to clarify this lack. It is due to the nature of a brief technological concept with no business details at all and in particular the weak relevance and the large amount of literature where such brief notes exist, likely in the hundreds or thousands. Therefore, it is omitted as a category.

Ab. Concepts and Value Proposition. In the early days of the first wave, one of the most seminal authors was Gerard K. O’Neill. In one of his early works he examines the economic rationales of space manufacturing facilities and concludes it relies on three elements – solar energy availability, materials sources (with the Moon as a main source, due to ease of overcoming its gravity), and the ability to assemble very large objects free of all constraints of payload size (O’Neill, 1974).

Ac. Concepts and Cost Estimate. At the same time others have suggested specific projects such as advanced Earth-to-orbit transportation and facilities based on the external tank of the Space Shuttle with some high-level cost estimates (Salkeld, 1974).

Ba. Design or Calculations and No Business Focus is one of the two most popular categories when it comes to literature from the First Wave. A major study was done by O’Neill, et al. (1979) that covered a broad spectrum of the broader in-space manufacturing with a focus on space resources exploitation and large space settlements. A key group of issues included efficient habitats in space and time and cost analysis of a space manufacturing program plan. Related to that study was the work of Zachary (1981) that built upon the resource exploitation aspects (including from the Moon) and focused on feasibility arguments for the fabrication, in space, of integrated circuits, capacitors, resistors, printed-circuit boards, and wire. The author concludes that “laser beam, electron beam, ion beam, vacuum evaporation, and other developing technologies are in fact rather compatible with the relatively clean, vacuum environment of space”. In parallel, in Russia, Avduyevski, et al. (1985) did a comprehensive study of processing techniques, technologies and methods including space metallurgy, furnaces, melting, electrolysis, alloys, assembly and repairs in space across many types of materials. In terms of applications space tugs, solar power stations, propulsion systems for transport operations are the focal point. Further studies more focused on applications include the comprehensive ARAMIS study by NASA (Akin, et al., 1983), which covers broad set of areas and domains around manufacturing, robotics, and related as well as subsystems and components. Another key work by NASA was a study on space station automation with requirements derived from space manufacturing concepts (NASA, 1984). Lastly, Imstead & Rothblatt (1983), and Coppa (1989) examined telecommunication systems for large-scale manufacturing activity, and developments in very large truss construction in space, respectively. The latter focuses on applications to large 5 GW space power stations, an application which was very popular to discuss at the time.

Bb. Design or Calculations and Value Proposition also has several works falling under it. Drexel (1979) proposed high performance solar sails based on space-manufactured thin-film elements and argued they offer a truss-to-mass ratio of 20 to 80 times those of deployable sails. The author examined the near-Earth orbital transfers, deep space scientific missions (some quite unique), and non-terrestrial resource recovery as key applications. That work is complemented by the study of automatic fabrication of large space structures by Muench (1980) and composite beam building machine for construction of such structures by Goldsworthy (1983). In a similar vein, [Frost & Beckman \(1981\)](#) proposed a design of a large asteroid-borne optical telescope as well as a multi-antenna ultra-long baseline free-flying radio interferometer requiring fabrication in space from non-terrestrial materials. On the other end of the spectrum, Naumann & Herring (1980) reviewed applications of space processing such as metallurgical processing, and processing of semiconductor materials.

Bc. Design or Calculations and Cost Estimate. Johnson & Holbrow (1977) conducted a thorough space colony-focused fabrication techniques investigation with manufacturing of solar power stations and raw materials exploitations from the Moon and asteroids as a secondary focus. Another cost-focused study during the First Wave was the large-scale manufacturing of electronic and electrical components in space in a paper by Sparks (1987). The author further discussed the manufacturing of silicon solar cells, discrete and integrated semiconductors, fiber optics and transmission lines.

Bd. Design or Calculations and DRL. Besides the grandiose and aspirational space colony studies, some long term market studies were attempted. Notably, Dupas & Claverie's (1979) study of the solar power station market in 2025, which is going to be spectacularly missing the mark as the out year approaches and it is unlikely to see even a single such station, compared to the study's forecast of 24-40 TWh/yr. On another note [Miller & Akin \(1979\)](#) provide a more sober, and tightly-focused work on the topic of production of solar power station, location in space trade-offs on assembly and deployment locations.

Bf. Design or Calculations and Business Case. Even in the early stages of space manufacturing, scholars attempted to do detailed economic studies on materials processing in space and how it compares to Earth-based facilities along a number of parts and materials for various Earth industries (Wilcox, et al., 1977). In addition, Engle & Vajk, (1979) examine costing considerations for an in-space manufacturing enterprise with cost categories including research and development, procurement, lift (to orbit), depreciation, space and ground-based personnel, and others with a hypothetical facility considered.

Cb. Developed Technology and Value Proposition. One of the few cases of literature based on flown spacecraft was a Gimarc's (1985) plan to use the Space Shuttle's external tank to cheaply start an "inexpensive operation, modular components, and simple expansion" to a scaled solar power station manufacturing operation.

2.2.2 Second Wave – After the Mid-1990s

The more recent spur of interest is on-going and gathering strength as new technologies opened new possibilities and commercialization of space activities has expanded the human and financial capital involved in it. This section uses the same logic as the one for the First Wave of combining the depth along the Technology and Business Case dimensions and omitting combinations with no literature identified. The list is restarted and the comments on combination 'Aa.' from the previous section hold. Also, the treatment of each source is going to be briefer due to the volume of coverage in order to conserve space except for a few key ones that introduce many topics of interest in a single source.

Ab. Concepts and Value Proposition starts with a continuation of the First Wave's focus at the end on the Space Shuttle program as Taylor (1999) proposes to leverage its external tank as a building block

for space habitats and other projects. The author also discusses architecture and commercial aspects of a large torus. The ability to deploy large habitable structures, construct, and service exploration vehicles in low earth orbit is also pointed out by Hill (2012) as a key factor and explores low-cost manufacturing of composite materials and structures are described in context leading to the possibility of on-orbit and space-based manufacturing. ISU SSP's ASTRA report discusses various architectures to implement an asteroid mining facility, including assembly in LEO, and has a focus on analysis of robotics versus human operations as well as mixed operations (ISU SSP, 2010a). Moore (2013) explores technology development for enabling in-space infrastructure and proposes a strategy will begin to build the foundations for it. Another rich in detail value proposition study is (Lal & Mineiro, 2014):

By enabling manufacturing of hardware to occur entirely in space, AM has the potential to: (i) reduce the amount of payload that must be transported into space thus lowering launch costs, (ii) allow the design and manufacturing of materials and parts that cannot be created in a terrestrial environment (e.g., gossamer sails, trusses, and other structures that can only function in zero gravity), (iii) allow the design and manufacturing of materials and parts that cannot handle vibrations and other structural loads of a rocket launch, (iv) transform operations and logistics planning (via the ability to launch broad categories of materials that can be manufactured in situ into a range of parts with a wide variety of functionality) including on-orbit repair and maintenance that has the potential not only to increase life of satellites and spacecraft, but also offer the promise of reducing space debris. (Lal & Mineiro, 2014)

Beyond those works there are two other notable topics in this group:

- Intelligent, adaptable and programmable matter known as smart putty (Rajagopalan, 2014)
- On-demand spacecraft for exploration using crowdsourcing, using prepositioned orbiting 3D printers ([Johnson & Spangelo, 2011](#))

Ad. Concepts and DRL includes The Tauri Group's work for the Satellite Industry Association for its State of the Satellite Industry Report and provides analysis on overall revenue, growth within markets, and geographic distribution, and discusses trends among satellite services and applications (Guthrie, 2014), therefore educating use case decisions. The other entry under this technology and business combination framework is SpaceWorks' annual summary updates of global nano- and microsatellite activities (Buchen, 2014).

Ae. Concepts and Competitive Analysis consists of two pieces of literature that are discussed in more detail in section 2.3.2 under "Alternatives and Competition" – the first is focused on innovations in microsatellites and the arising need of a microlauncher (Davidian, 2013), and the second is a study on the application of industrial production coefficients to nano- and microsatellites, in particular, constellation of satellites with variable number of units (Rastelli, et al., 2015)

Af. Concepts and Business Case has a single study focused on solving the limitation of 7 ton to geosynchronous transfer orbit (GTO) by an orbital tug system named CARAVAN that is achieved by replacing the upper stage element of a satellite delivery allowing operators to double their payload dry mass (Singh-Derewa & Regina, 2013). This is both a potential use case spacecraft, but also potentially a part of the concept of operations of an in-orbit manufacturing facility.

Ba. Design or Calculations and No Business Focus includes a number concepts:

- “Multi body model approach to obtain construction criteria for a large space structure” (Shigehara & Shigedomi, 1997)
- “Multi-purpose modular plug and play architecture for space systems: Design, integration and testing” (Pitterà & D'Errico, 2011)
- “Solar-Based Power Station - New Conception” (Khartov, et al., 2012)
- “Concept For On Orbit Serviceable Spacecraft Building Blocks - Mechanical Interface” (Schervan, et al., 2013)
- “Design Guidelines For A Space Manipulator For Debris Removal” (Gasbarri, et al., 2014)
- “Autonomous Space Colony Construction” (Michio, et al., 2014)
- “Creating A Universal Space Interface Standard” (Hempsell, 2015)

Bb. Design or Calculations and Value Proposition is the most populous category. One of its richer in concepts works is by Kreisel (2015). The author examines on-orbit servicing (OOS) and assembly (OOA), as well as active debris removal (ADR) both through generic technology principles and associated economic factors. An integrated overview is provided to assess economic and other non-technical factors. Another seminal work is by Bekey (2002) who presents many concepts for the period of 2010 to 2030 and beyond. This includes alternatives and ideas competitive with in-orbit manufacturing, but also a slew of use cases spanning large aperture spacecraft and their equivalents in swarm spacecraft architectures.

Beyond these two key works, other literature includes:

- “Feasibility of Commercial Space-based Microchip Fabrication” (Johnson, et al., 2000)
- “Skyworker: Robotics for Space Assembly, Inspection and Maintenance” (Skaff, et al., 2001)
- “Autonomous Self-Extending Machines for Accelerating Space Exploration” (Lipson & Malone, 2002)
- “Larger, lighter space telescopes by implementing in-space manufacturing concepts” (Mooney, et al., 2007)
- “An Orbital Factory For Modular Solar Sails” (Krummenacher, 2012)
- “Robotic Refueling System For Space Platform Servicing” (Lavagna, et al., 2015)
- “Robotics Operations From Small Spaceplanes For Cubesats Servicing” (Palmerini, et al., 2015)
- “Energy-Efficient Capture Of A Non-Cooperative Spacecraft With A Space Manipulator” (Cocuzza & Cuccato, 2015)
- “Formation control of multi-robots for on-orbit assembly of large solar sails” (Hu, et al., 2015)
- “Large-scale shielding structures in low earth orbits” (Panov, et al., 2015)
- “Design of robotic manipulators for orbit removal of spent launchers’ stages” (Felicetti, et al., 2016)

The publications mentioned in section 1.1 of the introduction also belong to this combination - Archinaut (Molitch-Hou, 2016), Made In Space’s 3D printer on the ISS (Made In Space, 2016), DARPA’s Phoenix program in robotic servicing of geosynchronous satellites (DARPA, 2016). One additional concept is MDA Corp’s plan for assembly of an antenna for spacecraft (Selding, 2016).

Bc. Design or Calculations and Cost Estimate has two works that have presented some level of cost assessment for a well-developed design. The first is a study of Flexbus, an architecture that harmonizes a modular component concept with a design and development approach, as a whole providing the means to offer high quality products quickly at competitive pricing. (Settelmeyer, et al., 1996).

