Contribution of In-Orbit Servicing on Space Sustainability

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Executive Summary

As a challenge of congestion in space environment has accelerated a need to rethink about adopting sustainability concept in to space activities, this dissertation is intended to examine an arrangement of space ecosystem suited to a new paradigm of sustainability. The suggestion on the arrangement derived in this work was based on advantages of In-Orbit Servicing (IOS), an advance technology that can change ways to conduct space missions. The study explored related information from literature reviews, business concepts, and interviews on national policies. An economic tool, design principles for Common-Pool Resource (CPR), was applied to figure out missing pieces of current space governance that need to be fulfilled and required synergize from multi levels since private sector, States, and international bodies. The suggestion covers the ways that all actors working together, agreement formulation, monitoring and sanction mechanisms, including the structure of governance effective to sustain the space ecosystem.

The concept of sustainability has been embedded in many ecosystems, including space. The space domain has been challenged by a critical problem of the increasing number of space debris which could endanger in-orbit assets, including social and economic activities on earth that depend on satellites. This industry has adopted the term sustainability and interpreted the concept to meet how space missions have been undertaken. Many efforts trying to establish practices and guidelines, for instance, Guidelines for Long-Term Sustainability of Outer Space Activities (guidelines for LTS) initiated by United Nation United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS) and Inter-Agency Space Debris Coordination Committee guidelines (IADC guidelines) for space debris mitigation.

However, only international mechanisms are not enough to solve the problem as they are voluntary and mostly provide inactive advices. Then, various technology developments are presented to enable proactive solutions for space actors. Among the technology, the In-Orbit Servicing (IOS) is highlighted here as it is indispensable for the creation of a circular value chain for space objects, which is critical for sustainability paradigm. New services and offerings enabled by IOS open a new market in the space economy. For instance, Northrop Grumman life-extension service for satellites, iBOSS standard satellite interfaces from DLR, PERASPERA In-Orbit Demonstration project by EU, and Orbit Fab's in-orbit gas station. The domain has welcomed new players and institutional actors who are pioneers in the novel market.

The interviews of experts from France, Japan, and Thailand were conducted. Their comments illustrated trends and activities related to space sustainability and IOS activities in their countries. For France, their idea on achieving sustainability of space is to create a new space paradigm. Space objects' value chains should transfer from linear to circular. Almost resources and energy should be harvested in orbital areas instead of launching new inputs from the Earth. IOS businesses may not be viable in the long term without the whole new paradigm. For Japan, they initiated several programs to strengthen the capability of the private sector in the country. The programs serve both technological and commercial supports. The public sector will be an investor financing in a main in-orbit infrastructure, such as GEO robotic platform and GEO city, allowing the companies to utilize them for business purposes. For Thailand, they designed national space policies follows the IADC guidelines and the guidelines for LTS. The research and technology development to achieve space sustainability are prioritized. For IOS, as their satellites were manufactured by the companies, they would like to hear suggestions from the companies before selecting any IOS services for their satellites. They also added that cost of the service is significant and insurance for the service may affect their considerations.

The interviews showed that the three countries have agreed that to achieve space sustainability is importance. They are aware the advantages of IOS in upholding the sustainable space environment. Each country has prioritized different fields of space mission depending on their legacy and current assets in-orbit. Therefore, international mechanisms should take different opinions in to accounted on formulation of governance for space sustainability in global level.

In this study, a concept of tragedy of common is employed. The tragedy refers to a situation when a finite resource can be accessed freely by users and they jointly pay costs for maintaining the resource equally. Overconsumption of an individual can make the users gain more benefits, while he still pays for the costs in the same amount. Then each user is motivated to overharvest for private benefit, leading to depletion of the common resource. The resource is accounted as a Common-Pool resource (CPR). The challenge of congestion in orbital areas is consistent with a concept of tragedy of common, where the CPR is Earth's orbits. This tragedy of common raises the question on "What are essential factors of governance structure for a sustainable space ecosystem that IOS activities can contribute?"

To response the problem, a recommendation is derived using an economic concept of CPR. Earth's orbits are projected as finite resources that needed to be preserved to sustain space environment in the long-term. The classical design principles are used to examine gaps in the current space governance that should be considered as follows.

- Common practices that IOS-related actors should formulate and follow:
  The IOS appropriators in the system consist of two groups, 1) direct users who own in-orbit assets or capability to access space, 2) beneficiaries who are not executing the space missions directly but they are affected by the activities, such as non-profit organizations and insurance companies. The actors should follow existing practices, the IADC guidelines and the guidelines for LTS. The practices should be revised on regular basis. The revisions of the guidelines should be opened for participation of beneficiaries, private sector, and emerging actors.
- Mechanisms of work in sustainable space ecosystem:
  Three important mechanisms to ensure sustainability of space environment are addressed, 1) monitoring, 2) sanctions, 3) mechanism to settle disputes. Monitoring and sanctions each other should be undertaken by appropriators in the system. The actors should be supported to develop their capability, in order use the mechanism responding to misbehaviors. Facilitation from public sector to IOS private companies can advance the capabilities in monitoring and sanction process of the ecosystem. The IOS could increase complexity of space activities. The mechanisms to solve conflicts in the system should keep up progress of the technology.
- Different levels of the governance structure for sustainable space ecosystem:
  The governance structure in space ecosystem can be separated in to national, regional, and international level. Each level has a different design of governance. In national level, governmental sector can enforce the sustainable practices to domestic space activities. The regional level entities are able to establish legal obligation treaties among the member in addition to technology program that many countries use the same standards. The regional agencies can disseminate standards and practices in sustainability that they support from local to global level. International cooperation can present a more proactive role to promote space sustainability through a funding to support space missions that comply with the guidelines.

Transfer to the paradigm of space sustainability requires support from all sectors, technology, business, public entities, and international cooperation. IOS can be a powerful tool to make the scenario become real.

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Acknowledgment

I would like to express my thanks to the interviewees and all authors of publications referred in this work. Their stories contribute a pathway to sustainability, and also inspire me to work for a better paradigm of the space ecosystem.

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1. Introduction

The global economy is growing. Even though, pandemic and wars retard the size of world commercial value and break industrial supply chains, but new solutions from rapidly progressive technology, new financial tools, and emerging players have enlarged markets. The economic growth is not come from empty. It needs some resource to fuel business activities and production process. Natural resources have been extracted and utilized to support human livings. Some resources can be reproduced, while some cannot. When the finite resources are consumed until depletion, definitely the economic activities that relied on them will be affected and human will confront negative effects from the scarcity. Therefore, a concept has foreseen the terrible future scenarios and introduced that, human activities should be conducted sustainably in order to preserve the limited natural resources to be able to benefit human in long-term. The resource should not be exploited by a few generations and lasts only leftovers for the next generation. The concept on sustainability is widely accepted and embedded in many national policies and business plans.

Up into space, Earth's orbits are valuable assets for all humankind, allowing discoveries of scientific breakthroughs, ensuring national security, and providing unique information for social development and economic growth. Space programs were started by a driving force for military purposes from a few countries during wartime to declare their defense capability overarching land, sea, air, and space domain. Many satellite projects had been conducted to respond to surveillance demands to protect national security and strengthen their competitiveness over opponents. Various innovations had been developed and produced under military entities. The establishment of space agencies like the National Aeronautics and Space Administration illustrated the capability of the civil sector to lead and conduct space missions. The great success of the Human on the Moon mission raised the era of the civil space sector and has brought up the peaceful purposes of using the outer space to the area of intergovernmental forum, the United Nations, where 5 space treaties were initiated to emphasize that space should be used for benefits of all (United Nations, Outer Space Treaty, 1967). The civil space program is an important foundation to build up Newspace, the time of the private sector, institutions, and startups, in the space ecosystem.

The concept of peaceful purpose reflects some aspects of sustainability. As space is finite even, it is vast comparing the area on Earth' surface. But concerning that, objects in Low Earth Orbit, the lowest orbit of Earth above, are orbiting around the globe at around 17,000 miles per hour (NASA, 2017). Placing a satellite in the orbit needs a much larger occupied area than a normal object on Earth to reduce the probability of a collision between space objects. Then, if the number of space objects reaches a certain level, congestion could occur. Moreover, once an object is launched to space, it will spend time orbiting around the Earth before naturally de-orbiting to the ground, for 25 years at an altitude of 500 km, 100-150 years at the latitude of 800 km, 2,000 years at a latitude 1,200 km, and, unfortunately, staying forever in the orbit at 36,000 km which is Geostationary orbits for communication satellites (ESA, 2021).

Currently, Newspace has opened up novel approaches for private sector to conducting space missions, new technologies, players, markets, processes, funding approaches, and policies. All of these have fueled new business models to generate revenue from space infrastructures. Big companies in other industries have invested in the industry resulting in space projects with no need to rely on the government budget anymore. They can launch their space objects as much as their finance allows. The financial investment has been fed from new channels such as angel investors or venture capital. In addition, they are no rigid regulations to limit the number of launch. The natural limitation of frequency interference was broken down by technology advancement of high throughput innovation. The progress reflects that there are no limits in space to gather all resources and generate business interests on Earth. Even Newspace sounds good from the economic point of view, the activities could be threats to space environment as they reduce orbital areas available to provide services to the ground and increase risks of possible collision and explosion of space objects.

There are various solutions have been suggested to deal with the problem of congestion in Earth's orbits. Active Debris Removal (ADR) is in the demonstration phase to eliminate defunct satellites or space debris which could disturb space mission operations or destroy satellites. Another concept developed in parallel is, with the same core technology, In-Orbit Servicing (IOS), which repairs, extends life, and upgrades missions of satellites. The new functions enabled by IOS can change the life-cycle and operation of a space object. The service is not new but mostly had been undertaken by government space agencies for the maintenance of high-value space infrastructures, such as the International Space Station and Hubble Space Telescope. The concept had been far from reality to be business before until the success of the first commercial service on In-Orbit Servicing in 2020 by Northrop Grumman, ramping up the Technology Readiness Level of the techniques and hardware. As much as it is applicable, the scenario of less congestion in orbits and space sustainability is not so far to be seen anymore.

Concerning that, today, abundant socio-economic activities depend on the good performance of in-orbit objects, preservation of the Earth's orbit resource should be paid attention to ensure all of the activities can sustain for the long term. This study recognizes the issue and tries to answer a research question on,

"What are essential factors of governance structure for a sustainable space ecosystem that IOS activities can contribute?"

The question can be divided into sub-questions below,

- What are common practices that IOS-related actors should formulate and follow?
- What are mechanisms of work in sustainable space ecosystem?
- How the actors in different levels a should work together in sustainable space ecosystem?

This report is structured as follows.

Part 2. the Materials and Methodology describes the methods used for information acquisition comprising literature reviews, interviews of experts, and economical principles for the formulation of managerial recommendations.

Part 3. literature review consists of an empirical framework and a theoretical framework. The review of empirical explores covering the topics of space sustainability, some key technologies that enable attainment of space sustainability, business opportunity from the IOS, and a summary of interviews of experts from space agencies talking about their national plans to uphold sustainable space. The theoretical framework explains the economic concept of CPR and of eight design principles used to derive the recommendation drawn up on the information acquired.

Part 4. Results analysis casts the situations from all aspects the study went through into a suggestion on governance for space sustainability contributed by IOS.

The report ends with the conclusion.

2. Materials and Methodology

the study aims to examine the way to achieve space sustainability paradigm from benefits of IOS by reviewing materials from primary and secondary resource.