The second is a space debris recovery pair of satellites working together in LEO, where the high quality aluminum, steel, and other space-worthy materials reside. The author suggests that retrieved debris could be recycled or reused, using the pair of satellites – a stationary one, which beams power to the other, a rover, which in turn would rendezvous with and capture debris. “The calculations show that

the owner of the rover could profitably retrieve 3000 pounds of debris per month while selling it for \$200 per pound.” (Roseman, 1997)

Bd. Design or Calculations and **DRL** has two works within it. The first is “The Potential Role of Space Solar Power in Beginning Large-Scale Commercial Manufacturing in Space” by Mankins (1997), and the second is by [Ellery, et al. \(2008\)](#) who summarize the part of the work relevant to this literature review as follows:

Rather than dealing with technology issues, however, we deal with issues concerning the potential market (the “demand” side) for OOS. We present the case that robotic OOS is not only commercially feasible, but also even more strongly assert that it is essential. We consider in particular the recent high incidence of on-orbit failures in geostationary telecommunications platforms. We present the sobering statistics of such failures, and determine that only OOS can mitigate these and future failures. OOS represents the first space-based commercial opportunity that serves the space industry itself rather than Earth-oriented applications more typical of commercial space activities, and to that end provides the basis for future space infrastructure development. ([Ellery, et al., 2008](#))

Be. Design or Calculations and **Competitive Analysis** combination consists of three works that are not necessarily competitive analysis, but present ideas that could be considered competitive with in-orbit manufacturing. All three are later reviewed in more detail in section 2.3.2 under “Alternatives and Competition”:

- “Research on Design and Structure Dynamics of Variable Topology-Transformable Spacecraft” (Ning, et al., 2010)
- “Design And Dynamics Of Transformable Spacecraft” (Ning, 2012)
- “Output consensus and collision avoidance of a team of flexible spacecraft for on-orbit autonomous assembly” ([Chen, et al., 2016](#))

Bf. Design or Calculations and **Business Case** has a rare, close to full business case addressing a profitable venture related to in-space manufacturing and related to the sale of homes built from off-Earth materials and solar energy. In the author’s words “An initial city of 1,000 condos housing 10,000 workers is constructed from Lunar materials over a ten year period for \$20 billion” (Malpass, 2001). The other publication is NASA’s “On-Orbit Satellite Servicing Study” (NASA, 2010) which is thoroughly examined further in the literature review.

Ca. Developed Technology and **No Business Focus** brings together four works from different fields – two from material processing in space and two related to robotics.

The material processing includes Akishin’s (2001) comprehensive work on effects of space conditions on materials across a variety of material, and Prater’s (2013) study on technologies used for aerospace welding and evaluates their suitability for in-space applications, including processes such as gas metal arc welding, plasma arc welding, gas tungsten arc welding, electron beam welding, brazing, and friction stir welding. It also proposes a mobile friction stir welding unit for in-space structural repair/refurbishment.

The first robotics-related work is Yoshida’s (2015) thorough treatment of the topic, which is also reviewed later in more detail. The second one is Osinowo, et al’s (2012) summary of activities related to Canada’s on-going research and development in space-based robotics, including topics such as “mission architecture, operations concept, and top-level requirements for a light system with

elements from spacecraft proximity operations and docking, small and large manipulator systems, tools for robotic tasks, fuel transfer systems.” (Oshinowo, et al., 2012)

Cb. Developed Technology and Value Proposition

This combination contains a work summarizing the Made In Space, Inc., when it was under contract by NASA to establish an Additive Manufacturing Facility (AMF) on ISS by late 2014 (Dunn, 2013). Another journal article on Flexbus provides additional details and update on the architecture (Seltmeyer, et al., 1998). The most interesting work though is by Dorsey (2012), who suggests a new assembly approach, developed to incorporate:

- Intelligent Precision Jigging Robots
- Electron-Beam welding and low precision weldable structural elements
- Robotic handling/manipulation, operations assembly sequence and path planning

Cc. Developed Technology and Cost Estimate consists of two works involving some of the same authors, Hoyt, et al. (2013a) and Hoyt, et al. (2013b), since both are focused on the SpiderFab concept and are slightly redundant, while providing some differentiation with these elements of interest:

- For phased array radars, it enables order of magnitude increases in gain per stowed volume.
- For the New Worlds Observer mission, construction of a starshade can provide a ten-fold increase in the number of Earth-like planets discovered
- For communications systems, it changes the cost equation for large antenna reflectors, enabling affordable deployment of much larger apertures than feasible with current deployable technologies

Thus studies have performed proof-of-concept level testing of these approaches, demonstrating feasibility in each case and establishing the SpiderFab architecture at TRL-3.

Ce. Developed Technology and Competitive Analysis combines three sources, the first two of which are reviewed more thoroughly in section 2.3.2 under “Alternatives and Competition”:

- “Fabrication and Testing of Self-Deploying Foam Antenna Structures” (Haight, et al., 2006)
- “Advanced Self-Deployable Structures for Space Applications” (Sokolowski & Tan, 2007)
- “Using CubeSat/micro-satellite technology to demonstrate the Autonomous Assembly of a Reconfigurable Space Telescope (AAReST)” (Underwood, et al., 2015)

Cf. Developed Technology and Business Case holds the definitive guide on space power stations by Flournoy (2011) who does a comprehensive review of the topic, including some technology feasibility and commercial viability analysis and provides some cost reduction commentary.

Da. Technology Evaluation/Testing and No Business Focus

In this combination one of the authors, [Rhodes, et al., \(1995\)](#), focuses on verification tests of automated robotic assembly of space truss structures, which has implication on large aperture antennae and other large structures. The other author, Ellery (2014), summarizes a prototyping project focused on a shape memory alloy actuated motor design which demonstrates the feasibility of 3D-printable motors for mechanisms. Then next steps such as electronics through motor controllers, sensory capabilities enabled through quartz and selenium. Separately, the author reviews work performed on constructing a semiconductor junction solar cells from selenium and gold.

Ea. Deployed Technology and No Business Focus consists of three works:

- “Space Stations: Systems and Utilization” is a book that has a comprehensive treatment of all aspects of space stations, including their assembly and maintenance ([Messerschmid & Bertrand, 2013](#)).
- “Enabling Space Manufacturing: An Update From Made In Space” by Dunn (2014) is yet another update on the progress of Made In Space’s 3D printing on the ISS.
- “Wake vacuum measurement and analysis for the wake shield facility free flying platform”, which discusses results that could be relevant to in-orbit manufacturing, but also presents a shield use case in science ([Strozier, et al., 2001](#)).

Eb. Deployed Technology and Value Proposition

Sallaberger (1997) summarizes Canada’s programs related to robotics in space some of which were developing technological capabilities in the areas of:

- Automation of operations, autonomous robotics
- Vision systems, trajectory planning and object avoidance, predictive and preview displays
- Tactile and proximity sensors, and ground control of space robots
- Haptic devices, control via head-mounted displays
- Dynamic characterization of robotic arms

There are two other works in this combination. The first focuses on the benefits of consistent standards for ISS robotic interfaces and highlights emergency repairs versatility of robotic systems beyond their intended design scenarios ([Oghenekevwe, et al., 2009](#)). The second presents an updated NASA roadmap for additive manufacturing in space and includes sample testing techniques and mechanical destructive testing (Werkheiser, 2015).

Fb. Roadmap of Deployed Technology and Value Proposition highlights NASA’s roadmap for in-space fabrication and repairs via 3D printing in microgravity. Specific activities and technologies include qualification and inspection of in-orbit parts using optical scanners, printable small satellites, in-orbit plastic feedstock recycling demonstration, and in-space metals manufacturing process demonstration along with a path forward through 2040 (Johnston, 2014).

Fc. Roadmap of Deployed Technology and Cost Estimate includes two pieces of literature:

- “Robotic assembly and maintenance of future space stations based on the ISS mission operations experience” ([Rembala & Ower, 2009](#)), which is reviewed in more detail later in the literature review.
- “Additive Manufacturing at NASA Marshall Space Flight Center: In-space and For-space Initiatives Additive Manufacturing for Defense and Government Symposium” (Clinton & Morgan, 2015), which has a general 3D printing focus within the space industry and NASA in particular, but does include space-based uses.

Fe. Roadmap of Deployed Technology and Competitive Analysis has just one paper, but it is an important example of the type of work for which this current report is attempting to serve as a foundation or as an auxiliary tool. In it, [Selva & Krejci \(2012\)](#) examine how miniaturization of spacecraft hardware and the Cubesat standards have created the promise to combine the temporal resolution of GEO missions with the spatial resolution of LEO missions and eliminating a traditional trade-off in Earth observation mission design. Also, it includes a thorough review of Cubesat bus technology, and identifies potential limitations and their implications on 17 different Earth observation payloads.

2.2.3 Gaps in Existing Literature

A summary of all use case-related literature is displayed in Figure 2-1. There is a clear gap in the area associated with both higher levels of technology focus and technology maturity and detailed analysis of business dimensions such as costs, market size. The goal of this report is to setup an approach that will serve as a foundation for further research to step on. This refers both to suggesting promising use cases that need and are worth exploring in-depth by space business and economics researchers or for private entities to pursue. Also, the methodology will be able to identify use cases that create high value and therefore technology research on them would be less likely to stall due to lack of interest by industry.

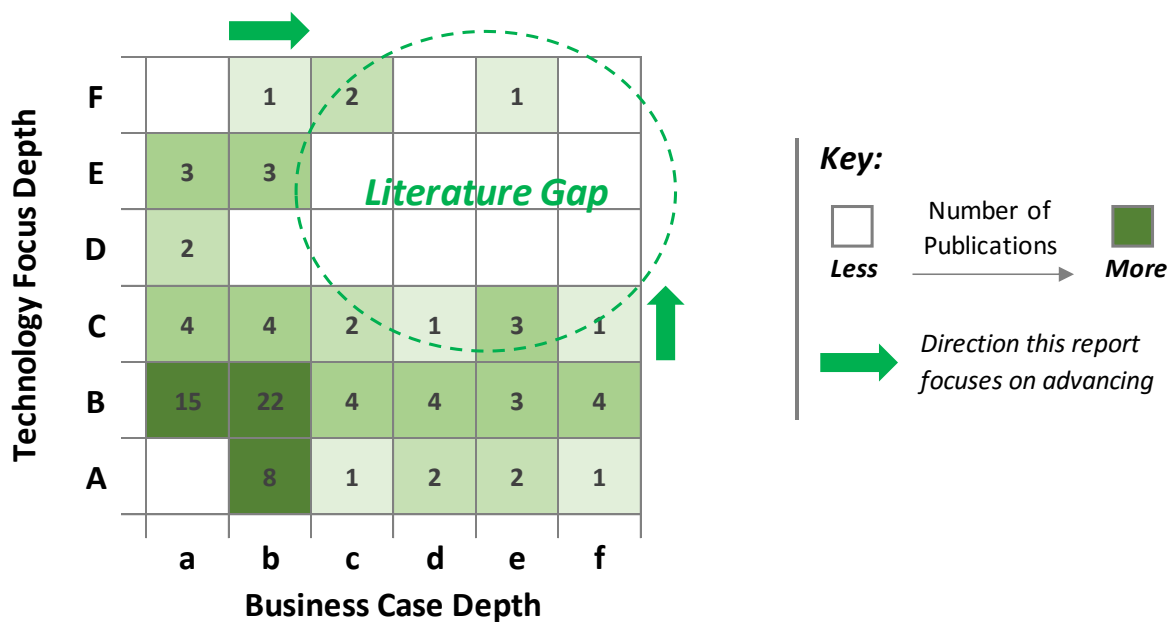


Figure 2-1: Use cases and concepts categorized by depth of technology and business aspects focus
A. Concepts (incl. standards), B. Design or Calculations, C. Developed Technology, D. Technology Evaluation/Testing, E. Deployed Technology, F. Roadmap of Deployed Technology; a. No Business Focus, b. Value Proposition, c. Cost Estimate, d. DRL, e. Competitive Analysis, f. Business Case

2.3 Additional Related and Support Literature

A review of literature that would support analyzing the various aspects of viability of a use case as a business case. These involve topic in technology maturity, economics of the satellite and launch industries, as well as topics such as standards in space technology, alternatives to in-orbit manufacturing, and longer term aspects such as lunar and asteroid mining.

2.3.1 Technology Readiness Level Evolution

Technology Readiness Level (TRL) is an important aspect of assessing technology related to space. Assessing TRL-related literature therefore is key to this study. Within the space industry a TRL of 6 is a critical step and is the “Valley of Death” as argued by Johnson & Mulqueen (2015, p. 680). Guglielmi (2016) corroborates that “TRLs are indeed a necessary tool to talk about technology”. Furthermore, he discusses that TRL 4 are “Application independent”, and TRL5 to TRL9 are application dependent. In particular, TRL5 corresponds to the point at which an accurate cost and time estimate can be

produced for the full development (up to TRL9). A comprehensive study by Peisen (1999) of NASA projects across technologies has revealed an interesting statistics that could be very helpful in projecting TRL progress and is summarized in Table 2-2.