The information from the primary source is obtained through interviews of three professionals working in national space agencies and having duties to uphold sustainable of space industry and in-orbit technology development. All experts have actively engaged the issues and driven their projects consistent with the focus of this study. The names of the professionals who shared information and opinion for this research are as follows,

- the case of France: Mr. Michel Sylvain, Strategy Department, Deputy Industry and Ecosystem Department NewSpace and ecosystem, Centre national d'études spatiales (CNES)
- the case of Japan: Mr. Hiroshi Ueno, J-SPARC Producer, Business Development Group, Business Development, and Industrial Relations Department from Japan Aerospace Exploration Agency (JAXA)
- the case of Thailand: Dr. Sittiporn Channumsin Director of Space Technology research center gave an interview and Mr. Yossavin Sombutpanich Senior Satellite Specialist provided additional information. Both experts were from Geo-Informatics and Space Technology Development Agency (GISTDA).

Each interviewed was conducted in virtual mode and lasted about 1 hour per time with consent from the interviewee to have recording. The professionals also provided documents, news, and valuable data to assist the study.

The secondary source contains of information from texts, academic papers, publications, reports, official websites of the companies, and media news. The topics of information input received from the secondary sources are shown below.

- Concepts of general sustainability, space sustainability and their practices which are oriented intergovernmental fora, United Nations and Inter-Agency Space Debris Coordination Committee
- In-Orbit Servicing from technological aspect surveyed from academic publications including business perspectives obtained from successful commercial services and on-going IOS projects by private companies and space entities.
- Economic frameworks related to fundamental concepts, tragedy of common, Common-Pool Resource concept, and eight design principles developed Elinor Ostrom, a pioneering economist developing who partly shared Nobel Prize in Economic Sciences.

3. Literature review

3.1 Empirical framework

3.1.1 A concept of sustainability

The term of sustainability has been used prevalently in various interpretations and its a concrete definition is not expressed. It has been introduced around mid 1980 in academic territory and developed over the time (Portney, 2015). In the early phase, it has been used regarding the environmental destruction. After that, the term has been broadened overarching economic activities and other areas. The essence of sustainability concept is human can consume natural resources in the way that holistic biophysical environment can sustain no be depleted or polluted. It is not only environment protection from particular harms but covering support all ecosystems to stay healthy and well functioned.

In general, sustainability has been referred in three areas, consisting of economic, social, and environmental (Goodland, 1995). These three components link together and overlap in many issues.

1) The economical sustainability concerns human economic growth which is challenged by finite ecosystem and limited capitals, in particular natural capital such as forest and air. The scarcity of input from natural resources is affecting economic production process and can deter economic growth.
2) The social sustainability focuses on human well-being which is constrained by vulnerability of life-support system and economic conditions. Poverty is a primary topic that activities in social sustainability are working on together with inequity, education, etc. It is inevitably also involved with environment problems and economic troubles.
3) The environment sustainability is dealing with an input resource that fuel economic and social activities. Well-organized environmental system could benefit us by natural resources. On the other hand, ineffective governance on usage of the resources could turn to be threats for human, such as pollution and climate change.

The all three aspects are known as three pillars of sustainable development which is aiming to arrange resources and solve the problems from all aspects.

In global level, the concept of sustainability was adopted by the United Nation (UN). The term sustainability can be interpretated through the definition of sustainable development given by United Nations Brundtland Commission in 1987 as,

“Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. (United Nations Brundtland Commission, 1987, p. 41)”

The definition did not specify only economic, social, and environmental aspects but was enlarged to other dimensions that assist living of human. The UN also has declared the 17 Sustainable Development Goals (SDGs) and the actions that State members of UN adopted to implement in their countries. These goals have been distributed to committees under the forum to formulate agendas in consistent with the SDGs.

3.1.2 Space sustainability

United Nation United Nations Committee on the Peaceful Uses of Outer Space (COPOUS), the intergovernmental fora of States dedicated to topics of space affairs, expressed in its Guidelines for Long-Term Sustainability of Outer Space Activities (guidelines for LTS) that the whole orbital area is a limited resource due to finite volume for accommodating satellites orbiting around Earth and a curtain radio frequency range for communication between ground and space (United Nations, Guidelines for Long-Term Sustainability of Outer Space Activities, 2021). Currently, the industry is at a turning point. More actors and new technology enable more easily accessibility to space, leading to a proliferation of space objects such as satellites, rocket bodies, spacecraft, and space stations. These activities increase congestion in orbital areas. Dealing with a finite such as Earth’s orbits with a purpose of preserving it in the long-term for future missions, there is important to bring the idea of sustainability to embed in planning, manufacturing, operation, and end-of-life management of all space objects

The United Nations Office for Outer Space Affairs (UNOOSA), a secretary office of UNCOPUOS, defined the scope of the long-term sustainability of outer space activities in the Guideline for LTS as follows,

"… the ability to maintain the conduct of space activities indefinitely into the future in a manner that realizes the objectives of equitable access to the benefits of the exploration and use of outer space for peaceful purposes, to meet the needs of the present generations while preserving the outer space environment for future generations. (United Nations, 2021, p.2)"

The definition emphasizes space accessibility for all. It enlarged the word "equitable access" as not only referred to differences in economic and knowledge resources but covered the difference in time period. It reiterated that future generations should access benefits from space equal to current actors. Future space missions should not be confined by the effects of irresponsible actions today. This is where the sustainability of space activities has been underpinned. The definition has been globally embraced by the public sector and used as a ground principle for the formulation of national regulatory frameworks and domestic measures for the space industry.

Space has unique attributes (Weeden & Chow, 2012). First, even the physical volume of space that produces benefits to Earth seems spacious compared to Earth's surface, but it is finite, especially for Low Earth Orbit (LEO) and Geostationary Orbit (GEO). Having that space objects orbiting at very-high-speed velocity, a space object needs a safe area much larger for its occupation to not be risk from collision with nearby objects, at least in the distance of around 20-30 kilometers for a satellite member in a pre-design satellite cluster. Second, a spacecraft requires radio frequency for communication to the ground, where the frequency band is limited. Then, the allocation of the electromagnetic wave for satellites has to be well managed to avoid interference. Even with the great achievement of high throughput technology, the band frequency range is not limitless. Therefore, the sustainability concept should be concerned to leverage these limited resources. In this work, the term of Earth's orbits is focused.

As an increasing number of actors both public and private sectors enter the domain, the number of space activities is dramatically grown accordingly accounting for many stimulations for trends on number of space objects. It is because barriers to space accessibility have been lower, thanks to low-cost reusability launching, rideshare of payloads and rockets, etc. This plenty of missions created economic, social, scientific, and national security values. Orbiting infrastructure elevates communication across the globe through broadband and broadcasting, producing value for the satellite communication market. Global Navigation Satellite System (GNSS) is a part to support navigation systems integrated into cars, ships, and aircraft commonly used around the world. Even though a lot of value that space can enable, these wealthy and advanced activities have created a great number of debris which is returning to destroy the whole space ecosystem.

What is the trigger that brought the concept up to the floor? In March 2022, Orbital Debris Quarterly News (NASA, Orbital Debris Quarterly News, 2022) revealed the total number of objects on Earth's orbit is reaching 26,000. About half of them are fragmentation debris that were generated by collisions or breakups and cannot be controlled. The rest are operating spacecraft, mission-related debris (defunct space objects), and rocket bodies. The fragment debris are very dangerous as they cannot be controlled and small pieces are hardly trackable. The number of fragments also produces a continuously high probability of destruction within the space environment. The International Space Station and operating satellites have to be maneuvered more often to avoid space debris, consuming limited fuel and operation time that should be spent on conducting their missions. The risks of collision and damage are getting more severe due to launches of mega-constellations of satellites consisting of nearly ten thousand space objects.

To illustrate a clear picture of possible devastation that can be produced by several pieces of space objects, Kessler and Cour-Palais (1978) created a mathematical model predicting a trend of orbiting space debris flux. A collision between space objects or a breakup of a spacecraft can generate numerous fragments, which increase prospects of becoming new origins creating uncountable smaller debris endlessly, similar to a chain reaction. The smaller debris is, the much harder it is to be detected and tracked. The model's result also showed that, at a certain time, even no new space objects were launched into the orbits, the number of debris fragments still increase exponentially. This phenomenon, the Kessler syndrome, is a major threat to the whole space ecosystem and can haul all space activities, causing catastrophe to economic growth on Earth. Then, the term sustainability in space has been introduced since the concern proliferation of space objects has been earnestly aware. The space sustainability considered here is in a category of the environment sustainability that a natural resource providing benefits for social and economic activities but it can be depleted and polluted by harm actions of human.

Most of the satellites are designed, developed, and operated as disposal products. All precious rare-Earth elements and top-grade materials were fabricated and formed with meticulous manufacture and passed a series of highly strict environmental testing consuming a great deal of energy. Eventually, after less than 15 years, they not only will be left as worthless trash, with no communication with ground stations due to running out of energy, but they will become uncontrollable dangerous monsters threatening other operating satellites and astronauts' life. The situation is truly getting worse. If still no concrete measures to deal with it, Earth's orbit will be a thick wall preventing the next generation to take advantage of this valuable resource.

COPUOS, an intergovernmental forum, is aware of the urgency of the challenge as indicated in the guideline for LTS that,

"International cooperation is required to implement the guidelines effectively, to monitor their impact and effectiveness, and to ensure that, as space activities evolve, they continue to reflect the most current state of knowledge of pertinent factors influencing the long-term sustainability of outer space activities, particularly about the identification of factors that influence the nature and magnitude of risks associated with various aspects of space activities or that may give rise to potentially hazardous situations and developments in the space environment. (United Nations, 2021, p.5)"

Hence, the space agencies as a part of the government sector can have a direct role to oversee more than business interests today but have to evaluate how much future opportunities would be sacrificed for growing the current space business. Meanwhile, the private sector should understand the importance of space sustainability and embrace the concept in to their business plan for securing their business. In this way, the sustainability of space has been brought up to the table and the question of how we can make the space missions more sustainable has been raised.

The approach to achieving sustainable space is relevant to preserving space environment, which the study will go deep down further. It involves minimizing and avoiding harms to the space environment from both natural and manmade objects.

As these challenges have been recognized at national and international levels. Let's take a look at how space actors respond to the problem. A list of guidelines attempted to cope with the issue by providing suggestions on the way space missions should be undertaken sustainably have been announced and called for sustainable decisions of all space sectors. The guidelines reflected mutual concurrences of international bodies on how to reach the space sustainability.

Guidelines for Long-Term Sustainability of Outer Space Activities (United Nations, 2021)

The guidelines for LTS are a set of guidance on policy and regulatory frameworks for designing, planning, and undertaking space activities in sustainable ways. They were proposed by COPOUS and have been adopted in 2019 by States represented as members of the committee. The States are in charge of Guidelines implementation owing to they possess authorization to regulate and facilitate space affairs in their countries. According to a great advantage of the strong international cooperation platform of the UN body, the Guidelines for LTS were grounded on peaceful purposes and consensus among the State members. It also links to the Sustainable Development Goals by proposing space as an enabler and a driver to sustainability. The guidance is provided for both governmental and non-governmental agencies' activities. It can be implemented on a voluntary basis of a State and adapted to compile with each national conditions.

Since the Outer Space Treaty (United Nations, 1967) has been announced, it states that the national regulations should concern safety, liability, reliability, and cost when conducting space activities. It emphasized that space activities should be conducted with peaceful purpose and encourage importance of international cooperation related to space. Afterwards, the guidelines for LTS reiterate the concepts and add the idea of sustainability. Given government entities are national focal points for implementation, the Guidelines for LTS pointed out that States should bear responsibilities for supervising national space activities, both governmental and non-governmental as well as establishing appropriate procedures to enhance the sustainability of outer space activities. Regarding the guidelines, practices for the safety of space operation that a State should do covering topics of supporting data sharing of space objects and orbital situations, space data accuracy development, ensuring conjunction assessment for orbital phases of a space object, assisting launch process, re-entry process, and tasks related to space weather. The practices could be done through support, encouragement, providing assistance, information sharing and exchange, capacity building, and international cooperation.

Among the guidelines for LTS, the guideline B.8 indicated an active response measure for preserving space environment. It suggested designs of space objects, in particular small-size, should be easily trackable in orbit throughout their life cycle. The guidelines also pointed out that States should encourage space object manufacturers and operators to use suitable on board-technology for the design. It aims to limit the time that the space objects stay in a protected orbital region and make them de-orbit or re-orbit to avoid causing harm for functioning satellites.

In fact, not all countries fully have the capability enough to implement guidelines for LTS thoroughly and effectively. Some require more advanced technology, new forms of national governance and regulation, or financial resources to establish support physical and knowledge infrastructure. The guidelines for LTS also encourage the strengthening of international cooperation to create support mechanisms from space fairing countries towards emerging space countries, helping them develop capacity and capability. The widest the guidelines are implemented, the more sustainable space can be ensured and enhanced to be able to equitably deliver social and economic benefits for all in long term.

The guidelines for LTS were designed on the current paradigm and existing technologies which can be abruptly faded out of trend if concerning plausible disruptive missions of current spacecraft in Newspace. Then information exchange and revising the guidelines for LTS on regular basis are necessary. The COPOUS also recognized the situation and determined to establish a new working group, LTS 2.0, dedicated as a forum to exchange experience from implementation, in addition, to updating current circumstances, latest technology, and progress on private space activities in the space industry (Secure World Foundation, 2020). Some advancements can be threats to sustainability, however, new things always allow new solutions.

IADC Space Debris Mitigation Guidelines (IADC, 2021)

Inter-Agency Space Debris Coordination Committee (IADC) is an international forum cooperatively working on the topic of manmade and natural space debris. Most of the members are public space agencies and inter-governmental entities that possessed launch systems and rocket technology. It provides a forum on exchange information, seeking research cooperation related to space debris, and formulating recommendations for space debris mitigation. The procedure provided by the committee is the IADC Space Debris Mitigation Guidelines (IADC guidelines), which have been widely accepted by public and private organizations including inter-government entities. The first full version was published in 2009 then the document has gone through 8 times of revisions. The latest edition released in 2021 is considered in the study.

The IADC guidelines provide recommendations on orbital debris reduction to preserve space environment for safe space missions. The guidelines can be standard guidance for spacecraft manufacturers and operators to design and control a satellite or an orbital stage launched into orbits, consistent with space sustainability. The IADC guidelines defined protected regions as areas that should be free of orbiting debris and decommissioned satellites. The protected region is an orbit or a segment of orbit capable of providing unique services to activities on Earth but tends to be congested by space objects if no mitigation measures. Basically, all orbital regions are finite and can be crowded by debris, but for now, two regions should be protected below,

1) Region A, the Low Earth Orbit (LEO) a spherical region from the Earth's surface to an altitude of 2,000 km
2) Region B, the Geosynchronous Region - a segment of the spherical shell between 35,586 km and 35,986 km with the latitude between $\pm$15 degrees.

Any object launched to the above-protected regions should compile with measures suggested by IADC hereafter. All action during an operational phase that will create fragments should be avoided to limit the population of orbital debris. After the end of the operation, all resources, such as propellants or batteries, that could generate an explosion should be depleted. Intentional destruction or collision should be prohibited, except for executing at a very low altitude. Regarding measures at the disposal phase, in the case of GEO orbit, the spacecraft should be re-orbit to above the GEO orbit ensuring that they will not interfere with the rest of the operating satellites. For objects in LEO orbit, they should be de-orbit to Earth's atmosphere after mission completion or re-orbit to the orbit that allows them to stay no more than 25 years before being burned by the atmosphere.

The IADC guidelines promoted the sustainable orbital environment through recommendations dealing with potential harms and interferences caused by breakups, explosions, and collisions. The guidelines stated a clear definition of protected regions and applicable measures the operators should follow at the end-of-life of a spacecraft residing in the mentioned orbit. The suggestion provided offhand solutions to tackling the current problems mainly by prevention methods such as minimizing the opportunity of emerging new debris and removing the existing satellites from the protected region. However, the IADC guidelines did not touch on activities related to the illimitation of decommissioned space objects, which lack the energy to de-orbit or re-orbit. These types of passive objects are the most numerous in Earth's orbit. The recommendation also did not include substitute methods to further enlarge the capacity of the current satellite's life cycle. Even more, given the number of generated fragments from a collision can be more than tenfold of the precursors, more active measures are still required to cope with the severe problem that already happened.

There is a good movement having the above applicable measures guiding space mission operators on what should be conducted during and after missions to mitigate space debris issues. But considering that simulations conducted by Virgili, et al. (2016) on orbital population from 2021 to 2071 presented that a high-success rate of post-mission disposal of constellation satellites is the important key to achieving a sustainable space environment. But in reality, currently, the post-mission disposal rate of satellites is too low leading to a proliferation of space debris over a long time. This study combined the fact that several satellite constellations are continually launching. It is obvious that the current guidelines cannot cope with the real space debris issue. Then more proactive procedures to manage the failed space objects are needed before the situation gets worse.

3.1.3 Some key technologies enabling space sustainability

As mentioned before, the current circumstance of space missions is far away from sustainability. To pave a way for more sustainable Earth and space, technological capability is expected to be a key architecture enabling sustainable space missions. Changes of satellite design, the new operation process of space missions, and emerging actors in the space economy are all that are necessary to be shifted to a new paradigm that required technical approaches and effective policies to break barriers. The main obstacle to preventing achieving space sustainability is space debris. In general, there are two approaches to deal with the problem (Palmroth, et al., 2021). The first choice is the reduction of producing new debris, by mitigating chances of collisions and explosion, de-orbiting or re-orbiting at disposal, and extending the life of satellites by In-Orbit Servicing. Most of the guidelines has followed in the approach but the solution does not answer the question that how the existing space debris problem can be solved. The second approach is using Active Debris to dispose of existing debris. This approach is also relevant to the In-Orbit Servicing as they share the same core technology. Many reports, the Active Debris Removal is one of the In-Orbit Services (Davis, Mayberry, & Penn, 2019; OSAM National Initiative, 2021; European Space Policy Institute, 2020). While some publications separated In-Orbit Servicing, In-Orbit Assembly and manufacturing, and Active Debris Removal (Eckersley, et al., 2018). Then, for reviews on the technology assisting space sustainability, this study focuses on In-Orbit Servicing.

a) In-Orbit Servicing

The term In-Orbit Servicing (IOS), or On-Orbit Servicing, refers to "the provision of support services by a spacecraft (servicer) to another space object (serviced) while in orbit (European Space Policy Institute, 2020)". The history of IOS emerged when the first space station was launched as space stations regularly need maintenance. Hubble Space Telescope went through 5 times of IOS by repairing failed components and replacement with newer equipment (NASA, 2022). The service can be executed by humans or robotics. This study mentions only the robotic operation.

There are two types of satellites for receiving the service, cooperative and non-cooperative (or uncooperative) satellites, which much affect the operation.

A non-cooperative satellite is a legacy-design satellite having no specific equipment for capturing or docking by another servicer. It was designed to be disposed of after usage, and have a single purpose, and its equipment is unintentionally changeable. By the way, a non-cooperative satellite can receive IOS from the tailor-made design of the servicer. For example, in the case of Mission Extension Vehicle docking with Intelsat IS-901. The service provider, Northrop Grumman, choose a liquid apogee engine as the point for attachment because it is a common feature of most geostationary satellites, allowing the company to apply the same technology to other non-cooperative satellites (Foust, 2020).

A cooperative satellite is designed from the beginning to be compatible with a service-providing vehicle for approaching or capturing. The satellite could comprise of special communication system between satellites. It could include IOS with their operation plan.

Considering a common satellite design and operation, when it is launched to space, there is no repair like a car. No satellites have been brought up to Earth for checking up or reconfiguration. With current technology and procedure, its value chain since spreads as a linear articulation of phases. A satellite's life cycle can be described in figure 1 (Skomorohov, Hein, & Welch, 2016).

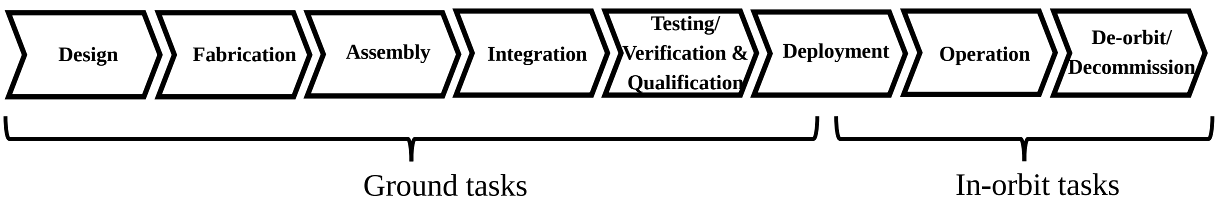

Figure 1 Current satellite's life cycle

With the contribution of IOS, a new value chain of a satellite including the new activities is illustrated are shown below.

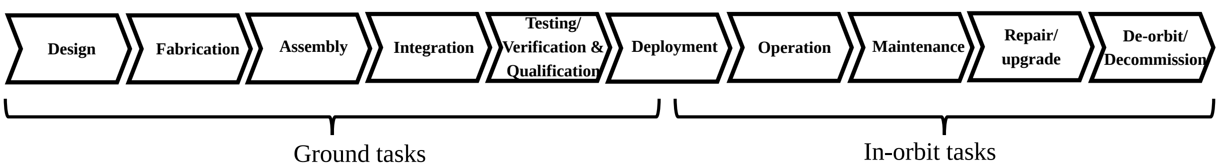

Figure 2 Satellite's value chain with In-Orbit Servicing

The In-Orbit Operation, covering servicing, assembly, and manufacturing, will expand the operational fleet of a satellite, making it able to provide value more. The engineering lifetime of a space object can be extended by different types of services to solve malfunctions that occurred in the satellite without leaving it to be space debris as before.

IOS overarches a broad set of satellite services. There are no official definitions and many boundaries of activities are overlapped or performed similar tasks by the same technology or instrument. To have a big picture of the services, The table 1. shows here are some examples of offerings the technology can or provide (Eckersley, et al., 2018; Davis, Mayberry, & Penn, 2019; European Space Policy Institute, 2020; OSAM National Initiative, 2021; Skomorohov, Hein, & Welch, 2016). The services with the same procedure of operations are grouped and each type can respond purposes of the mission with more than one objective. Please note that the technology is rapidly progressive, then it is absolutely possible that, shortly, new services emerge, a few services will be combined, or a service can serve more purposes.

Table 1 In-Orbit Services and purposes

Service	Life-extension purpose	Mission enhancement purpose	Orbit modification purpose
Adding or installation new equipment	✓	✓	✓
Replacement	✓	✓	
Refueling or charging	✓		
Repair or correction of the mechanical failures	✓		

b) Purposes of In-Orbit Services

life-extensions refer to all actions making the serviced satellites continue implementing their mission at their original orbits with full capability. Regarding the real cases of Mission Extension Vehicle, the serviced satellite can be operated 5 years more. The missions are interested in current In-Orbit Services and are expected to drive the market. The life-extensions suit satellites having economic value needed to be kept up. For example, a communication satellite broadcasting television services having a footprint covering a particular region, malfunctioning of the satellite leads to damage to television businesses destroying customers' trust. Inability to deliver service in a few days causes a major loss in the television business revenue. Extending the life of the satellite have good economic effects on businesses relying on the operation of the satellite. In addition, a satellite in orbit can malfunction at any time. Employing the service to adjust the satellite's system, making it operates as the time duration they could do, is the service that can assure the efficiency of a satellite and that its missions will be done as expected.