Table 2-2: Statistics for NASA Technologies Making Transition from TRL 1 to TRL 9 – Requiring Enabling or New Technologies (Peisen, et al., 1999)

Years to TRL 9 from TRL:	Technologies Needing Enabling Technologies		Technologies Needing New Products	
	Average	St Dev	Average	St Dev
1	13.2	7.1	17.9	12.5
2	11.4	6.7	16	12.1
3	9.9	5.8	14.8	12.2
4	7.7	5	13.4	12.5
5	5.8	4.5	11.8	12.7
6	5.2	4.3	8.5	6.3
7	3.4	2.8	5.8	4.6
8	1.7	2	2.9	3.6

2.3.2 Economics of Satellite Manufacturing and Deployment

Spacecraft Manufacturing and Satellite Industry

Factors and innovations impacting spacecraft manufacturing on Earth have a direct impact on viability of in-orbit manufacturing. 3D printing is changing the terrestrial space industry as well as rocket engines and other launcher parts get increasingly fabricated using this new technology (Mohon, 2015). Increased production scales on the ground also lead to economies of scales and new technologies such as Software-Defined Radio (SDR) can drive a further space hardware commoditization (Bridges, 2016). Another element of this topic is categorization and typical groupings of satellites within mass, cost, and response time dimensions. For the purposes of the report, the information presented at an ISU lecture by Laufer (2016) is used, presented in Figure 2-2.

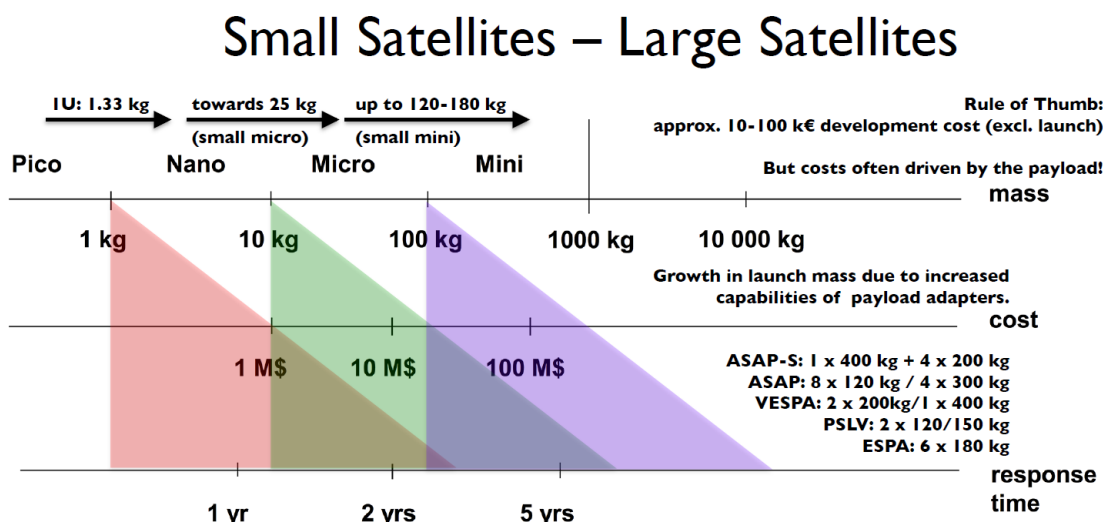


Figure 2-2: Categorization of satellites (Laufer, 2016), based on (Sandau, et al., 2010)

According to Ellery, et al. (2008), GEO services yield revenues of \$13.6 B per year compared with MEO revenues of \$4.0 B per year and LEO with \$1 B per year (as of 2000). Related to that, he presents results of an 18-month study into robotic on-orbit servicing (OOS) dealing with issues concerning the potential market (the “demand” side) for OOS:

We present the case that robotic OOS is not only commercially feasible, but also even more strongly assert that it is essential. We consider in particular the recent high incidence of on-orbit failures in geostationary telecommunications platforms. We present the sobering statistics of such failures, and determine that only OOS can mitigate these and future failures. (Ellery, et al., 2008)

Standards and Standardization

Standards are an important part of the development of a mature industry. As the Cubesat standard has shown they can have a significant impact on propelling an industry. This in part increases competition as well, so it is important to consider. On the other hand, it could provide an advantage to the first-mover that establishes a standard. For example NanoRacks have standardized launches of nanosatellites from the ISS on top of the Cubesat standard itself and have now partnered for 3D printing satellites with Made In Space (Molitch-Hou, 2016). Standards have been part of the assembly of the ISS itself using the docking system across modules relevant to assembly in space (Messerschmid & Bertrand, 2013). Earlier concepts such as the Flexbus (Seltmeyer, et al., 1998) are also an important factor in in-orbit manufacturing considerations.

Important potential new areas for standards include thermal, power, mechanical, and logical or control interfaces. There is a number of proposed standardizations. One example is the iBOSS (Intelligent Building Blocks for On-Orbit Satellite Servicing) full modular and serviceable satellite architecture (Schervan, et al., 2013). It combines on-orbit servicing with a spacecraft's generic modularization. It also aims to create a framework to enable to building large orbital multipurpose platforms by dividing the satellite on subsystem level and creating independent building blocks with standard 4-in-1 interface (mechanical, thermal, power and data). Further work based on iBoss includes work done by Kreisel, et al. (2015) that outlines a generic context of spacecraft modularity and standardization.

Costs

Although this report does not aim to estimate a cost associated with a specific spacecraft within a business case, the high level business case commentary requires some level of understanding of literature on the topic. There is no definitive authority on costs, but there is a number of methods and sources that focus on it. Space Mission Engineering: The New SMAD (Wertz, et al., 2011) provides a detailed cost breakdown structure for a space mission, including spacecraft aspects. It has scalable cost estimating relationships for determining the subsystems on both a launcher and a spacecraft, based on modeling and historical data. Two alternatives to it are the “NASA Cost Estimating Handbook, Version 4.0” (NASA, 2015b) which gives a bottom-up engineering-based cost breakdown structure based on work breakdown structures, and “Guidelines and Metrics for Assessing Space System Cost Estimates” by RAND Corporation (Fox, 2008). A paper by Trivailo et al. (2012) discusses COTS cost estimation methodologies which may be useful for new commercial companies using COTS and previous government-transferred technology for high TRL and/or space qualified systems. Given the broad coverage of costs methods, this report will focus on the foundational methodology and use case analysis that will setup up the development of business cases to the point where these methods can be utilized by future studies.

Alternatives and Competition

There are a number of potential alternatives to solving some of the problems that in-orbit manufacturing is pursuing as value propositions. This includes autonomous self-extending machines (Lipson & Malone, 2002), flexible spacecraft for on-orbit autonomous assembly (Chen, et al., 2016), or even transformable spacecraft (Ning, 2012) where work has been done on designing and examining architectures and dynamics of such spacecraft. The biggest threat to in-orbit manufacturing though is possibly self-deploying structures that are an alternative to large aperture and various other use cases. These are a strong focus of research and technology development with fabrication (Earth-bound) and testing of self-deploying foam antenna structures explored by Haight (2006). Furthermore, “cold-hibernated elastic memory structures technology is one of the most recent results of the quest for simple, reliable, and low-cost self-deployable structures” as argued by Sokolowski & Tan (2007) who also discuss its space applications, including advanced solar-sail structural concepts. Beyond all of these alternatives with threat potential, concepts such as inflatables, spacecraft servicing, disposable spacecraft, and recycling could be viewed as both alternatives and opportunities, and are addressed in other parts of this report.

2.3.3 Lunar and Asteroid Mining

There is good coverage of literature on the topic of Lunar and asteroid mining. It spans methods of processing lunar regolith and in-situ resources to prepare them for utilization, including in 3D printing such as the studies by Taylor & Meek (2005) and Balla (2011). The former offers a detailed look at microwave sintering of lunar soil and the latter is a demonstration on direct laser fabrication of lunar regolith parts. The broader topic of asteroid mining is exhaustively covered by the ASTRA project (ISU SSP, 2010a). Nevertheless, it is a long-term prospect that is out of scope since the first steps in would be in 2025 at the earliest following the plans of the companies Planetary Resources and Deep Space industries (Wall, 2015). Lunar mining is also explored by the space academic community, but is often regarded as a long term perspective and an area related to space colonies (Michio, et al., 2014), which is beyond the scope of this report. Overall, it is a consideration for the longer term future.

2.4 Concept-of-Operations and Facilities

There are several existing or planned concepts of operation when it comes to in-orbit manufacturing. Made In Space, Inc. has deployed and tested a 3D printer on the ISS and proposed concepts focusing on manufacturing in space and in-orbit in particular (Molitch-Hou, 2016). The company’s recently announced other initiative, Archinaut is “the first additive manufacturing, aggregation, and assembly of large and complex systems in space without astronaut extravehicular activity” (Made In Space, 2016). This was preceded by Tethers Unlimited’s similar concept – SpiderFab (Hoyt, et al., 2013a) that focuses on introducing an architecture process for in-orbit construction of kilometers apertures. A relatively different approach is undertaken by the Phoenix program of DARPA, which also uses advanced robotics, but is focusing on modular satellite architectures and improved geostationary satellite usefulness, lifespan, and reliability (DARPA, 2016). The common characteristics addressed by all of those concepts are related to new broader industry needs. An earlier study focused on on-orbit servicing also presented several concepts across various orbits and locations (NASA, 2010). Those are partially in-orbit manufacturing based on this report’s definition. This showcases that astrodynamics are an important part of the final concept of operations. Nevertheless, it is a relatively trivial issue that is well understood and examined, for example by Macdonald (2015), but also many others.

Assembly and existing examples of robotics and manipulators are also of key importance as they are at the core of in-orbit manufacturing. Messerschmid & Bertrand (2013) and Yoshida (2015) have

extensive coverage on all activity related to the topic that has been done so far on the ISS, including Canadarm and other robots. Robotic assembly and maintenance of future space stations based on that experience is treated as well by Rembala & Ower (2009). NASA’s On-Orbit Satellite Servicing Study also extensively reviews and analyzes those topics for implications on future robotic missions (NASA, 2010). Its trade space is summarized in Figure 2-3. Beyond those broad studies, there are a few other specific topics uncovered by this review:

- Human and robotic repair of a solar arrays during ISS assembly (Oghenekevwe, et al., 2009)
- Teleoperation strategies for exploring and utilizing resources in space (Potter, et al., 1997)
- Robotic manipulators design for orbit removal of launchers’ stages (Felicetti, et al., 2016)
- Study of capturing non-cooperative spacecraft with a space manipulator in an energy efficient manner (Cocuzza & Cuccato, 2015)

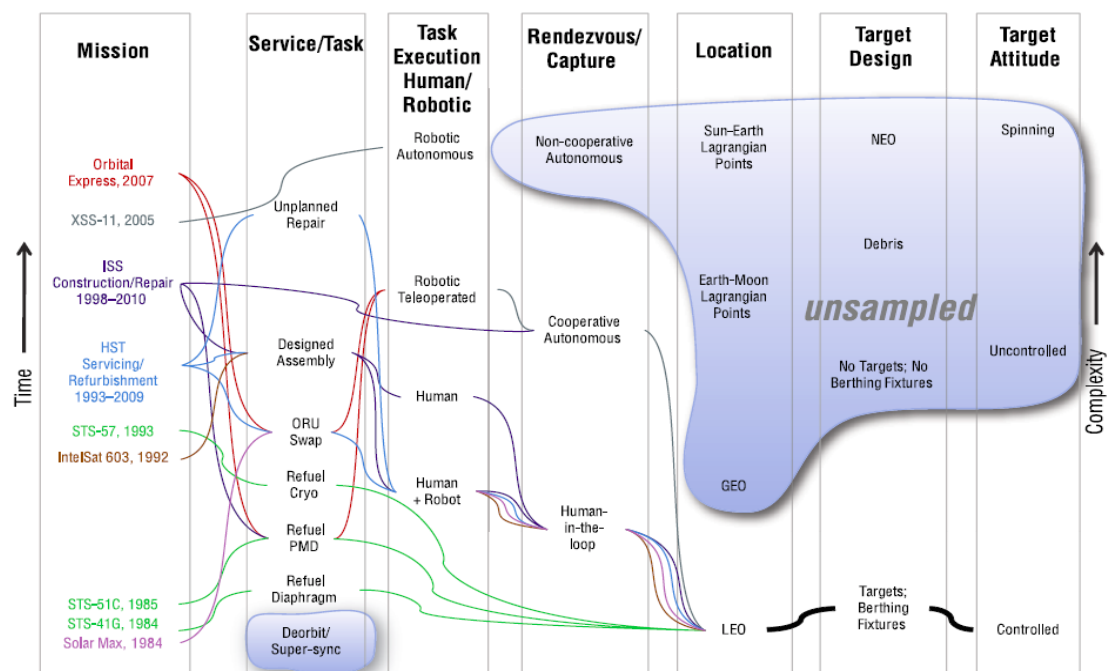


Figure 2-3: Seminal Mission Coverage of the Servicing Study Trade Space (NASA, 2010)

2.5 Literature Review Summary

The literature review has revealed that there is no good assessment methodology for in-orbit manufacturing use cases, prompting a refocus of the report efforts on developing one. Furthermore there is a gap in terms of literature that combines depth in technology examination and evaluation and business case analysis. Although the report is not setting a course to fill that gap, it is going to focus on providing a foundation for further research and analysis to fill the gap and to provide more confidence to both engineering team and industry on what the focal areas should be within the broader in-orbit manufacturing domain. In addition, it has become more clear that on-orbit servicing has many points of contact with the report’s topic and should be incorporated within the value chain since there are any points of contact and overlap, and even synergy.