Mission enhancement is an activity to upgrade the capability of a satellite or mission repurpose. These tasks were performed many times with the Hubble Space Telescope by adding new or more advanced equipment to the satellites making it was upgraded with the latest technology and avoiding the need of launching a new satellite with new performance criteria. However, satellites can be upgraded in a limited time. Some systems or components cannot replace or substitute with additional instruments un limitedly. A space object has its lifetime depending on materials or fine elements. At some point, only recycling can extract value from the rest of them. By the way, this concept of purpose leads to a satellite can be more flexible. It creates an opportunity for a second-hand market for satellites which is the maximization of a space object.

Lastly, orbit modification covers Active Debris Removal, tugging, and relocation of a space object. It also includes performing station keeping and orbit maintenance. By carrying this purpose, the satellite has no damage, expiration, or failure of its hardware. Sometimes, the satellite changes its location in orbit. Intentionally, the change can be made because of avoiding space debris or other satellites which are approaching, relocating the satellite to a new altitude, or inclination to serve different mission purposes, including moving nearly a decommissioned geostationary satellite to the graveyard orbit responding to IADC measures. Unintentionally, the change of location can be happened due to space weather factors, solar storms, other phenomena, or even malfunctions of a satellite. Normally, the position correction can be done by a satellite itself. But when it is running out of fuel, the assistance from servicer spacecraft can help it to keep performing well. Almost the objectives require services related to attitude control and propulsion, whether by adding a new instrument, replacing with the same version of the component, or renewing with higher capability equipment.

c) Service tasks

To perform IOS, there are plenty of tasks achieving the above purposes. Below are some examples of the services that servicer spacecraft are able, or on the way to develop, to provide to the customers' satellites.

Adding or installation of new equipment which is not part of the design before or not integrated into a satellite before launch. The areas the most mature services in the field as it was proven in-orbit. The service needs to alter inside a satellite but to design of the missions is complex as many factors need to be concerned. Then, as of now, they are only commercial IOS available for satellite operators who require test execution before determining the service for their assets. Two successful commercial cases were done from attachments of Mission Extension Vehicle (MEV) to geostationary satellites which were running out of fuel in order to expand their operation. The tasks can serve other purposes missions such as orbit modification.

Replacement service is similar to adding and installation but some parts of the satellite should be taken off and integrate new parts to function instead. Many concepts have demonstrated components considered can be replaced, for instance, battery and solar array. The service can help with the problems of unexpected anomalies of the subsystems.

Refueling or charging refers to the service of supplying energy to serviced satellites. The energy can be fuels, propellants, gas or fluid for pressure systems, and coolant solutions for the thermal system. To promote this service, some concepts for in-orbit power stations have been proposed.

Repair, correction, and reconfigurations of the system or equipment failures are collapsed with replacement as some repair procedures need to change failed equipment. They can be accounted as a replacement service for the life-extension purpose. They are separated to highlight the actions on fixing problems a satellite faces, not only changing but, including correction, reconfiguration, and fine-tuning to make a satellite work at full capability.

The service types elaborated here are the only examples of IOS. Exploring customers' needs and pain points can be important information to design the missions to meet their value proposition further.

IOS can be conducted effectively and successfully, the execution needs a bunch of contributions from neighborhood technologies, for instance,

- In-orbit inspection
  In-orbit inspection complement SSA and STM by providing data on the space environment gathered in the orbital area. A spacecraft performing the inspection of another spacecraft, both active and dead, can execute from a distance away and no contact is needed to observe external health status and anomalies from debris or space environment. It is one of the very steps before implementing Active Space Debris Removal or In-orbit Servicing
- Rendezvous and Docking (RDV&D) and proximity operations
  Rendezvous is a process of autonomous or remote-controlled maneuver of two separated spacecraft into a curtain station-keeping distance at a proximity level. Docking refers to the procedure, after Rendezvous, that the two spacecraft physically

connect. The two processes required high-precision sensors such as GPS, LIDAR, and onboard cameras including Guidance Navigation Control and proximity operations of the spacecraft. They are preliminary phase earlier performing Active Debris Removal and other IOS. In addition, given the latency of data downlink of ground command, RDV&D is required to implement autonomously using important input data from sensors and processing systems installed onboard spacecraft including information exchange between a servicer and a target. The less dependent on remote control from the ground, the much more efficient and precision of the in-orbit operation activities are.

- Space Robotics
  Space robotics generally are manipulator arms which design to be able to execute a versatile mission, such as docking, changing components, or moving on another satellite. The technology is specified as an inevitable technology for the next generation of space missions such as space exploration and in-situ resourcing.
- In-Orbit Assembling and Manufacturing
  The type is an advanced step of In-Orbit Servicing. Assembly refers to a process of the combination of two or more space objects to create a new one. Manufacturing activities which are involved at least three technologies: fabrication or elaborate production from raw material, assembly at the component level, and integration which is bringing together subsystems and ensuring their function. The concept is at the highest level of technology leading to space sustainability as it allows plenty of space mission ideas to be true, for example, building a large-aperture satellite in orbit without restriction from the rocket and launch conditions and recycling factory to transforming defunct satellite to be a new one. With functions of the concept, a value chain of the satellite can become a close-loop and will transform the space paradigm completely.

Besides the list above, a collection of technologies' unique capabilities to alleviate the challenge are required to be implemented concurrently. The crucial technologies for shifting to the space sustainability paradigm include Space Situation Awareness, Space Traffic Management, data image processing, advanced material science, additive manufacturing, and many more.

3.1.4 Business opportunity from the In-orbit servicing

To achieve space sustainability, the technologies mentioned earlier should be advanced until their Technology Readiness Level increase, to create an effective foundation and infrastructure for the paradigm. One of the powerful drivers is financial resource. Then, seeking and scaling up business opportunities for In-Orbit Operations and related activities such as Active Debris Removal are main tasks of the government agencies to accelerate the transformation from current circumstance to the scenarios that satellite projects are conducted sustainably and the space environment is preserved. In this part, ongoing businesses in IOS for satellites are explored.

a) The Chicken-and-Egg problem

To commercialize IOS, a big problem is awaiting. The Chicken-and-Egg problem has been frequently mentioned when there is a question about why the IOS market does not fully exist (Davis, Mayberry, & Penn, 2019). One of the barriers for the business, the standardization of satellite interface and the model do not prevalent. Most of the satellites, even the one manufactured based on legacy heritage designs, are tailor-made products. The service providers have to carefully customize their hardware and mission operation procedure for each project, requiring high cost and hardly reaching economy of scale. In achieving a growth stage of market, satellites could be installed with standard features for receiving IOS or designed to be cooperative satellites, which will lower the prices of the services and increase the success rate of operation. But the satellite owners may not want to invest in a feature that might be hardly used throughout the satellite's lifetime. In addition, they are a few service providers so the operators may need to plan before launch that what kind of the services will be conducted and who is the service providers. In the meanwhile, there are more important factors related to the satellite have to be concerned about, such as the launch process and ground operation, rather than a service at the end of the operation. Sometimes, launching a new satellite will be better so why do they need to invest in something that might not be used beforehand. From the servicer's perspective, when there is uncertainty that the services they are offerings will be purchased or not. Moreover, the service is highly specific. Why do they need to invest money, time, and efforts to develop the technology which no promised customers? In this situation, no one wants to invest before, so the standardization is not adopted to space objects, retarding the progress of the development. Then the business is still far away from the mass market.

b) Successful cases

In-Orbit Operation activities have been executed in space since the manufacturing of space stations, the Moon mission, multiple times of maintenance for the Hubble Space Telescope, and in many space programs. The technology development has progressed continuously and mostly supported by governments with the purposes on scientific and national security. They were many concepts and efforts to commercialize the services and attract private customers but skepticism about the maturity and reliability of the technology were a big barrier. However, the dawn of the IOS business has just arrived with a historical milestone made by the success of Mission Extension Vehicle (MEV) - 1 from Northrop Grumman's subsidiary, SpaceLogistics, who providing a life-extension service to the Intelsat IS-901in February 2020 by integrating new thrusters and fuel supply to the satellite. This event was taken place in Graveyard orbit concerning that a collision or failure of execution might happen. Shortly after that, MEV-2 completed its first-time commercial docking in GEO orbit with the Intelsat IS-1002 satellite in April 2021 (Northrop Grumman, SpaceLogistics, 2022) without interfering telecommunication service that the satellite was providing. These two achievements newly defined the Technology Readiness Level of the technology creating dynamics in the market and bringing this niche business to the public's attention.

From the success of both MEV missions, the company gains the confidence to perform In-Orbit Services to satellites in GEO. Mission Robotic Vehicle (MRV), Northrop Grumman's 2nd generation service, has been enlarged from MEV and received a warm welcome from clients. MRV has got contracts with an Australian satellite operator, Optus (Erwin , 2022), and several clients to install Mission Extension Pods (MEPs) which are propulsion devices for extending the life of satellites that run out of fuel. It is scheduled to be launched in 2024. The MRV is a spacecraft specialized in Rendezvous Proximity Operations and Docking by robotics and can perform various services including MEPs or new payloads installation, inspection, repair, and de-orbiting (Northrop Grumman, 2021). MRV will stay in orbit for around ten years and is expected to provide services at least 30 times. The Mission Extension Pods can be sent separately when they are required. Thus, Northrop Grumman can provide the services for further customers by launching only additional MEPs or other selected equipment. The company will benefit if interface standard interfaces are adopted among manufacturers and operators which can lower the cost further.

Even the MEV mission had the customer, but many IOS companies are looking for more procurement. At this gap, the government can have a role in facilitating technology in an early phase and as a very first customer funding the research. In addition, public actors have advantages in establishing standards or common rules for the service. So they are important enablers for the business and technology development.

c) Different business opportunities in GEO and LEO orbits

Each Earth's orbit possesses different physical attributes, satellite missions, and operators. The business models could be developed for each Earth's orbit. The study goes deep into two orbits, GEO and LEO, which are protected regions identified by IADC.

The European Space Policy Institute (2020) expected that the early phase of the In-Orbit Servicing market will be driven by demand for life extension. During this period, most of the satellites are non-cooperative making each mission require specific technology and a tailor-made protocol for each execution. As almost the satellites that have economic value for investment in refueling are GEO communication satellites, it will be appealing to start the business and establish relevant architecture in in the GEO orbit. After the success of the refueling service, the IOS can be more commercially viable. Satellite operators can include attributes on receiving the IOS into their satellite orders. Demand from customers can convince satellite manufacturers to adopt common interfaces and satellite designs. But the vulnerability to cyberattacks could increase. This service responds value proposition of customers by offering cost reduction from the necessity of launching a new satellite.

The Institute also assessed the market of IOS from the number of satellites in the GEO orbit, which going to reach the end of life within the next decades, and indicated that there is an opportunity for business in this segment. The GEO orbit is an important orbit for many reasons. First, it is a protected area determined IADC that should be free from debris concerning the limitation of the Geosynchronous orbital slot. Secondly, almost all satellites in GEO are big satellites consuming a large budget and time for manufacturing making it not easy to relaunch a new one when a satellite unexpectedly fails before reaching end of life. Lastly, there are many communication satellites residing in GEO orbit and producing high economic value that their owners do not want any interruption happen. Hence, the GEO market is one of the market segments attracted many IOS providers. For the case of Japan, the GEO area has been chosen to be a place for GEO robotic platform, an infrastructure to provide support for further Japan's IOS activities.

At the same time, LEO is crowded with a high diversity of space objects, including thousands of satellites in constellations, small satellites weighing from a few kilograms and up to a few hundred kilograms, space stations where astronauts are living, and rocket bodies. The orbit is appealed for conducting low-cost space missions, so it seems that costly IOS is not attractive for the operators who prefer cost reduction. However, due to the congestion in the orbit, LEO is a place for enormous hazardous space debris generated from Fengyun anti-satellite in 2007, the Iridium-Cosmos collision in 2009, and the Destruction of Cosmos-1408 in 2021 (NASA, 2022). Combining that many huge debris from rockets is in the orbital region, Active Debris Removal, especially for the large pieces, is a business opportunity in the LEO. By the way, the Active

Debris Removal (ADR) service is not a popular business model accounting to no one but only a few big government space agencies want to pay for it, even though it is an indispensable activity for reaching space sustainability. The chance may come from the companies who launch satellite constellations that they should compile to the IADC guidelines and de-orbit their thousands of satellites after completion. It is possible that a small portion of those satellites will malfunction and cannot perform de-orbiting by themselves. ADR can be a solution for them.

Besides, the displacement of space debris, Skomorohov et. Al (Skomorohov, Hein, & Welch, 2016) showed that nanosatellites could be a type of IOS target concerning its subsystem element have high TRLs for receiving the service. Moreover, the number of nanosatellites could grow bigger in near future, to the fact that many Newspace actors are interested to carry on developing nanosatellites. It is reasonable to demonstrate the services suited the satellite'd class.

d) Examples of on-going IOS projects and businesses

Hereafter, some examples of projects promoting IOS activities that can boost commercial opportunities are elaborated.

iBOSS is a cooperative research program of the German Aerospace Center (DLR) collaborated with German research institutes and partners working on standardization of satellite interfaces and modularity (Kreisel, Schervan, & Schroeder, 2019). The program aims to create space system standard interfaces of a satellite as a building block for In-Orbit Servicing technology by proposing intelligent Space System Interface "iSSI." It is designed to support the Plug-and-Play principle allowing carrying the services of satellite in-orbit conveniently. The qualification technology of the product was proven by ground qualified and acquired TRL 6. The iSSI is a multipurpose device delivering various services, for example, coupling, de-coupling, extension servicing, upgrading, re-purposing, configuration, re-configuration, robotic-end-effector, late loading solution, and hosted payload adapter. The innovation has been expected to promote the growth of the Newspace business by introducing a new technological solution, space mission operation, and commercial model. It can be a step in reaching space sustainability where the scheme of space mission implementation is reconstructed. The project illustrates an effort to set up common interfaces among satellites. Once the proposal of the standard interface is adopted, the cost of developing IOS could be reduced as the developer can focus to invest in the specific technology that is compiled to the standard. Regarding its business model, being the first mover to deliver the practicable product to the market is important. The satellite operators and manufacturers could be convinced that by having the interface standard, their satellite can gain more advantages for further services, considering the number of customers has not reached the point of a mass market.

Made In Space is a private company focusing on manufacturing in space (Made In Space, 2022). The company has demonstrated manufacturing and fabrication techniques in the International Space Station to develop its hardware products in the microgravity environment. The first piece of equipment the company demonstrated in ISS was the 3D printer. Currently, more products have been certified including Additive Manufacturing Facility, Fiber Optics Manufacturing, and Recycler for 3D printing materials. With these products, the company can offer services in technical support for payload including hardware and software development and assembly using the unique advantage of microgravity which allows material processes conducted differently from doing on the ground. They develop a specialization in related technologies that allow manufacturing in space. They not only envisage in-orbit manufacturing but also aims to leverage the technologies to assist space exploration program. Made In Space also partnered with

Northrop Grumman and Oceaneering to conduct the Archinaut project, a platform that supports large-scale manufacturing in the space (Made In Space, 2022). The project is planned to manufacture some component part in space and assembly the component to create a large-scale space object that has a higher capacity and not is limited by the launcher's condition and harsh environment during the launch. The disruptive idea will transform the way space objects are produced and managed after disposal. The strategy that propels the company is "Nothing is launched from the Earth, everything is manufactured in space". All the expertise that Made In Space has been improving are important part necessary to complete a satellite value chain, making it a circular chain that depends on fewer input materials from Earth. The missions of the company promote the scenario of space sustainability.

One of the European projects on in-orbit manufacturing and assembly is PERASPERA In-Orbit Demonstration (PERIOD) undertaken by a consortium of European organizations (PERIOD partners, 2021). The objective of the project is to demonstrate technologies for building satellites in orbit by a robotic system. They presented the concept of In-Space Services, Assembly and Manufacturing (ISAM), an in-orbit factory conducting satellite assembly and refueling service, where robotic systems will be installed with the factory to capture satellite and perform service tasks to them. The factory will be remotely controlled from the ground. The program was based on European existing innovative building blocks, for instance, Space Robotics Control and Operating System, Goal-Oriented Autonomous Controller, Data Fusion For Space Robotics, and Integrated 3D Robotics Sensors Suite. The robotic systems are supported by Airbus technology on Active Debris Removal. They also set up standards of interconnecting parts for servicing satellited. The program is expected to increase the capability of European countries in IOS and space robotic technology. The impact of the project could create a new market for IOS, Assembly, and Manufacturing including demonstrating the technology and robotic system.

Orbit Fab, a concept of gas stations in space has been presented as an infrastructure accelerating In-Orbit Servicing market (Orbit Fab, 2022). They want to initiate a propellant supply chain in orbital areas. Their offerings include Rapidly Attachable Fluid Transfer Interface (RAFTI), a system for receiving in-orbit refueling for a satellite that is pre-designed for propellant transfer. They also have an agreement of partnership with Astroscale, a company delivering Active Debris Removal Service as the Orbit Fab will refuel 1,000 kg of a propellent to Astroscale's in-orbit servicing spacecraft, LEXI. Orbit Fab can supply the propellant for general satellite or other In-Orbit Operation infrastructure. The business depends on the prosperity of the diversity of orbital activities which will require more energy to drive various missions.

The satellite manufacturers could be the first group affected by the advancement of the In-Orbit Servicing technology. Once a company routinely perform refueling and mission upgrade for cooperative satellite, it is possible that the satellite technology could adjust to meet the requirement of receiving the service. The manufacturers who can offer their satellite product with a service package such as inspection, life-extension, maintenance, and mission augmentation, could gain higher competitiveness. Moreover, if a company can have a large piece of market share, it can establish a standard of a satellite which will return to reduce their cost due to economy of scale.

Northern Sky Research (2022) forecasted that the value of the In-Orbit Services market will generate revenue of around $4.7 Billion within 2031, mostly from the life-extension service. The high economic value of telecommunication satellites in GEO orbit are an interesting market for investors according to the report. Even, at first, the technology did not drive by the demand to attain space sustainability but by the need to solve early failures of expensive space objects or save cost in advance from developing and launching a new satellite. Undoubtedly, those beneficial activities enable many solutions to cope with the revere problem of space debris and create a circular value chain of a space object. Currently, the technology is not mature to completely change the paradigm in short term, but it shines the light on the way that further development could evolve further.

3.1.5 National practices for sustainable space

Considering the market of IOS, incentives from public actors to the business affect viability of the market in the early phase. Institutional actors, both governmental entities and legacy private companies, are key stakeholders to spark and scale up the business. Thus, this study carried out interviews with three professionals who have expertise in IOS technology. The topic discussions were two main parts, space sustainability, and IOS usage. For space sustainability, the interviews were guided by the issue of the scope of sustainability, regulation, and implementation, technology development and commercialization, and platform to support sustainable space. For IOS, the discussions covered plans for In-Orbit Servicing (both technology development and utilization, technological constraints, policy and regulation, facilitating private sector, and IOS market. The order of interviews showing in the study was arranged alphabetically. The table 2 presents some interesting agencies' actions shared by the experts during the interview starting from the agencies' general scope of responsibility, tackling space debris, plans to boost up commercial IOS, next actions for sustainable space, and obstacles in reaching space sustainability using IOS.

Table 2 Comparison of national practices towards sustainable space with IOS contribution for the cases of France, Japan, and Thailand

	France	Japan	Thailand
Mission scope of the space agencies	▪ formulate space policy ▪ implement space program ▪ carry out unprecedent space projects ▪ coordinate between space and non-space actors in the country	▪ implement space program ▪ develop cutting-edge technology in collaborating with companies ▪ support private actor in the country	▪ formulate pace policy ▪ implement space program implementation ▪ conduct research and development activities ▪ coordinate between space and non-space actors in the country
How to tackle the space debris problem	▪ propel circular economy with circular value chain of space objects ▪ propose rules and regulatory compliance to IADC guidelines	▪ use Active Debris Removal (ADR) ▪ adopt IADC guidelines	▪ conduct research related space debris and operate space weather forecast research and operation ▪ adopt IADC guidelines

Plans to boost up IOS commercial activities	▪ No policy to be a direct customer of IOS no plan to include IOS receiver to their future satellite ▪ provide financing, technology, and expertise for IOS businesses ▪ stimulate collaborative networks among different actors through a common vision in order to avoid some actors to leave the industry before the technology mature ▪ life-extension market is ready but this business model may not sustain over a long time due to the current linear value chains	▪ No policy to be a customer of IOS and no plan to include IOS receiver to their future satellite ▪ procure an ADR service from the companies who are demonstrating both ADR and IOS technology ▪ assist private companies to improve and validate the technology to help them to enter the global market ▪ GEO market has high economic value and worthwhile to invest	▪ Determining to be a customer for the service depends on suggestion from the satellite manufacturer and no plan to include IOS receiver to their future satellite ▪ The agency has no plan for support IOS private sector in the country
The ways towards space sustainability	▪ establish a platform to accelerate sustainable space ecosystem by proposing 1) a concept that in-orbit resources, such as space debris and solar power, can be shared among actors 2) the new paradigm will consist new circular value chains of space objects, new missions, and new actors ▪ identify all stakeholders affected of the coming the new paradigm, both	▪ initiate GEO robotic platform concept, a cluster of smallsates for self-sustain ecosystem in orbit that all materials and energy circulate and transform in the ecosystem with least adding new inputs ▪ forward actions; 1) weight reduction (life-extension) 2) Active Debris Removal 3) 3D-printing technology for in-orbit manufacturing	▪ formulate national space policy and space strategy that include ADR, IOS, and associate technological projects ▪ create and strengthen international cooperation with oversea entities and multilateral for a.

	current and possible actors in the future		
Obstacles in reaching space sustainability using IOS	▪ switching cost to new innovations and infrastructure, current actors may not want to change ▪ IOS standards can be a disadvantage for startups and small companies	▪ lacking of standardization and modularization retards advancement maturity level of IOS ▪ Chicken-and-egg problem, no one want to invest before the others	▪ cost for IOS is high comparing building a new satellite ▪ IOS technology is not mature enough, high risks, and has limited options

The table 2. Shows the comparison of national policies dealing with challenge on space sustainability. The three countries have the same mutual goal in reaching sustainable space. They all adopted the IADC guidelines and have encouraged actors in their countries to follows the approach. They are aware the capability of IOS that can create novel innovation. The three countries posited themselves in the facilitator role but focused on different areas of implementation. France has placed importance on value chain, supplied resource, and new types of space missions. Japan aims to stimulate a common platform that many space operators can use together, which will enlarge capability of space missions to be able to conduct sophisticate missions such as recycle in space. Thailand is in a phase of designing the space national policy to accelerate capacity building in research and development including strengthen international cooperation. The three countries are a part of space actor sample that have their own agenda and focus areas. Therefore, international mechanisms should include their different opinions to formulate a governance that can responds various needs and create harmony among countries in order to drive sustainability issue in the global space ecosystem.