3. METHODOLOGY

One of the goals of this report is to introduce a helpful new methodology focusing on in-orbit spacecraft manufacturing incorporating both technology and business dimensions. Throughout this methodology decisions are educated by the initial literature review. The classification of the domain in particular relies on mentions collected during the review and fills in gaps if necessary.

Literature also serves to identify attributes and criteria as well as use cases and auxiliary facts. The methodology starts with the spacecraft lifecycle and its definition, placing in-orbit manufacturing's value chain in it. Then the use case classification and categorization sub-methodology is introduced, followed by the prioritization and selection methodology. The concept of operation and business analysis approaches are briefly discussed as well.

3.1 Spacecraft Lifecycle and Spacecraft Manufacturing Value Chains

The spacecraft lifecycle and its elements are defined in Table 3-1. It is educated by the literature review and will serve as the basis for the value chain analysis. The factors incorporated include traditional spacecraft lifecycle, primarily driven by Earth satellite-based industry, as well as emerging elements such as in-orbit or on-orbit servicing and additional proposed or planned activities expanding that lifecycle. Some elements consist of more than one activity that are grouped based on similarity or adjacency in order to simplify the proposed chain and later analysis.

Table 3-1: Spacecraft lifetime element descriptions utilized by the report

Spacecraft Lifecycle Element	Description
Design	Design of the spacecraft and all its subsystems, including designing elements for fabrication by 3D printing
Fabrication	The producing of components by various methods, including 3D printing or by welding, furnaces, smelters, etc.
Assembly	The process of combining fabricated or pre-fabricated components into subsystems or entire spacecraft or direct complex 3D printing
Integration	Bringing together subsystems into one system and ensuring that the subsystems function together as a system, including software; also includes potential processes associated with activities before or after upgrades, deliberate disintegration, and re-integration of subsystems
Testing/ Verification & Qualification	Performing tests and follow-up activities to ensure the spacecraft functions properly, and product assurance
Launch	The delivery of mass, components, or entire spacecraft to orbit (e.g. LEO or GEO)
Deployment	Operationalizing a spacecraft by delivering it to its final desired orbit and starting nominal functions
Maintenance	Activities such as re-fueling, updates of software, and reconfiguration as necessary
Upgrade/Repair	Upgrading involves substituting subsystems with newer or more capable ones as desired by the owner or adding capability; Repair involves similar activities addressing an issue or damage with the spacecraft
Recycling/Repurposing	Taking apart a subsystem of a functioning or dead spacecraft and re-using it in some fashion, or modifying a part or the entire spacecraft to serve a new purpose
De-orbiting/ Decommissioning	Removing the spacecraft from its orbit and bringing it down to Earth B4:C15 in a safe fashion (with or without it surviving) or parking it in a safe orbit and seizing active functionality

3.2 Use Case Categorization Attributes

Each use case is defined by five key attributes identified during the research phase of this study. Namely, these are:

1. Value Chain
2. Spacecraft Types (addressed)
3. Applications
4. Subsystems (and potential elements)
5. Value Propositions

These attributes are the basis for the next sections and will serve to classify and analyze technology maturity and business viability.

3.2.1 In-orbit Manufacturing Value Chain

In this value chain and in the definitions the report departs from the usual set of definition popular among some parts of the space community. In-orbit manufacturing goes beyond additive manufacturing and includes many other elements. Sometimes it incorporate on-orbit services (past deployment – see Figure 3-1).

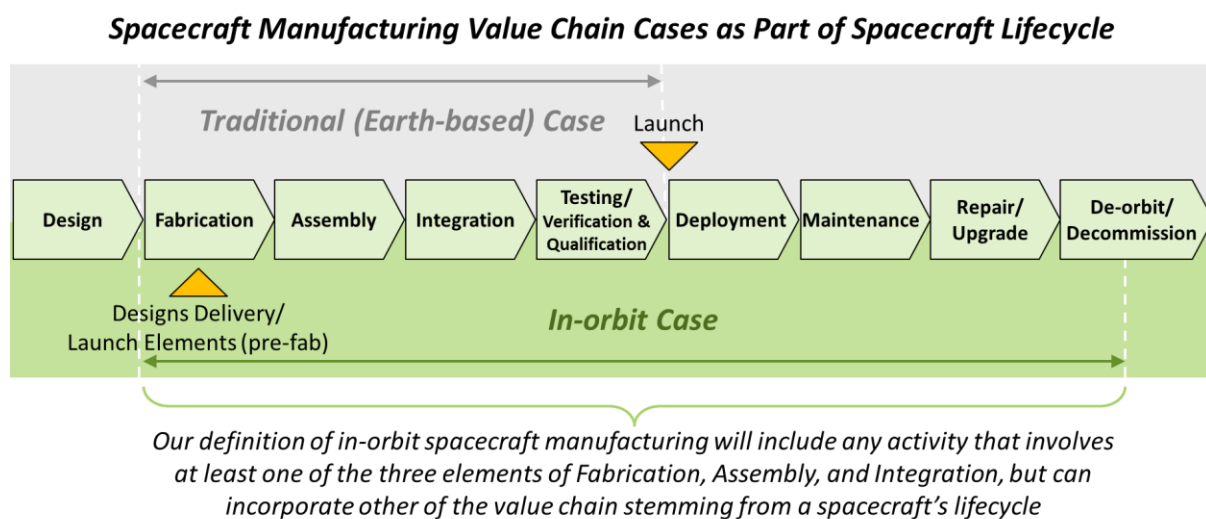


Figure 3-1: Spacecraft manufacturing value chain - traditional and in-orbit case

3.2.2 Spacecraft Types

Spacecraft types are based on the ones observed in literature whether they currently exist or not and are sometimes aggregated or re-labelled to make them more relevant for in-orbit manufacturing. For example GEO/Molnya satellites are split from Traditional Satellites as they pose as specific set of challenges and opportunities for in-orbit manufacturing. Other spacecraft, the category that encompasses far-reaching long-term concepts such as orbital settlements and planetary-scale structures is included for completeness, but is out of scope of the analysis.

Table 3-2: Spacecraft type attribute cases and descriptions utilized by the report
Other Spacecraft is in gray since it is out of the scope but is left there for methodology completeness

Spacecraft Type	Description
Nanosatellites	Primarily Cubesats, but also any other standard or non-standard satellites in the 1-10 kg bracket or that order of magnitude
Serial Production Satellites	Small standardized satellites produced in large numbers; currently does not exist, but recent interest in constellations could drive it
Traditional Satellite	Typical LEO and MEO satellites that are prevalent in the present, e.g. navigation or telecommunication satellites
Custom Satellite	Single unit or highly customized satellites, for example space telescopes or orbital tugs
GEO/Molnya Satellites	Geosynchronous orbit and highly-elliptical orbit satellites with higher launcher service requirements and higher value
Large-aperture Spacecraft	Oversized spacecraft that cannot fit in present day or future launchers design to be in Earth orbit, e.g. large scale telescopes
Swarm Spacecraft	Spacecraft smaller than Nanosatellites that fly in coordinated "swarms" or constellations
Space Stations	Include ISS-like structures as well as other new applications such as solar power stations (manned or unmanned)
Interplanetary	Spacecraft designed to travel outside of Earth's orbit; although imprecise, within the report, this includes anything beyond GEO
Other Spacecraft	Includes Orbital Settlements, Space Elevators, and Planetary-scale Structures that out of the time horizon scope of the project

3.2.3 Subsystems

Subsystems are based on Technische Universität München’s classification (2011) and are enhanced with the variety of possible elements and components that have been detected in the literature review. These include some that are feasible for in-orbit manufacturing near term and some that are not. This will be analyzed in the next chapter.

Spacecraft Subsystems and Elements Appropriate for In-Orbit Manufacture

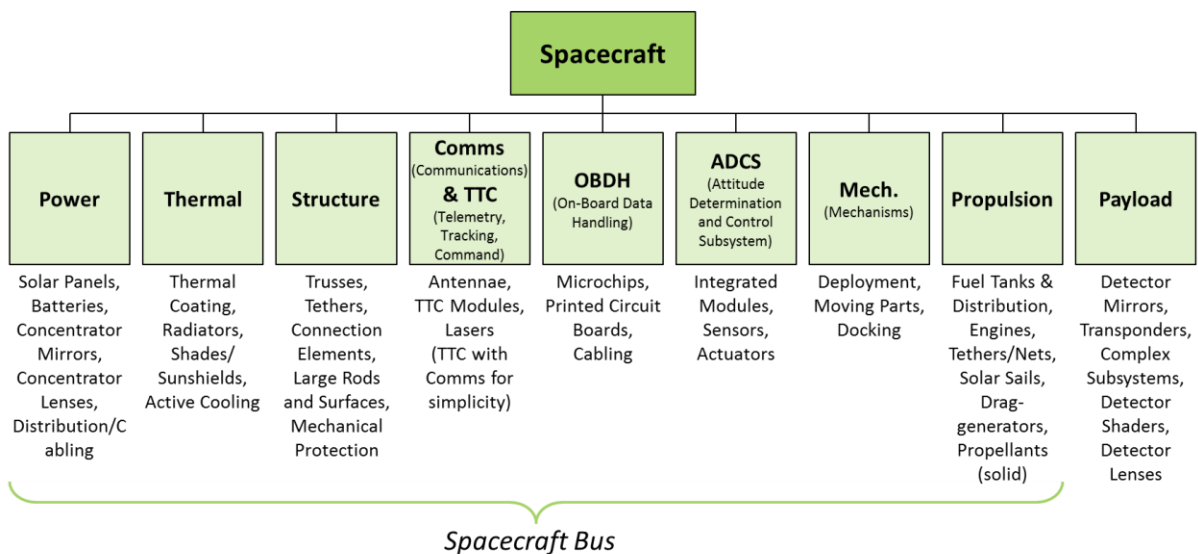


Figure 3-2: Spacecraft subsystems and elements attribute cases utilized by the report

3.2.4 Applications

Applications are also defined based on all possible cases detected in literature, including some future ones. These can be theoretically applied across spacecraft types, but in reality have certain combinations that are valuable. Those combinations are identified and analyzed later after various filters to eliminate easy to eliminate cases are applied. The set of seventeen applications considered in this report are detailed in Table 3-3. Some of them bare similarities at a high level, but are kept separate due to in-orbit spacecraft manufacturing concerns and differentiation.

Table 3-3: Spacecraft application attribute cases and descriptions utilized by the report

Application	Description or Examples
Scientific - General	ISS (space stations); Using solar sails for propelling science missions (interplanetary); scientific Cubesat missions; excludes telescopes
Scientific - Telescopes	Distinct case highly relevant to large structure in space and therefore in-orbit manufacturing, so has distinct category
Earth Observation	Weather, imagery, surveillance; observations mostly in the visible part of the spectrum using optical instruments
Remote Sensing	Observing Earth primarily with non-visual part of the spectrum; excludes Earth Observation as described above (typically part of it)
Telecommunications	Deep space transcieving (large aperture); e.g distributed communicaiton (swarms, regular telecommunications)
TV/Radio Transmission	Primarily GEO satellites focused on broadcasting TV signal over a fixed area on Earth
Navigation	Global positioning systems and other spacecraft that assist in navigation on Earth or beyond
Transportation (space)	Refers to transportation within space, e.g. space tugs (orbital) or large truss architectures for interplanetary travel or cargo delivery
De-orbiters	Small spacecraft that identify dead satellites and intercept them to de-orbit together or large spacecraft that assists others
Space Launch	Examples include tethered launch, tethered propellantless orbital transport, laser propellers for interplanetary spacecraft
Sunlight Shades	Shade provision for either space telescopes or blocking sunlight from reaching the Earth (e.g. to lower global temperatures)
Sunlight Lenses	Examples include illuminators providing light on Earth, or assisting power collection in space
Sunlight Mirrors	Examples include illuminators providing light on Earth, or assisting power collection in space
Solar Power Station	Future application envisioned since the dawn of the Space age, collects and transmits power to Earth or to other spacecraft
Hotels/Habitats	Tourism application or a living space (even residence) for a small number of people
Industrial Facilities	Facilities such as extractors of material mined on asteroid or the machines that extracted them; include in-orbit manufacturing facilitiw
Large-scale Stations	For example, artificial gravity large rotating (space station)

3.2.5 Value Propositions

Value propositions are also based on the broader literature review and might not all be applicable during the analysis portion of the report, but are included for the completeness and future applicability of this framework. The broad set is detailed in Table 3-4, but within it there are four general categories. The first is cost savings, which is a typical desire of any industry. The second is circumvention of Launch Constraints such as mass and volume restrictions (with value beyond simple cost savings). The third is Time, in the context of shortening processes or prolonging spacecraft lifetime. The fourth is the enablement of New Capabilities that transform an industry or provide an entirely new modes of operation.

Table 3-4: Value proposition attribute cases and descriptions utilized by the report

Value Proposition (incl. Needs and Pain Points)		Description
Costs Savings	S/C Launch Test Savings	Testing related to vibrations and structures that need to withstand a launch in assembled form do not need it anymore, saving capital
	Lower Volume/Mass Constraints (launch-related)	Financial savings from volume/mass constraints lowering (launch-related), excludes technology benefits
	Late Design Changes	Ability to make design changes further in the process of a mission or a satellite launch
	Economies of Scale (launch mass)	The ability of the in-orbit manufacturer to use larger launchers at better prices to lift a large amount of material or pre-fab elements
	Economies of Scope (launch and development)	Economies of scope related to launch and to developing a spacecraft;
	Decreased S/C Replacement Need	The ability to salvage beyond its replacement time or continually extending its life in some fashion (e.g. raising its orbit)
	Decreased S/C Complexity	Lower cost due to decreased complexity of eliminating certain systems from the initial ground-part spacecraft construction
Launch Constraints	Large Aperture Elements	Examples include limits imposed by standards such as Cubesat that can be a limitation on the spacecraft design
	Mass Constraints Circumvention	Lowering the number of systems or components that is launched allows the spacecraft to fit within a launcher mass constraints
	Testing Availability (not expenses)	Lack of availability of facilities to the spacecraft owners or manufacturers (relevant in smaller projects or in test time shortage)
Time	Time to orbit - responsiveness	How quickly can the customer's spacecraft be deployed and whether it is improved by in-orbit manufacturing
	Increased S/C Lifespan	Extension of the useful life of a satellite by refueling, repairing or renewing a satellite in any shape or form
New Capabilities	Payload-driven Value Props	Combined category holding value propositions arising from manufacturing payloads in-orbit that are otherwise impossible
	Increased S/C Resilience	Better spacecraft integrity and less likelihood of failures; preventive measures or benefits
	Improved S/C Usefulness/ Upgrade/Repurposing	Improvement or exploitation of the spacecraft by the in-orbit manufacturer either salvage parts of it
	New Revenue Streams	New revenue unlocked for the customer of in-orbit manufacturers that was previously impossible to exploit

3.3 Use Case Identification and Generation

The existing used case identification was performed using the categories in the classification devised in the previous sections and the literature review we identify existing cases. Some of the cases have defined using permutations of the comprehensive set of attributes, others had to be filled in using the categories described in various parts of this section and identifying viable gaps using preferred characteristics. In addition some of them were either a product of or further validated by conversations with industry specialists (mostly in the domain of nanosatellites). The set was then recorded in a database format for sorting and initial pre-filtering.

3.4 Use Case Filtering, Prioritization, and Selection Criteria

Using a number of filters to reduce use cases using easy rule of thumbs, the list was then to be shortened to viable combinations of Spacecraft Type, Application, and Subsystem. Then use case scores with various weights of where a use case falls in the 2x2 matrices generated using the dimension in Figure 3-3. The scores can be 1 for Low, 2 for Medium, and 3 for High along each dimension. Then the individual dimension scores are multiplied within each 2x2 matrix to create a geometric scale in order to separate best cases and create a distinguishable differentiation.

Dimension A		Dimension B	
Volume (High=Good / Low=Bad)	VS	Value (High=Good / Low=Bad)	
New Technology Risk Tolerance (High=Good / Low=Bad)	VS	Average TRL (High=Good / Low=Bad)	
Competition Barriers (High=Good / Low=Bad)	VS	Demand Readiness Level (High=Good / Low=Bad)	
Sustainability of Business Model (High=Good / Low=Bad)	VS	Market Opportunity (High=Good / Low=Bad)	

Figure 3-3: Dimension combinations of the 2x2 matrices for use case scoring

The various dimensions detailed in figure 3-3 will also be used for a preliminary filtering using heuristics and simple scoring, e.g. of adding up number of applications or spacecraft addressed to select an initial shorter list of the thousands of combinations and iterations between all the attributes.

Long-term factors such as raw material supply chain and processing from in situ resources in space as well as hard to incorporate aspects of costing into this methodology are out of scope of this analysis. This is done since the methodology prescribed here is aimed at producing in a quick and simple way potential prospects that would be then subjected to these factors in later works.

3.5 Business Case Generation

Once there is a short list of use cases and they are run through the prioritization, the resulting even shorter list is examined for complementarity and use case close to each other are put in a single business case. This is done in five major steps, some of which were covered in previous sessions. The steps are described in Figure 3-3. In summary, they include a classification and landscape mosaic (step 1), pre-filtering (step 2), use case identification and generation (step 3), ranking and filtering (step 4), and prioritization and selection (step 5).

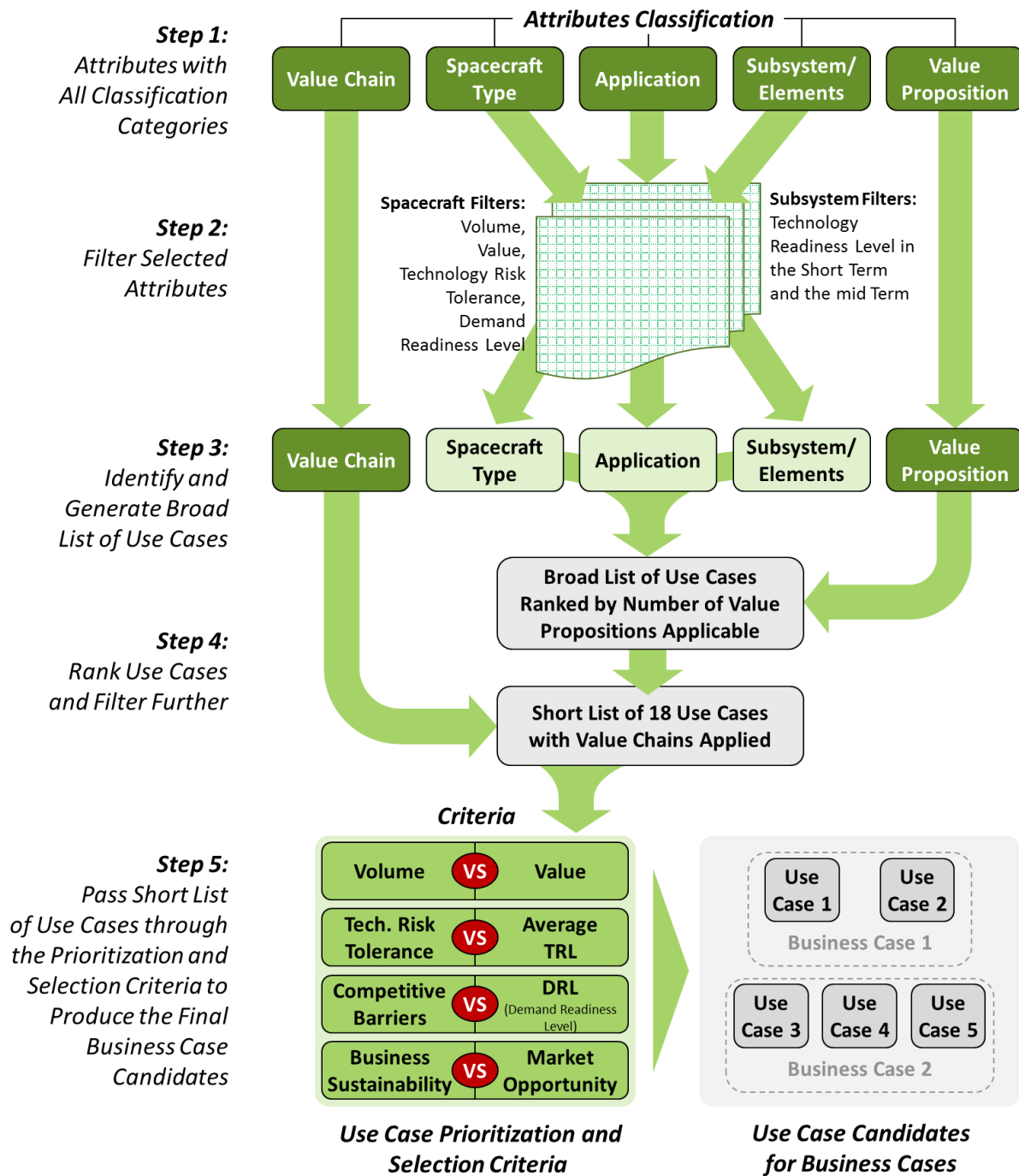


Figure 3-4: Five-step process of generating a preliminary set of business cases

3.6 Preliminary Business Case Analysis

The preliminary business case analysis is based on a Strength, Weaknesses, Opportunities, and Threats (SWOT) analysis. The combined strengths of the attributes of the use cases incorporated in a business case are listed, then threats in terms of alternatives and competition are discussed. Finally, the combined opportunity is commented at a high level.

The elements that are ignored and out of scope are, again, raw material supply chain and processing of resources from and in space as well as key cost aspects. Within the latter, current trends and dynamics are assumed to hold within the short term which in this report includes the near to mid-term. A list of key further questions and recommendations is provided for further consideration in next steps of developing a more complete business case.

3.7 Concept-of-Operations Design Approach

Concept of operations analysis follows closely the methodology offered for on-orbit servicing by NASA’s On-Orbit Satellite Servicing Study (NASA, 2010), in particular its Servicing Study Trade Space Regions, but are selectively used here. These are the focal concepts for and are expanded further with the resulting set summarized in Table 3-5.