The below sections are summaries of expert interviews in the topic of IOS and space sustainability.

a) The case of France
Interview with Mr. Michel Sylvain, Strategy Department, Deputy Industry and Ecosystem Department NewSpace and ecosystem, France

CNES is a French space scientific and technical public agency, responsible for proposing space policies, supporting and executing space programs, providing intersection among public and private actors, including stimulating research in scientific technological, and industrial topics. The expert is a member of the innovation department, working on seeking disruptive innovation, promoting a circular value chain, and amplifying IOS. He has experience in broad space programs, foe examples communication satellites, Automated Transfer Vehicle for ISS resupply missions, rendezvous missions, Hyperspectral Earth Observation satellites, and space debris removal. Currently, He is working with more than 25,000 CNES officers, from different departments and skills, to set up a frame for disruptive innovation creation and common vision inside CNES. He is also collaborating with space and non-space people in the space ecosystem, biomimicry, and blockchain for space through various activities such as raising awareness on space debris and space circular economy including seeking new solutions from collective intelligence. The works are based on the idea that CNES should carry on unprecedented projects, no matter whether the projects are at testing or feasibility study the levels, they can generate dynamic or trigger something new in the French space ecosystem.

CNES intends to establish an effective platform to accelerate Newspace's sustainable ecosystem. Many space and non-space actors have the capacity and resources enough to be parts of many major space programs such as the Moon mission, but they did not recognize it. CNES, then, aims to identify competent companies and induced them to be parts of the ecosystem by proposing a clear vision in Newspace. A large number of actors are important to strengthen the French and European space industry. Enlarging the economy also allows more demands for space activities.

Fostering a sustainable space ecosystem comes with a circular life-cycle of a space object. Many associative technologies can contribute to the paradigm such as In-Orbit Servicing, Assembly, Manufacturing, recycling, and many more. The diverse activities required different companies and various professionals from many fields of knowledge to work together. The design of structures, dynamics, and components in new value chains supporting the new ecosystem is an essential mission that CNES is working on.

In the case of the IOS business, its market did not exist yet which also has a good advantage of no competitors in the market. CNES's strategy to support the market intends to relieve the competitive atmosphere among the IOS companies by establishing a shared common vision, to avoid some actors to leave the industry before the technology reaches a maturity phase and the market arrives at a growth stage.

CNES has a plan in mind to support a circular economy by utilization of in-orbit resources and sharing among the in-orbit mission operators, concepts of energy farming to support the activities, and new design of satellites and their systems to expand their capacity and reduce sizes. All the activities need an infrastructure investor, which can be the public sector. If we need to transfer current space missions to fit in a sustainable ecosystem, we need to shift the whole space value chains to a new paradigm, with novel spacecraft designs, functioning, and operating. In general, the change to a new value chain requires switching costs for a new invention and operating protocol development including setting up new infrastructure which no one wants to pay for it. This is an initial obstacle needed to be confronted to create sustainable space.

Regarding the plan for In-Orbit servicing, CNES has implemented In-Orbit engineering research in-house. It also promotes the development of the technology for French Newspace actors by supporting financing, technology, and expertise, including creating a marketplace for the IOS business. Whereas, when coming to satellite development projects carried on in CNES, there is no policy to equip In-Orbit Servicing receiver parts or features for their future satellites.

Technology constraints could also be significant factors retard the activities. For refueling in orbit, the challenge is the mission operation has to ensure that no avoiding leakage of fuel, propellant, or pressure. Spillovers can cause difficulties to achieve the objective, or even make the event worse by increasing the opportunity of breaking or explosion. Therefore, the establishment of a standard for the services such as refueling or other maintenance could ease the risks of performing In-Orbit services. The case of the Starlink project from the United States has demonstrated obvious competitiveness using a first-mover advantage in the satellite constellation market. The greater number of their satellite model has taken up a ratio of overall orbiting satellites, the easier to set their satellite heritage to be a standard for servicing market. Then, standardization hands over the disadvantage for small startups and newcomers. The European actors are trying to propose a standard for satellite manufacturing driven by European

Cooperation for Space Standardization through satellite procurement contracts with their customers.

For policy and implementation to mitigate space debris issue, CNES has a role as a policy formulating body for the French government and has been working on the process to move regulatory and action plans serving a change of current linear space economy to a circular economy. There are some regulations upholding a sustainable space environment that has been used as a practice in the country, for instance, satellites in LEO orbit should follow the IADC guideline by de-orbiting within 25-year after the end of the mission. The regulation has applied to all public entities and private companies, rigorously for the case of satellite constellations. By the way, they are trying to avoid the establishment of a rigid regulation on IOS standards for the reason that the technology is not fully mature. The research and development need trial and error. Then leaving an open space for companies to experiment with their ideas and business models could accelerate IOS technology to the front line.

To support private companies, CNES aims to originate a mutual vision of the paradigm that all stakeholders can share infrastructure and gain benefits together from resources harvested in orbits such as space debris and solar power. The service providers could be incentivized as the public sector support establishment of the infrastructure. The Moon mission can be a neighborhood market of the services and also supplement the new value chain.

As for the market of IOS, life-extension service is existing and customers are ready to purchase. Apart from that, refueling and service have yet mature until the standardization of satellite interfaces is prevalent and installed in satellites. But the market will not have lasted in the long term. CNES keeps going to try new technology and equipment to make satellites more advance and trackable so related services will change accordingly. When the new paradigm of space arrives, there will be a new type of satellite with a new value chain, then the business plan of the current IOS might have to be adapted.

To summarize, two issues need to be addressed. Firstly, if the companies build business models based on the current paradigm, which consists of linear value chains, they might face a financial challenge to start the business and provide the service. Moreover, the business models for In-Orbit Servicing might not last in long term due to satellite technology is rapidly changing. Then creating a new paradigm enabling circular value chains should be done before, to map a big picture of opportunities in a sustainable space ecosystem. Secondly, transferring between the two paradigms requires identifying all stakeholders affected by the emergence of the new paradigm, creative ideas on how to extract values in the new value chains, and a strategy to bridge a gap between the two scenarios. From his point of view, technology is not a major barrier, but value management and benefits distribution could be great contributors to achieving space sustainability.

b) The case of Japan
Interview with Mr. Hiroshi Ueno, J-SPARC Producer, Business Development Group, Business Development, and Industrial Relations Department from Japan Aerospace Exploration Agency, Japan

Over the 20 years, Japanese space-related agencies, now consolidated as Japan Aerospace Exploration Agency (JAXA) have worked on robotic technology, In-Orbit Servicing, and space exploration fields in the KIBO module program, Japanese Experiment Module Remote Manipulator System (KIBO's robotic arms) including space probes exploring the Moon, comet, and planets. In 1997, Japan successfully demonstrated in-orbit docking between two satellites, "Orihime" and "Hikoboshi" which are separated from a satellite name "Kiku No. 7". The mission was equipment exchanging between them using a robotic arm. It is the very first orbital service in the world. The expert, Mr. Ueno was in charge of the assembling at that time.

Given that JAXA own deep knowledge of space technology, they seem do not interest in small satellite projects which are popular in the Newspace industry which have outstanding uniqueness. The government agency have paid attention to carry out heavy satellite projects while encouraging the private sector to develop small satellites for its own business. JAXA's strategy is to develop cutting-edge technologies and they are many joint projects between JAXA and private companies to transfer the knowledge and expertise.

The expert believed that, in order to preserve the space environment from orbital debris congestion and allows safe space operation, a self-sustain ecosystem in orbit is needed to be achieved. The self-sustain ecosystem can be described that almost all materials and energy circulate and transform internally throughout various activities in the ecosystem sustainably with least adding new inputs regularly. The beginning step is a weight reduction of overall space objects which can be done in different ways. The first way is the life-extension making satellites can be operated longer, than a necessity of launching a new satellite has been postponed in a certain time. Secondly, Active Debris Removal could have a role in removing harmful dead satellites by de-orbiting or changing their position to the graveyard orbit. Thirdly, 3D-printing technology can transform waste from parts of defunct satellites into materials that can be useful for in-orbit manufacturing activities. The life-extension mission and Active Debris Removal were successfully demonstrated. The concept of 3D printing in microgravity has been proven in some level of TRL in ISS and is under research process.

Even though JAXA has a list of satellites developing or will be developed, they did not intend to use In-Orbit services for their satellite. the determination on whether to assemble IOS receiving equipment in developing satellites or not has been placed on satellite project managers' consideration. Launching a new satellite to continue a mission can be a better choice as it can increase the capability with the latest technology. In addition, JAXA has no direct policy trying to standardize their incoming satellites as well.

Regarding In-Orbit servicing commercialization, JAXA has pointed out improvements and validating of technology maturity for helping private companies to enter the market. The agency has no direction to be a client of them for now considering that the technology is not mature enough. JAXA then initiated J-SPARC, research, and development program to assist the Japanese private sector by facilitating them with JAXA's assets and in-orbit technology. The goal of the program is to advance Japanese Newspace businesses to the global market. One of them is In-Orbit Servicing.

How does the organization think about the market? The market for In-Orbit Servicing can be classified into two markets, GEO and LEO orbits. In nature, the GEO orbit has been prioritized as where the high economic value satellites have resided. With an attribute of the orbit that allows a space object in the region fixed in the sky compared to a position on Earth's surface. Many of them are heavy satellites providing telecommunication services. They have some economic value to do refueling, upgrade, or modification to continue satellite operation to gain revenues. On the other hand, the satellites in LEO are smaller and have a lower cost. When an LEO satellite reaches its end of life or becomes malfunctioning, its satellite operator can select to launch a new one that is more economic in terms of cost and functionality. GEO satellites' value is relatively higher than LEO satellites. GEO is more feasible because the IOD cost is very high.

Standardization and modularization are the keys the IOS needs. Without them, the activities will be very complex. For telecommunication satellite operators, the continuity of providing services is very important for their revenue. They want any interruptions as less as possible. Standardization can reduce the time of conducting the service and decrease the risk of failures. However, to set up a standardization or commonality of satellites, they have to confront the Chicken and Eggs problem. Who should be the first to invest using In-Orbit Servicing, operators, or manufacturers? The lacking of standardization and modularization are key drawbacks that In-Orbit Serving has to overcome before growth a stage of market dynamics emerges.

Another relevant market the JAXA has promoted that shares the same core technology is Active Debris Removal. JAXA launched the project Commercial removal of debris demonstration (CRD2), a technology demonstration on removing large-scale debris from orbit, in collaboration with the private sector for the exchange of technology. In the commercial aspect, JAXA is also a direct customer. The agency has procured the service to remove JAXA's decommissioned satellites for phase 1. Then, the agency will continue to purchase the service for other debris in space that can endanger Japan's assets in space for phase 2. By encouraging the business, the companies can broadly experiment with other applications of the technology, one of them is In-Orbit Servicing. Then the subsidy Active Debris Removal can reinforce the In-Orbit Servicing demonstration.

In addition, JAXA has opened an opportunity for a private company to use JAXA satellite after their mission completion but the satellite still performs well in project RAISE-2. The company can continue operating the satellite, design utilization of systems onboard, and provide data of the missions to JAXA still has received data from the company for further service. With this idea, if In-Orbit Servicing is mature enough can regularly upgrade the capability of satellites, it can open a market of second-hand satellites. When a satellite completes its primary mission, its systems can be upgraded or changed to provide new missions. So, the satellite can still have value and be able to be sold to the next operator. The model can be another revenue stream for In-Orbit Services and the sustainability of space that JAXA is trying to demonstrate.