Table 3-5: The tradespace for Fabrication, Assembly, and Integration with each elements covered by the set of options

<i>Location</i>	<i>Transport/ Deployment</i>	<i>Operation Approach</i>	<i>Control Type</i>	<i>Functionality Type</i>
LEO - Sun-synchronous	Re-usable vs Disposable transports	In-situ	Robotic/ Autonomous	Single-purpose
LEO - Polar orbit	Space Tugs (chemical, electric ion, etc.)		Robotic/Tele-operated	
LEO - Cubesat-optimized	Launchers (Earth, Moon, orbital)	En Route	Manned vs Unmanned	Multi-purpose
LEO - ISS adjacent	Capture Systems		Manned Indirectly/ Teleoperated on board ISS)	
MEO	Mass Drivers (orbital)	At Destination	Manned and On Board ISS (or other space habitats) - IOSM/ Processing	Modular/ Platform
HEO/Molniya	Tether Systems			
GEO	Solar Sails			
GTO				

4. RESULTS AND ANALYSIS

4.1 Broad Set of Use Cases and Preliminary Filters

Key definitions and inputs throughout the analysis are based on literature review findings and original logic. An initial broad laundry list case of use cases was considered (full list might be an Appendix A-1) These were subjected to initial filtering based on Table 4-1 starting with S/C risk tolerance. Further, Any S/C beyond the short-term demand horizon were eliminated in the further analysis except swarm spacecraft. Spacecraft-Application combinations were also identified and summarized in Table 4-2.

Table 4-1: Key evaluation elements associated with the Spacecraft category attribute

Spacecraft Category	Risk Tolerance	Market		Demand/Market Horizon		
		Volume	Value	Short Term	Mid Term	Long Term
Nanosatellites	High	High	Low	✓	✓	
Serial Production Satellites	Medium	High	Medium	✓	✓	✓
Traditional Satellite	Medium	Medium	Medium	✓	✓	
Custom Satellite	Low	Low	Medium	✓	✓	✓
GEO/Molnya Satellites	Low	Medium	High	✓	✓	✓
Large-aperture Spacecraft	Low	Low	High		✓	✓
Swarm Spacecraft	High	High	Low		✓	✓
Space Stations	Low	Low	High		✓	✓
Interplanetary Spacecraft	Low	Low	High		✓	✓
Other Spacecraft	Low	Low	High			✓

Table 4-2: Spacecraft categories and associated applications attributes based on literature

Spacecraft Category	Application																	
	Scientific - General	Scientific - Telescopes	Earth Observation	Remote Sensing	Telecommunications	TV/Radio Transmission	Navigation	Transportation (space)	De-orbiters	Space Launch	Sunlight Shades	Sunlight Lenses	Solar Mirrors	Solar Power Station	Hotels/Habitats	Industrial Facilities	Large-scale Stations	
Nanosatellites	✓	✓																
Serial Production Satellites		✓		✓			✓											
Traditional Satellite		✓	✓	✓		✓												
Custom Satellite	✓						✓	✓										
GEO/Molnya Satellites		✓	✓	✓	✓													
Large-aperture Spacecraft	✓	✓	✓	✓				✓	✓	✓	✓							
Swarm Spacecraft	✓			✓														
Space Stations	✓												✓	✓	✓	✓		
Interplanetary Spacecraft	✓	✓					✓								✓			
Other Spacecraft*	✓						✓	✓					✓	✓	✓			

* Includes Orbital Settlements, Space Elevators, and Planetary-scale Structures that out of the time horizon scope of the project

Table 4-3: Spacecraft subsystem and potential elements attributes with associated TRL levels in the Short-Term and Mid-Term case with spacecraft type and application combinations analysis for the ones with high enough TRL levels (in bold) to be considered for further analysis

Note that subsystem elements without the capability to reach the needed TRL of 7-9 in at least one of the time periods are omitted in the right-side analysis.

Subsystem and Potential Elements		TRL Case (Short-Term)			TRL Case (Mid-Term)			Spacecraft Type and Application													
		Pre-fabricated	3D Printed/AM	Assembly/Integration	Pre-fabricated	3D Printed/AM	Assembly/Integration	Nano-satellites		Serial Production			Traditional Satellite			GEO/Molnya Satellites			Swarm Space-		
								Scientific - General	Earth Observation	Earth Observation	Telecommunications	De-orbiters	Earth Observation	Remote Sensing	Telecommunications	Navigation	Earth Observation	Remote Sensing	Telecommunications	TV/Radio Transmission	Scientific - Telescopes
Power	Solar Panels	7-9	3	7-9	7-9	5-6	7-9	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Batteries	7-9	n/a	1-2	7-9	n/a	5-6														
	Concentrator Mirrors	5-6	4	5-6	7-9	5-6	7-9														
	Concentrator Lenses	n/a	4	n/a	n/a	5-6	n/a														
	Distribution/Cabling	7-9	3	3	7-9	5-6	5-6														
Thermal	Thermal Coating	7-9	3	5-6	7-9	5-6	7-9													✓	✓
	Radiators	7-9	4	7-9	7-9	5-6	7-9	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Shades/Sunshields	7-9	4	5-6	7-9	5-6	7-9	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
	Active Cooling	4	n/a	5-6	5-6	n/a	7-9														
Structure	Trusses	7-9	5-6	7-9	7-9	7-9	7-9	✓				✓						✓	✓		
	Tethers	7-9	3	5-6	7-9	5-6	7-9	✓													
	Connection Elements	7-9	4	7-9	7-9	5-6	7-9	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Large Rods and Surfaces	7-9	4	7-9	7-9	5-6	7-9				✓	✓					✓	✓			
	Mechanical Protection	7-9	4	5-6	7-9	5-6	7-9														
Comms & TTC	Antennae	7-9	5-6	7-9	7-9	7-9	7-9	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	TTC Modules	7-9	3	3	7-9	5-6	5-6														
	Lasers	1-2	n/a	3	5-6	n/a	5-6														
OBDH	Microchips	7-9	4	5-6	7-9	5-6	7-9	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Printed Circuit Boards	7-9	4	5-6	7-9	5-6	7-9	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Cabling	7-9	4	5-6	7-9	5-6	7-9	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
ADCS	Integrated Modules	7-9	n/a	3	7-9	n/a	5-6														
	Sensors	7-9	3	4	7-9	5-6	5-6														
	Actuators	7-9	3	3	7-9	5-6	5-6														
Mech.	Deployment	7-9	1-2	5-6	7-9	5-6	7-9	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Moving Parts	7-9	3	5-6	7-9	5-6	7-9	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Docking	3	1-2	3	5-6	5-6	5-6														
Propulsion	Fuel Tanks & Distribution	7-9	4	5-6	7-9	5-6	7-9	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Engines	7-9	3	4	7-9	5-6	5-6														
	Tethers/Nets	3	1-2	5-6	5-6	5-6	7-9														
	Solar Sails	5-6	3	5-6	7-9	5-6	7-9	✓			✓				✓	✓	✓	✓			
	Drag-generators	5-6	3	5-6	7-9	5-6	7-9	✓			✓										
	Propellants (solid)	5-6	3	4	7-9	5-6	5-6														
Payload	Detector Mirrors	5-6	4	5-6	7-9	5-6	7-9		✓	✓		✓			✓						
	Transponders	7-9	4	5-6	7-9	5-6	7-9				✓						✓	✓		✓	
	Complex Subsystems	n/a	n/a	3	n/a	n/a	5-6														
	Detector Shades	7-9	4	5-6	7-9	5-6	7-9		✓	✓		✓			✓						
	Detector Lenses	n/a	4	5-6	n/a	5-6	7-9														
Entire Satellites		5-6	3	1-2	7-9	5-6	5-6														

After a prioritization based on TRL following Table 2-2 statistics, and looking at the technology availability and market maturity matches, summarized in Table 4-3, we applied the value proposition scores (sum of all value propositions addressed with each having the value of 1). That produced the short list of top 18 cases in Table 4-4.

Table 4-4: Short list of filtered use cases ready for prioritization and selection procedures

F=Fabrication, *A*=Assembly, *I*=Integration, *D*=Deployment, *R*=Repair, *U*=Upgrade, *RR*=Recycle/Repurpose

Use Case #	Use Case Name	Spacecraft Types	Applications	Subsystems	Value Chain(s)	Value Proposition(s)
1	End-to-End Trusses for Science Cubesats	Nanosatellites	Scientific - General	Trusses	A>I>D F>A>I>D +RR?	S/C Launch Test Savings, Lower Volume/Mass Constraints (launch), Late Design Changes, Economies of Scale, Decreased S/C Complexity, Large Aperture Elements, Mass Constraints Circumvention, Testing Availability, Increased S/C Resilience
2	End-to-End Antennae for Science Cubesats	Nanosatellites	Scientific - General	Antennae	A>I>D F>A>I>D +RR?	S/C Launch Test Savings, Lower Volume/Mass Constraints (launch), Late Design Changes, Economies of Scale, Decreased S/C Complexity, Large Aperture Elements, Mass Constraints Circumvention, Testing Availability
3	Assemble Radiators for Science Cubesats	Nanosatellites	Scientific - General	Radiators	A>I>D	S/C Launch Test Savings, Lower Volume/Mass Constraints (launch), Late Design Changes, Economies of Scale, Decreased S/C Complexity, Large Aperture Elements, Mass Constraints Circumvention, Testing Availability
4	Assemble Radiators for EO Cubesats	Nanosatellites	Earth Observation	Radiators	A>I>D	S/C Launch Test Savings, Lower Volume/Mass Constraints (launch), Late Design Changes, Economies of Scale, Decreased S/C Replacement Need, Decreased S/C Complexity, Large Aperture Elements, Mass Constraints Circumvention
5	Assemble Solar Panels for Science Cubesats	Nanosatellites	Scientific - General	Solar Panels	A>I>D	S/C Launch Test Savings, Lower Volume/Mass Constraints (launch), Late Design Changes, Economies of Scale, Decreased S/C Complexity, Large Aperture Elements, Mass Constraints Circumvention, Testing Availability
6	Assemble and Upgrade Solar Panels for EO GEO S/C	GEO/Molnya Satellites	Earth Observation	Solar Panels	A>I>D>R>U	S/C Launch Test Savings, Late Design Changes, Economies of Scale, Decreased S/C Complexity, Large Aperture Elements, Mass Constraints Circumvention, Increased S/C Resilience, Improved S/C Usefulness/ Upgrade/Repurposing
7	Assemble and Upgrade Solar Panels for RS GEO S/C	GEO/Molnya Satellites	Remote Sensing	Solar Panels	A>I>D>R>U	S/C Launch Test Savings, Late Design Changes, Economies of Scale, Decreased S/C Complexity, Large Aperture Elements, Mass Constraints Circumvention, Increased S/C Resilience, Improved S/C Usefulness/ Upgrade/Repurposing
8	Assemble and Upgrade Solar Panels for Comms GEO S/C	GEO/Molnya Satellites	Telecommunications	Solar Panels	A>I>D>R>U	S/C Launch Test Savings, Late Design Changes, Economies of Scale, Decreased S/C Complexity, Large Aperture Elements, Mass Constraints Circumvention, Increased S/C Resilience, Improved S/C Usefulness/ Upgrade/Repurposing
9	Assemble and Upgrade Solar Panels for TV/Radio GEO S/C	GEO/Molnya Satellites	TV/Radio Transmission	Solar Panels	A>I>D>R>U	S/C Launch Test Savings, Late Design Changes, Economies of Scale, Decreased S/C Complexity, Large Aperture Elements, Mass Constraints Circumvention, Increased S/C Resilience, Improved S/C Usefulness/ Upgrade/Repurposing
10	End-to-end Antennae for EO Cubesats	Nanosatellites	Earth Observation	Antennae	A>I>D F>A>I>D +RR?	S/C Launch Test Savings, Lower Volume/Mass Constraints (launch), Late Design Changes, Economies of Scale, Decreased S/C Complexity, Large Aperture Elements, Mass Constraints Circumvention
11	End-to-end Antennae for Mass-produced De-orbiters	Serial Production Satellites	De-orbiters	Antennae	A>I>D F>A>I>D>R +RR?	S/C Launch Test Savings, Lower Volume/Mass Constraints (launch), Economies of Scale, Decreased S/C Complexity, Large Aperture Elements, Mass Constraints Circumvention, Increased S/C Lifespan
12	End-to-end Trusses for Mass-produced De-orbiters	Serial Production Satellites	De-orbiters	Trusses	A>I>D F>A>I>D>R +RR?	S/C Launch Test Savings, Lower Volume/Mass Constraints (launch), Economies of Scale, Decreased S/C Replacement Need, Decreased S/C Complexity, Large Aperture Elements, Mass Constraints Circumvention, Increased S/C Lifespan
13	Assemble or Repair Structures for Comms GEO S/C	GEO/Molnya Satellites	Telecommunications	Large Rods and Surfaces	A>I>D>R	S/C Launch Test Savings, Lower Volume/Mass Constraints (launch), Economies of Scale, Decreased S/C Replacement Need, Large Aperture Elements, Increased S/C Lifespan, Increased S/C Resilience
14	Assemble or Repair Structures for TV/Radio GEO S/C	GEO/Molnya Satellites	TV/Radio Transmission	Large Rods and Surfaces	A>I>D>R	S/C Launch Test Savings, Lower Volume/Mass Constraints (launch), Economies of Scale, Decreased S/C Replacement Need, Large Aperture Elements, Increased S/C Lifespan, Increased S/C Resilience
15	Assemble Radiators for Mass-produced Comms S/C	Serial Production Satellites	Earth Observation	Radiators	A>I>D	S/C Launch Test Savings, Lower Volume/Mass Constraints (launch), Economies of Scale, Decreased S/C Replacement Need, Decreased S/C Complexity, Large Aperture Elements, Mass Constraints Circumvention
16	Assemble Radiators for Mass-produced EO S/C	Serial Production Satellites	Telecommunications	Radiators	A>I>D	S/C Launch Test Savings, Lower Volume/Mass Constraints (launch), Economies of Scale, Decreased S/C Replacement Need, Decreased S/C Complexity, Large Aperture Elements, Mass Constraints Circumvention
17	Assemble to Repair Radiators for EO Cubesats	Serial Production Satellites	De-orbiters	Radiators	A>I>D>R	S/C Launch Test Savings, Lower Volume/Mass Constraints (launch), Economies of Scale, Decreased S/C Replacement Need, Decreased S/C Complexity, Large Aperture Elements, Mass Constraints Circumvention
18	Assemble to Repair Radiators for Mass-produced De-orbiters	Nanosatellites	Earth Observation	Solar Panels	A>I>D>R	S/C Launch Test Savings, Lower Volume/Mass Constraints (launch), Late Design Changes, Economies of Scale, Decreased S/C Complexity, Large Aperture Elements, Mass Constraints Circumvention

4.2 Evaluation of Use Cases

Combinations of various use case categorizations with value dimensions from filtering, prioritization and selection mechanisms, e.g. Spacecraft types vs. Volume, Value, New Tech Tolerance, etc. This was Low-Mid-High allocations and is presented in Figure 4-1, which has symbolic quadrants. Full scoring is available in Appendix A-1.



Figure 4-1: Results of the use case selection and prioritization methodology applied to the short list of 18 use case identified previously (see list above)

4.3 Short-list Use Cases Prioritization and Business Cases

After steps 1 through 4 of the methodology described in subsection 3.5 was applied, six use cases float to the top of the prioritized list. Those selected use cases are:

1. End-to-End Trusses for Science Cubesats
2. End-to-End Antennae for Science Cubesats
3. End-to-end Antennae for EO Cubesats
4. Assemble and Upgrade Solar Panels for EO GEO S/C
5. Assemble and Upgrade Solar Panels for Comms GEO S/C
6. Assemble or Repair Structures for Comms GEO S/C

There is a natural grouping of the first and last three and many synergies, so two preliminary business cases are generate below for further analysis and to suggest what key areas of further research and studies would be needed to develop them in to proper business cases.

4.4 Preliminary Business Cases

A brief descriptions of each business case is provided and is followed by a high-level Strengths, Weaknesses, Opportunities, Threats (SWOT) analysis is performed on them with key highlights from the information available so far from the report.

4.4.1 Preliminary Business Case 1: Nanosatellites Trusses and Antennae in LEO

Assembly of prefabricated components of antennae and trusses in the short term and 3D printed/fabricated components in the mid-term, primarily for LEO nanosatellites.

- **Strengths:** high volume, easy proof-of-concept roadmap with nanosatellites, higher TRLs for the subsystem elements in question
- **Weaknesses:** small value per transaction, intense sales process involving more potential customers; no direct overhead contact with facility imposes additional limits on teleoperation
- **Opportunities:** ability to expand scope more in the modular approach and add 3D fabrication in the mid-term to serial production small satellites
- **Threats:** microlauncher services, decreasing launch costs minimizing value add for customers, deployable antennas can suddenly substitute the entire case except for truss manufacturing

Additional key further questions and recommendations for further consideration in next steps of developing a more complete business case include:

- Cost comparisons between pre-fabrication and fabrication in-orbit
- Inventory analysis on needs of required parts, supply chain and logistics
- Specific LEO orbit, level of tele-operation, automation or manned intervention requirements
- Future long term access to raw materials trade space and analysis from Earth or space

4.4.2 Preliminary Business Case 2: GEO Satellite Solar Panels and Structure Repair

GEO satellite servicing with an additional focus on assembly of solar panels, and structures as well as repairs (possible general, if robotics allows it).

- **Strengths:** high value per customer
- **Weaknesses:** low volume, likely high initial capital costs, high latency for tele-operators
- **Opportunities:** ability to serve the entire GEO segment with minimum propulsion necessary
- **Threats:** modular spacecraft, improved transformation spacecraft

Additional key further questions and recommendations for further consideration in next steps of developing a more complete business case include:

- Analysis of existing GEO satellites state and needs or pain points
- Future long term access to raw materials trade space and analysis from Earth or space
- Potential for recyclability and refurbishments of graveyard orbit spacecraft

4.5 Potential Concept-of-Operations Designs

From the two business cases, “Business Case Analysis 1: Nanosatellites Trusses and Antennae in LEO” has higher chances of also serving as a proof of concept since it addresses spacecraft among which, there are on average more high technology risk tolerance customers. Therefore the concept of operation is design for that case. In order to further improve this analysis, synergies arising from some of the top use cases that were filtered out should also be considered if they can be automatically addressed by a certain setup. This would lift up some business cases more than others (e.g. base business case is antennae for cubesats, but that allows large antenna production as well and although one would not pursue it by itself, it is a good “gravity” potential/extra revenue source).

4.5.1 Proposed Modular Concept-of-Operation

Modular concepts are an aspect supported by NASA report (NASA, 2010). This is why the report suggests a design with a minimum effort starting module, i.e. a minimum viable product (MVP):

- Start with assembly capability module, fuel station, and inventory bay
- Focus on antennae first – using pre-fabricated pieces
- Add trusses later
- Add solar panels later
- Add fabrication later, for the mid-term starting with antennae elements, trusses
- Add launch capability to be able to address orbits that are beyond feasibility to reach with the entire facility but would be easy to deploy satellites to if they do not have their own propulsion

A more thorough location trade-off analysis beyond the scope of this project should be executed to further the concept’s details and identify whether certain type of LEO orbit would be better, e.g. flying with the ISS, or having a polar orbit. Other considerations are discussed in the next sub-section.

4.5.2 Additional Considerations

Additional considerations for the concept of operations include factors such as other business cases that could transform the sequencing logic. In addition, raw materials supply chain when it comes to fabrication efforts need to be examined. The latter is out of scope along with other elements that also need to be examined, such as robotic manipulators needs and options, tele-operations limitations, and others.

4.6 Case Studies Comparison

4.6.1 Case Study: Archinaut

Archinaut is the Made In Space concept recently approved by NASA to be developed further and tested (Made In Space, 2016). It is an evolution of the SpiderFab approach or rather a first step in it. Details on the concept of operations and its spot in the report’s methodology are in Figure 4-2 and Table 4-5.

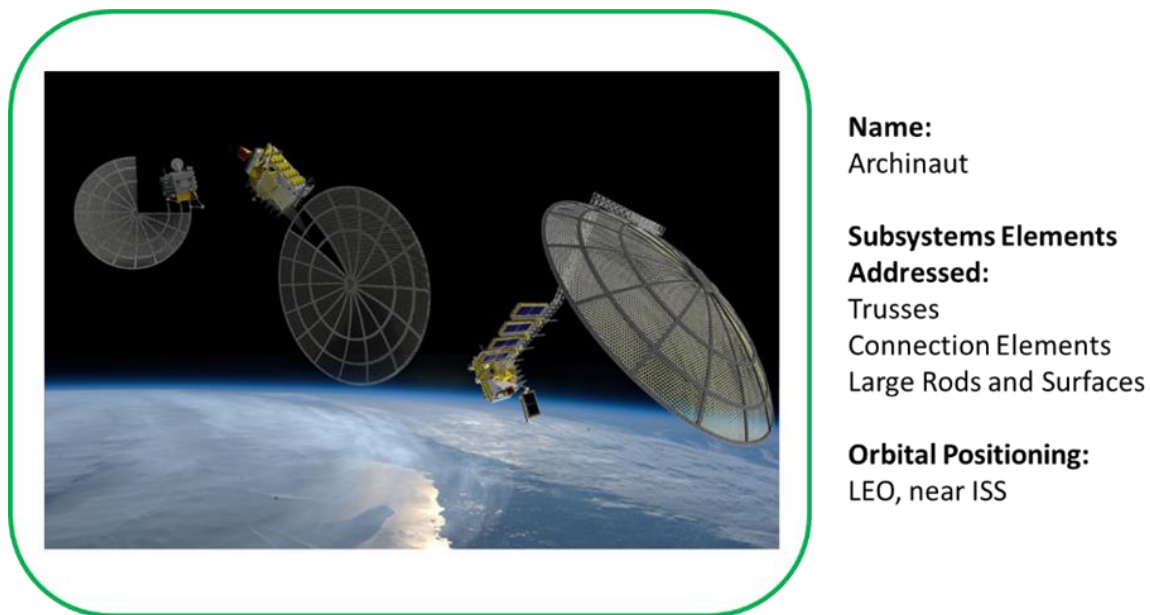


Figure 4-2: Archinaut concept of operations (Made In Space, 2016)

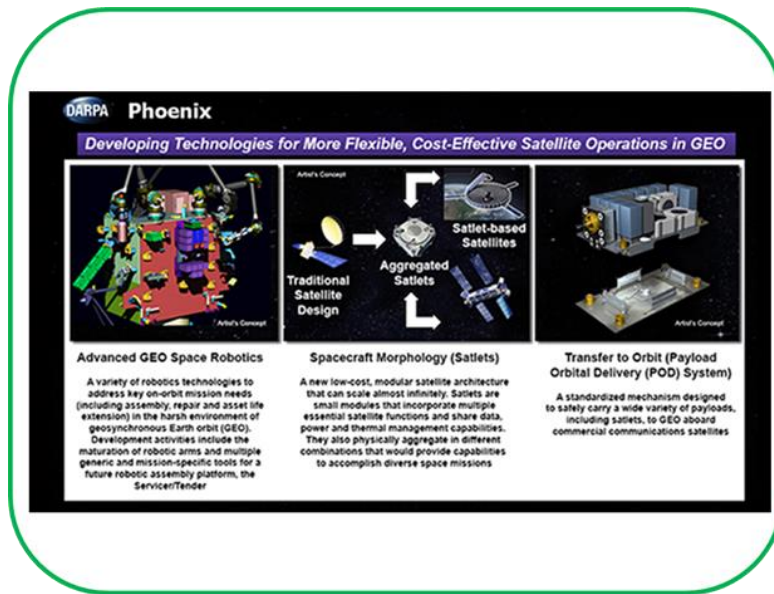
Archinaut is the continuation of the Made In Space and NASA partnership and although it involves a private partner, NASA is likely motivated by developing the commercial space and subsidizing this activity rather than providing space for a sound business venture. Its initial focus on large aperture structures for telescopes shows that there is no secure steady stream of clients. This might be the reason why Made In Space created a partnership with NanoRacks, who have access to many small nanosatellite customers that could benefit from the ability to construct extra structures in orbit (Kohlenberg, 2015).

Table 4-5: Archinaut assigned values for the prioritization and selection criteria

Archinaut			
Volume (High=Good / Low=Bad)	High	Low	Value (High=Good / Low=Bad)
New Technology Risk Tolerance (High=Good / Low=Bad)	High	Mid	Average TRL (High=Good / Low=Bad)
Competition Barriers (High=Good / Low=Bad)	High	Low	Demand Readiness Level (High=Good / Low=Bad)
Sustainability of Business Model (High=Good / Low=Bad)	High	?	Market Opportunity (High=Good / Low=Bad)

4.6.2 Case Study: Phoenix

The Phoenix program is a DARPA initiative that explores robotic concepts in space environments. One of its projects is a GEO facility that focuses on refurbishing satellites and re-deploys them along with other elements (DARPA, 2016). Details on where its concept of operations puts it in the report’s framework are below in Figure 4-3 and Table 4-6.