In the short term, Japan also envisages opportunities in the Active Debris Removal market, which has not been commercialized yet. Active Debris Removal has two main applications. Firstly, removing large space debris which can reduce the probability of collision to create countless small fragments. By the way, the market potential is quite low as they will be only some government agencies enthusiastic about a clean space environment. Even it genuinely yields high benefits for the public. Secondly, the End-Of-Life service can target serving satellite constellations. For a constellation, around 1 – 10% of the satellites have some possibility to be damaged. The risk can increase more if an unpredictable sun storm is taken into consideration. These broken satellites required an Active Debris Removal service to deorbit down to Earth's atmosphere. These kinds of services can be a business opportunity in the Active Debris Removal market.

In the long-term, the GEO robotic platform concept (Ueno & Kamimura, 2020) a cluster of small satellites performing distinct tasks is being proposed to JAXA. The cluster will consist of observation satellites as sensors, communication satellites providing serving all contacts between the whole cluster and a ground station, robotic service avatars controlled from the ground, and GEO service management & energy transfer systems delivering energy to the satellites. All spacecraft in the cluster will communicate internally by wi-fi. The concept can enlarge the capacity of satellite systems by distributing each function to a specific satellite in the group. A few private companies can cooperate on the operation of satellites or some specific service. All the platforms will be commercialized to provide satellite as a service for general customers who no need to operate their satellite. The government is probably a customer of the concept. In the long-term, the concept will be enlarged towards GEO city which will house modules for waste management in addition to diagnosis, precaution, and repair of spacecraft.

An interesting business case in Japan is Astroscale, an Active Debris Removal company started in Japan. The company aims to offer a service like a car repair service. Once they can successfully remove debris actively, their technology will be proven that they can provide other services having the same core technology, such as refueling or change of equipment. Orbital servicing companies are considering a similar strategy.

Even though reaching the scenario of a self-sustain ecosystem will take a long time more than 10 or 20 years, all articulate activities have to be demonstrated, planned, and prepared from now. Beginning with a realization of the necessity of a sustainable space environment could be a good step to formulate the policy level's priority, shape technology direction, and create norms of safe space operations among all space actors.

JAXA is aware of the space debris issue and adheres to international guidelines and rules on space debris mitigation, for example removing space objects from orbit within 25 years on after the end of the operation. The agency implements the international guidelines together with moving the commercial space sector in the country. JAXA also creates and supports rules and regulations on doing some sort of IOS, Safety standards for on-orbit servicing.

c) The case of Thailand
Interview with Dr. Sittiporn Channumsin Director of Space Technology research center and additional information from Mr.Yossavin Sombutpanich Senior Satellite Specialist, THEOS-2 Project Office from Geo-Informatics and Space Technology Development Agency, Thailand

Thailand, through the space agency GISTDA, holds the principle of guidelines for LTS in planning and implementing their space projects. Several projects related to space sustainability comprising of 1) Flight Dynamics Software, 2) Space Traffic Management System, 3) Onboard Flight Software for satellites 100-500 kg, and 4) Space weather forecast research and operation. Most of the projects are currently in the operation phase of their satellite and have not yet transferred to a private entity. The agency has also placed projects on Active Debris Removal, IOS, space information analyses, and prediction, in their research and development strategy and national space policy. Many products have been launched providing services such as conjunction prediction for a specific satellite, onboard flight software, and space weather forecast system. For satellite development, GISTDA is undertaking several small satellite projects. Some of them will host multiple payloads. They have created international collaborations, for instances, in European institutions and international multilateral for a as well.

Regarding using in-orbit technology for space sustainability, the first important drawback the country is concerned about is the budget. The agency has operated (an) Earth observation satellite(s) to deliver the socio-economic benefits for the country. The economic value of the satellite depends on downstream usage of geo-informatic data from satellites, which can be substituted by other satellite data providers (space agency partners or private companies) and other infrastructures (drones and high-altitude platforms). Then, they have less economic value to maintain leading to low interest in using in-orbit servicing for the life-extension of the satellite.

For Thailand, there is no current plan to purchase In-Orbit Service for their current and future satellites. The agency gave comments that,

1) Their satellite was not originally designed for in-orbit servicing. The satellite is a small class (under 1000 kg). The platform is an enclosed type with all units integrated, tested, and validated on the ground. It's simply not feasible to perform any service (repair or replacement) in orbit. Moreover, for the commissioning, it has surpassed the original lifetime by over 2.5 times with some redundancy lost.

2) In-orbit servicing of the satellite is limited to very small options such as in-orbit docking of the add-on propulsion module. As the module cannot communicate directly with the satellite, it requires dedicated operation (TMTC exchange) with the ground system without interfering with the communication between the main control ground system and the satellite. The satellite was also designed and optimized for Earth imaging (Compact platform with three-axis control) where the AOCS does not have a large margin to accommodate additional mass and intertie without compromising the agility.

3) As the satellite was procured from a satellite manufacturer, the agency relies not on only the in-orbit servicing provider but also on the manufacturer. Hence, the advice and comments from manufacturing companies are important for them in determining whether to use a service or purchase a service from whom.

4) Satellite technology keep evolving through the years, it is more rational to consider replacement program rather than costly In-Orbit Servicing.

Apart from the technological constraints, they shared the opinion that to consider in-orbit servicing in the first place means that the satellite has a very high value (commercial communication satellite or scientific mission). Their satellites are neither of these cases. Another issue to be considered includes the cost of in-orbit service needs to be reasonable (cost of the service and all additional infrastructures such as ground control system), the scope of warranty that comes with the service, risk of failure from improper docking or insufficient structure strength leading to mission failure. Furthermore, In-orbit servicing of the satellite which has been operating far beyond its design life is subjected to the risks of unpredicted end of life. Having Low heritage satellite bus is also an important factor. They might not be interested until the same heritage has been proven with a successful In-Orbit Servicing mission.

To address the market, even as a service provider or customer, the market is quite limited due to only a few services mature and reliable. For them, it's more feasible to design the satellite with adequate reliability rather than taking a risk in implementing this kind of service.

Innovative technology pertinent to in-orbit operations has been marked in many national policies as a strategic technology to create or maintain the competitiveness of national space capability by many countries. The technology was placed in different priority and different aspects depending on their policies. The UK has supported Surrey Space Centre and Surrey Satellite Technology to demonstrate and set a baseline for the capability including seeking potentiality in determining their decision on the "make or buy or partner" Strategy on this technology. Italy has emphasized the research and development aspect of in-orbit servicing aiming to boast up space economy and open opportunities in the space exploration (European Space Policy Institute, 2020). United States, China, and Russia, the major players of in-orbit operations in the world, have attached great importance to them by allocating large expenditures and consistently demonstrating the technology with dual-purpose, civil, and security.

Besides technology transfer and financial support, public sectors should jointly create international mechanisms setting norms of safety space operation and develop guidelines upholding sustainability in space. As the ESPI report stated that *"the demand of IOS capabilities and the emergence of proper business models is greatly impacted by the adoption of common norms influencing IOS directly – e.g. RPOs guidelines and standardization of "cooperative" target satellites* (European Space Policy Institute, 2020, p.37)". Considering that space is an area where people from all around benefit together, intergovernmental bodies are important focal points to advocate for the issue that needed to be moved in the long-term and needs some degree of national regulation.

There are many more mechanisms to drive space sustainability. European Space Agency started Clean Space Initiative in 2012 aiming to improve the sustainability of activities in space and on Earth. The initiative opened calls for concepts of In-Orbit Servicer spacecraft and identifying of customers. ESA has provided financial support of €50 million for business case assessment and technology development on IOS [12] not including the budget spending on Active Debris Removal technology which can be applied to In-Orbit Servicing. ESA intends to build technological capacity on the supply-side alongside growing the demand side in business.

The international norms and guidelines play an important role in public policy and regulation of countries on their space affairs. They are also the first factor to determine the viability of the IOS business and the emergence of the market.

3.2 Theoretical framework

In this study, the tool for deriving the way to sustainability comes from economic concept which also related to administrative idea. The theoretical framework part expresses since academic though regarding to the foundation framework working on attempt to change a scenario, the concept of goods which is important to mention as the goods refers to a resource that has to be manage sustainably, and the economic theory of Common-Pool Resource as a main tool in this work to shape the recommendation.

3.2.1 Frameworks for transforming an economy

Regarding to reviews in the empirical frameworks section, the input information shows some characteristics of space economy in a perspective that IOS activities are involved. Firstly, the literature reviews indicated that the most official international forum in space which has impel the space sustainability issue, COPUOS, is represented by States who give direction and priority of actions to the committee. The States also have authority to regulate and facilitate space activities in their countries. Secondly, space program is a strategic mission of a country as it also presents national security capability and IOS is one of the most advance fields of research in space technology, then the market cannot be free without closely watching from the States. Moreover, many IOS technologies were transferred from government sector to the private companies. Thirdly, opinions from the experts suggested that, to achieve sustainable space paradigm, governmental support is an indispensable contribution to platform creation and primary budget for space actors, particularly for IOS missions.

On evaluation of information elaborated in the empirical framework, a suitable theoretical tool is important to organize diverse arrays of information and derive a set of recommendation. There are many techniques and tools that have potential to assist transformation of a system to another paradigm, for instances, Game theory, Nudge theory, and Common-Pool Resource concept.

Game Theory

Game theory has been always brough up when dealing with situations on maximization of benefits for actors in a situation. A famous model of the concept is the prisoner's dilemma. Two suspects are interrogated separately for their guilt in a crime with no adequate evidence to arrest them (Fudenberg & Tirole, 1991). They cannot communicate each other. There are two choices for the suspects, admitting or denying. They acknowledge the rule. If both suspects concurrently choose a cooperative strategy by denying, holding common benefit, they are not fault with current evidences. The police then propose that, for the one who testify the other, he will be released and obtain rewards, which is more utils than the first case that both of them deny. However, if both of them admit, choosing a noncooperative strategy, they both will go to jail but still get the rewards for testifying. The police can adjust weight of payoffs, rewards and years of imprisoning, to persuade the suspects.

The game theory can also be a theoretical framework to explore equilibrium points of the situation and manage players' decision, to reach expected scenarios. By the way, the theory is based on a condition that communications between internal actors in the situation are limited or almost prohibited (Ostrom, 2010). It is not likely for the case of a global industry that all stakeholders actively cooperate together via plenty of agreements. The stakeholders also participate in design norms and standards for applying to their activities. Whilst, the theory suggests that outcome improvement comes from observers outside the situation. Moreover, the theory fits with a limited number of actors which restricts applying the theory to a large-scale economy.

Nudge Theory

Nudge is a theory in behavioral economics describing aspects that influence decisions or behaviors of groups or individual to choose some choices considered better than other alternatives. The theory proposes techniques to induce decision of people rather than suggest forbidding or forcing actions. The actors are free to making a choice but under a specific architecture; such as information, processes, or policies; particularly designed to influence them to select better ways. The Nudge theory contributes economic activities by reinforcing a player in a situation to make more sustainable choices with less rigid regulations and lower cost of implementation. Thaler and Sustein (2008) made reviews applying the theory in various cases including environmental problems. Considering the situation that people tend to do not voluntarily pay some costs to relieve an environmental problem such as limiting greenhouse gases, they offered recommendations derived from the Nudge concept that a government should intervene by providing 1) better incentives 2) feedback and information. The incentives cover raising taxes on harmful activities for environment and giving a right to pollute which can be traded (cap-and-trade system). The feedback and information technique highlight disclosure major environmental effects to let people learn that cost of pollution they have made. The pressure from citizen can motivate the government to ware and take some actions on the problem.