Name:
Phoenix (program concept)

Subsystems Elements Addressed (only pre-fabricated):
Solar Panels, Thermal Protection, Radiators, Shades Trusses, Connection Elements Large Rods and Surfaces, Antennae, Engines, Transponders

Orbital Positioning:
GEO

Figure 4-3: Phoenix GEO concept of operations (DARPA, 2016)

Phoenix GEO is entirely focused on high-value targets and fills in a gap of servicing high orbit satellites, where human presence is not possible at the moment and will likely be impractical financially for the near term future. The concept addresses similar issues such as the ones introduced by the second business case generated by this report. This is a government initiative and it is likely to be motivated by developing the capability to manipulate robotically distant spacecraft.

Table 4-6: Phoenix GEO concept assigned values for the prioritization and selection criteria

Phoenix			
Volume (High=Good / Low=Bad)	Low	High	Value (High=Good / Low=Bad)
New Technology Risk Tolerance (High=Good / Low=Bad)	Mid	Mid	Average TRL (High=Good / Low=Bad)
Competition Barriers (High=Good / Low=Bad)	High	High	Demand Readiness Level (High=Good / Low=Bad)
Sustainability of Business Model (High=Good / Low=Bad)	High	?	Market Opportunity (High=Good / Low=Bad)

4.6.3 Comparisons

The comparisons performed are two and introduce the MVP concept of operations generate based on Business Case 1: Nanosatellites Trusses and Antennae in LEO. Table 4-7 shows the comparison across spacecraft addressed and Table 4-8 is focused on the value chain elements each addresses.

Table 4-7: Comparison of spacecraft categories addressed by various concepts of in-orbit spacecraft manufacturing operations (? = unknown or undecided)

SPACECRAFT CATEGORY	Archinaut	Phoenix	MVP Concept
Cubesat	✓	✗	✓
Serial Production Satellites	✓	?	✓
Traditional Satellite	✓	?	✗
Custom Satellite	✓	✓	✗
GEO	?	✓	✗
Large-aperture Spacecraft	✓	?	✗
Space Stations	✓	?	✗
Interplanetary	?	✗	✗

Table 4-8: Comparison of value chains addressed by various concepts of in-orbit spacecraft manufacturing operations (? = unknown or undecided)

VALUE CHAIN	Archinaut	Phoenix	MVP Concept
Design	✗	✓	✗
Fabrication	✓	✗	✓
Assembly	✓	✓	✓
Integration	✓	✓	✓
Testing/Verification& Qualification	?	?	?
Launch	✗	✗	✗
Deployment	✓	✓	✓
Maintenance	✓	✓	✗
Repair/Upgrade	✓	✓	✓
Recycling/Repurposing	✗	✓	?
De-orbiting/Decommissioning	✗	✗	✗

5. PERFORMANCE TO PLAN DISCUSSION

The performance to plan in the preparation of this report was relatively normal until the last two weeks. In general, the initial plan to cover the desired set of topics was achieved. The initial project plan was updated, albeit with a delay, based on the initial literature review and first scope adjustment. Later on, there was another re-focus of the scope, more towards methodologies rather than focusing on producing complete high level business cases, which were re-focused to be SWOT analysis. Case studies of existing concepts of operations were conducted under the guidance of Andreas Hein and the original plan for a modular concept of operations was de-prioritized.

The project was moving along at about one to two weeks behind schedule, which was within the limits of the slack time designed. Nevertheless, towards the end a number of external (related to other ISU work and beyond), and personal factors came together to create significant time pressure. In hindsight, this means that the design slack time was not enough to accommodate for factors beyond my control such as Team Project activities where we similarly had a constant two or more week delay. At the end I was faced with a decision to submit something very incomplete or keep on working while suffering a penalty. In the former case, the resulting grade would be low and the quality of the report would have been bad. In the latter case, the grade would also be low, but the quality of the report would be significantly higher. I chose the latter, since it would be more personally satisfying. It was very risky though as I stumbled upon several road blocks and writer blocks which pushed beyond what I imagined. Nevertheless, I hope for the best.

6. CONCLUSIONS AND RECOMMENDATIONS

This section revisits key highlights of the report in the Conclusions subsection 6.1, which is effectively a summary of the report. Then recommendations for future work and next steps are provided in subsection 6.2 that could be useful to readers interested in furthering the results of the report.

6.1 Conclusions

This report aimed at identifying and examining selected business cases for in-space manufacturing of spacecraft that are feasible within the near-term future. It achieves that through three major contributions. First, a comprehensive literature review that identified key gaps that steered the further work in the direction the report took. Second, a new use case classification, filtering, and selection and prioritization approaches were developed and combined into a single methodology. This methodology has applicability beyond the current report, and could be reused and evolved further. The methodology itself is an outcome of the report, but it was also applied to a certain set of use cases, that were also generated using the classification part of it. The results included a short list of use cases passed through a high level initial filter to scale down the number of possible permutations to ones that are likely to be valuable. This was balanced with having a high enough number in a short list of 18 that would allow a few that could turn out to not be important, but not lose the ability to analyze further. At the end, the following use cases were selected to generate two business cases:

Business Case 1: Nanosatellites Trusses and Antennae in LEO – End-to-End Trusses for Science Cubesats, End-to-End Antennae for Science Cubesats, End-to-end Antennae for EO Cubesats use cases

Business Case 2: GEO Satellite Solar Panels and Structure Repair – Assemble and Upgrade Solar Panels for EO GEO S/C, Assemble and Upgrade Solar Panels for Comms GEO S/C, Assemble or Repair Structures for Comms GEO S/C use cases

Of the two, the first was selected as more likely to succeed and easier to implement an MVP concept of operations for. The concept was developed at a high level and compared to two case studies of concepts currently planned or developed. These broadly aligned in the basic understanding of what the appropriate use cases are, but the motivation behind them was revealed to be different mainly due to the purely private entity focus of the report's versus public-private or state-focused concepts.

6.2 Recommendations

The authors of the report recommend that:

- The methodology proposed is further refined and streamlined to be more user-friendly
- The two business cases identified to be further developed into true business cases down to return on investment aspects
- More business cases to be generated and explored using the methodology
- The modular (and minimum viable product) concept of operations to be further developed and later brought to TRL of 3 through a comprehensive study
- Work on a real implementation of the concept by a private entity to ensue after that
- The methodology should be developed and used to generate a complete landscape of in-orbit manufacturing use cases beyond Earth orbit and beyond the near term

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APPENDICES

Appendix A-1. Additional use cases considered, and filtered out in the selection process

Spacecraft Type	Application	Subsystem
Traditional Satellite	Earth Observation	Antennae
Traditional Satellite	Remote Sensing	Antennae
Traditional Satellite	Telecommunications	Antennae
Traditional Satellite	Navigation	Antennae
GEO/Molnya Satellites	Earth Observation	Antennae
GEO/Molnya Satellites	Remote Sensing	Antennae
GEO/Molnya Satellites	Telecommunications	Antennae
GEO/Molnya Satellites	TV/Radio Transmission	Antennae
Traditional Satellite	Telecommunications	Trusses
GEO/Molnya Satellites	Telecommunications	Trusses
GEO/Molnya Satellites	TV/Radio Transmission	Trusses
Serial Production Satellites	Earth Observation	Antennae
Serial Production Satellites	Telecommunications	Antennae
Nanosatellites	Scientific - General	Connection Elements
Nanosatellites	Earth Observation	Connection Elements
Serial Production Satellites	Telecommunications	Large Rods and Surfaces
Serial Production Satellites	De-orbiters	Large Rods and Surfaces
Serial Production Satellites	Earth Observation	Solar Panels
Serial Production Satellites	Telecommunications	Solar Panels
Serial Production Satellites	De-orbiters	Solar Panels
Traditional Satellite	Earth Observation	Solar Panels
Traditional Satellite	Remote Sensing	Solar Panels
Traditional Satellite	Telecommunications	Solar Panels
Traditional Satellite	Navigation	Solar Panels
Swarm Spacecraft	Scientific - Telescopes	Antennae
Swarm Spacecraft	Telecommunications	Antennae
Traditional Satellite	Telecommunications	Large Rods and Surfaces
Serial Production Satellites	Earth Observation	Connection Elements
Serial Production Satellites	Telecommunications	Connection Elements
Serial Production Satellites	De-orbiters	Connection Elements
Traditional Satellite	Earth Observation	Connection Elements
Traditional Satellite	Remote Sensing	Connection Elements
Traditional Satellite	Telecommunications	Connection Elements
Traditional Satellite	Navigation	Connection Elements
GEO/Molnya Satellites	Earth Observation	Connection Elements
GEO/Molnya Satellites	Remote Sensing	Connection Elements
GEO/Molnya Satellites	Telecommunications	Connection Elements
GEO/Molnya Satellites	TV/Radio Transmission	Connection Elements
Traditional Satellite	Earth Observation	Radiators
Traditional Satellite	Remote Sensing	Radiators
Traditional Satellite	Telecommunications	Radiators
Traditional Satellite	Navigation	Radiators
GEO/Molnya Satellites	Earth Observation	Radiators
GEO/Molnya Satellites	Remote Sensing	Radiators
GEO/Molnya Satellites	Telecommunications	Radiators
GEO/Molnya Satellites	TV/Radio Transmission	Radiators
Swarm Spacecraft	Scientific - Telescopes	Radiators
Swarm Spacecraft	Telecommunications	Radiators
Swarm Spacecraft	Scientific - Telescopes	Solar Panels
Swarm Spacecraft	Telecommunications	Solar Panels
Swarm Spacecraft	Scientific - Telescopes	Connection Elements
Swarm Spacecraft	Telecommunications	Connection Elements

Appendix A-2. Scores of short-listed use cases for the prioritization and selection methodology step

Use Case #	Use Case Name	Volume	Value	Risk Tolerance	Average TRL	DRL/MRL	Competition Barrier	Business Model Sustainability	Market Opportunity	Score Without Value Proposition Score	Score With Value Proposition Score
1	End-to-End Trusses for Science Cubesats	3	1	3	3	3	2	2	2	22	31
2	End-to-End Antennae for Science Cubesats	3	1	3	3	3	2	2	2	22	30
3	Assemble Radiators for Science Cubesats	3	1	3	2	3	1	2	1	14	22
4	Assemble Radiators for EO Cubesats	3	1	3	2	3	2	2	2	19	27
5	Assemble Solar Panels for Science Cubesats	3	1	3	2	3	1	2	2	16	24
6	Assemble and Upgrade Solar Panels for EO GEO S/C	2	3	1	2	3	3	3	2	23	31
7	Assemble and Upgrade Solar Panels for RS GEO S/C	2	3	1	2	3	3	3	1	20	28
8	Assemble and Upgrade Solar Panels for Comms GEO S/C	2	3	1	2	3	3	3	2	23	31
9	Assemble and Upgrade Solar Panels for TV/Radio GEO S/C	2	3	1	2	3	3	2	2	21	29
10	End-to-end Antennae for EO Cubesats	3	1	3	3	3	2	3	2	24	31
11	End-to-end Antennae for Mass-produced De-orbiters	3	2	3	3	1	3	3	1	21	28
12	End-to-end Trusses for Mass-produced De-orbiters	3	2	3	3	1	3	3	1	21	29
13	Assemble or Repair Structures for Comms GEO S/C	2	3	1	2	3	2	3	3	23	30
14	Assemble or Repair Structures for TV/Radio GEO S/C	2	3	1	2	3	2	2	3	20	27
15	Assemble Radiators for Mass-produced Comms S/C	3	2	3	2	2	2	3	2	22	29
16	Assemble Radiators for Mass-produced EO S/C	3	2	3	2	2	2	3	2	22	29
17	Assemble to Repair Radiators for EO Cubesats	3	2	3	2	1	2	3	1	17	24
18	Assemble to Repair Radiators for Mass-produced De-orbiters	3	1	3	2	3	2	2	2	19	26