The Nudge theory can make behavioral changes of each small unit by creating an architect to nurture some desire situations. Using it for socio-economic problems can be expected that a small change in an individual could lead to a collective transformation of a whole ecosystem. In this study, concerning the information fed from expert interviews reflecting arrangement of, at least, a large-scale space economy in a country, a theory overarching a big picture of dynamics in the ecosystem is more required to synthesize a recommendation, than a concept focusing on behaviors of an actor likes the Nudge theory. By the way, the Nudge theory should be used in parallel with other theory to transform the space ecosystem, especially applying to private companies to nudge them making more sustainable decisions.

The two theories are widely accepted and have been used in many policy formulations in regulation of industries. But there are still have some limitations as mentioned before. Considering the needs for a new paradigm of space sustainability and the aspect that IOS can contribute, this study sought for a concept that emphasizes on governance structure for a complex system. The concept that was developed and relevant to the Game theory and Nudge theory is Common-Pool Resource, which will be examined in the next section. It is an economic instrument used to cope with challenges on management of a scarce resource based on a particular governance for each system. This concept relates a lot with the government affairs consistent with the situation of space affairs that. Without intervention from states, purely market mechanism cannot lead to sustainability industry (Tirole, 2017). Then some governance mechanisms are required to prevent overharvest of the resource and the Common-Pool resource then is applied in this work.

3.2.2 The concept of goods

Dealing with a market has no one solution that fit all. Each system has its own biophysical constraints, attributions of involved stakeholders, and rules in using the resources (Ostrom, 2010). To elaborate on a market which require government intervention, E. Ostrom suggest two factors for analyzing types of goods and services, subtractability of use and difficulty of excluding potential beneficiary.

Subtractability is an attribute related to sharing a good among actors. Some types of goods are produced to be occupied by a consumer and others cannot be benefited from the resource during utilization, such as houses and car parking lots. These types of goods are subtractable. One unit can be consumed by a customer in a period of time. The goods can be scarce or easily deteriorated. On the other hands, some products can be shared among the group of consumers without depletion, for instances, parks, national security, weather forecast. These types of resource are not subtractable. They can be shared among a certain number of beneficiaries than having a lower chance of depletion than subtractable resource.

Levels of excluding of potential beneficiary to use resources is also a crucial factor. Some resources are easily to manage them serving a specific consumer. For example, sellers of commodity can decide whether they will sell or not sell their products to a specific client. Theaters can announce their rules for exclude unwanted customers. The difficulty to exclude beneficiary of the goods is low and a government has less duties to intervene the markets. In contrast, some services are hard to manage. When a State provides security services, all people in a country benefit from the public goods, no matter they will be citizens or foreigners. Anyone can access and use a river. The difficulty rate of prevention some group of actors while allowing specific clusters to use the resource is very high.

The two characteristics classify goods in to four groups as below (Ostrom, 2010).

- Low subtractability of use and low excludability of beneficiary: Toll goods such as bus service and public parking lots. The services can supply many consumers in the same time. The service providers can set some conditions to screen users.
- Low subtractability of use and high excludability of beneficiary: Public goods such as fire protection, ocean. One service can serve all people in a community equally. The resources cannot be kept for a small group of consumers. Everyone can access the goods without barriers freely.
- High subtractability of use and low excludability of beneficiary: Private goods such as commodity, medical drugs, electricity. The products can be used for only one customer who pay for them solely.
- High subtractability of use and high excludability of beneficiary: Common-Pool Resource (CPR) such as irrigation systems, fisheries, pastures. The resources can be harvested by anyone. By the way, they can be occupied by a single consumer at a time.

This study focuses on the last type of goods, Common-Pool Resource (CPR). It possesses the both factors in high rates, can be subtracted to a unit of individual and hard for administrator to exclude beneficiaries to harvest them. The resource fallen in this category inclines to be overused until destruction or depletion in consistent with noncooperative strategy in the prisoner's dilemma. The ways beneficiaries harvest a CPR leads to level of sustainability of the system. If the resource has been overuse, the less sustainability of the system. Then, arrangement and preservation of a CPR could lead its system to be able to generate benefits in long-lasting period.

3.2.3 Common-Pool Resource and Tragedy of common

Earlier the idea of sustainability arose, thinkers and economists had contemplated issue of common resources. The concept caught researchers' attention and firstly used in environmental challenges related scarce natural resources. In 1968 Hardin described a situation on using a common pasture to feed animals as a tragedy of common (Hardin, 1968). Given a pasture is a common asset of a community and freely accessed by anyone. The pasture has a limited area. All people in a community bear cost of the pasture, for example maintenance and recovery, in equal proportion. An individual can harvest the common benefits and change it to be his own by let his animals graze in the pasture for growth. Once the cattle consume grasses, the common resource reduces. When he places more animals in the pasture, he gains more his own interest while spend the same amount of shared cost with the others to maintain the land. If he ignores to put more animals, the others will do then the portion that he can take benefit in the future is less. Therefore, each individual incline to put animal in the pasture as much as he can to maximize his own interest. When they do so, the common resource will be deconstructed from overgrazing and may not sustain anymore. The situation is accounted to a "tragedy of common" occurring again and again in irrigation systems, fishery industry, forest, and many more situations related to limited natural resources. The scarce resources are the Common-Pool Resource (CPR) with High subtractability of use and high excludability of beneficiary.

Elinor Ostrom was the economist that introduced the Common-Pool Resource concept and partly granted Nobel Prize in Economic Sciences from the theory. She noted a definition of CPR as follows, "The term 'common-pool resource' refers to a natural or man-made resource system that is sufficiently large as to make it costly (but not impossible) to exclude potential beneficiaries from obtaining benefits from its use (Ostrom, 1990, p.30)."

The CPR concept consistent with a social challenge on overharvesting of a limited resources, the tragedy of common. Many systems of finite natural resource have confronted the problem. Accessibility for the usage of an individual or a company leads to minimizing resource's portion that the others can consume, making those who have a high ability to enter the resource system grasp as much as they can, otherwise, the others will do it. The exploitation by overuse causes depletion of the finite resource. By the way, in many cases, the communities or beneficiaries of the resource are successful in arrangement local rules or arrangement governing uses of resources, making them can be sustain over long-time. The principles of arrangement could be considerations for any CPR system to survive exploitation and can create value sustainably.

3.2.4 Design Principles

During a path to understanding diverse resource institutions, E. Ostrom noticed some similarities sharing among businesses that can survive productively within unstable and complex surroundings over a long time. The regularities do not appear in a system failed to sustain. She then proposed a principle to examine mutual factors in successful cases that can sustainably manage the CPR. These factors were seen as essential part of sustainable arrangement of systems. The eight design principles for a large system consist of following items.

1) Clearly defined boundaries

The first thing to consider an interested situation is identification a scope of appropriator and definition of the CPR itself. An appropriator is determined as who own right to use or benefit from the CPR and also bear costs, societal and economical, on maintenance or recovery the asset. People or entities that cannot harvest the resource are outsiders that should be exclude from accessing the resource. The boundary of the CPR should also be mentioned what is the common property that will be managed for interest of the appropriators.

If considering CPR is a grazeland, beneficiaries or appropriators can be herdsmen who get interest from letting their animals to consume graze and will lose benefit if the pasture is destroyed by overharvesting. In addition, the pasture will be accounted as CPR with a clear mandate. It can be depleted and need a time for recovery to produce the advantage again. For the case of CPR as irrigation systems, number, sizes, geographic areas of irrigation canals are example factors that should be examined. The techniques to diverse water to a land should also be considered, for example, opening the gate to let water flow in, then the level of benefit a farmer get can be measured by the time of letting the gate opens.

2) Congruence between appropriation and provision rules and local conditions

When the appropriators jointly utilize CPR, it is possible that the tragedy of common may occur. To prevent exploitation of the resource, some rules regarding distribution, accessibility and harvesting the resource are need to be clarified and applied for all the users. The rules differ from situation to a situation, then they should be tailored-made for each CPR for a society. These agreements should compile with attributes of the boundaries, for examples physical conditions of the CPR, in addition to social and economic factors of the local appropriators. The established rules and regulations are necessary to foster CPR to be sustain and preserve it from exploitation.

For the case of irrigation systems, rules of using water rely on many specific factors, such as existing water storages, level of water available for use, certainty of water's level over a period of time, how much the farmers can take the water to their land, how the beneficiaries purchase for the resource, etc. There is no one rule fit all irrigation systems even they are located in the nearby area. The suitable regulation should reflect all limitation of the CPR and beneficiary.

3) Collective-choice arrangements

The main objective of arrangement the CPR is people get benefit from the resource. There should be no someone overharvest and reduce interest of the other appropriators. Then, for a self-governing system, gathering collective comments and opinions from the direct appropriators in the community can best design and revise the governance pattern on using the resource. Even the process did not assure that participation of all individuals can make them willing to compile the rules, but at least the arrangement can maximize the value from the finite resource. The arrangement in this level is not granted by external authority to govern over usage of the resource, but the agreement among local beneficiaries that govern themselves. Therefore, an individual could compile to the rules as long as the others do. Is To find a collective decision is necessary to make the rules effective.

4) Monitoring

At the step of applying the collective rules, monitoring should be conducted to ensure every appropriator compiles the mutual arrangement. The monitoring process can be cross-checking done by appropriators themselves without relying on external surveillance. It can be voluntarily. When people are aware that monitoring each other can protect their private benefit from overuse by someone, they can be motivated to conduct the process. The monitoring mechanism also contribute revision the collective-choice arrangement to be more applicable when surroundings or the conditions change.

Monitoring methods are diverse. Usually, they function together with sanctions. The systems can take benefit from unique attributes of the boundaries to set up an appropriate monitoring mechanism for a situation. In the water diversion from a common irrigation system for farming, when a farmer opens the gate and water flow to their land, another farmer who own the land next to him cannot receive water until the prior gate is closed. Then the neighbor has motivated to observe that the first farmer compiles the rules, opens and closes the gate in a designated time duration, to protect his incentive and receive an amount of water he deserves. Internal monitoring usually consumes less cost than performing by an external actor who does not a part of appropriator and has less motivation to effectively observe activities.

5) Graduated sanctions,

When the monitoring identifies a rule-breaking, sanction should be undertaken to keep all appropriator in track. Without sanctions, an individual may think the efforts he has spent to compile the rule are not able to give him interest from the resource. Then he resumes to grab the benefit for himself and enters the tragedy of common loop. Similar to the monitoring process, sanctions can be performed by appropriators in the community to sustain existence of common rules and enforcement. Penalty for breaking the rules can be done in different levels, since a small fine to exclusion from using the resource up to the violation and the local conditions. Reputation among the appropriator group can be a sanction technique used in a community.

6) Conflict-resolution mechanisms

During appropriators use the same common resource, it is likely that some conflicts could arise, even among appropriators or between appropriators and external individuals. Moreover, the rules or regulations of using the resource can be ambiguous and need clarification. Mechanisms to dispute and manage inconsistencies should be established for well arrangement of the CPRs. In some system, a court mechanism is founded to serve the problem. Whereas for a global situation, arbitrary mechanism is required.

7) Minimal recognition of rights to organize

Regarding arrangement of limited resource, a government of the country can exercise the jurisdiction over accessibility and using of a specific CPR. Besides, in many cases, the rules set by local appropriators governing behaviors of using the resources in detail are also applied. For example, to manage a fishery system, national overarch general regulations in fishery activities where the local appropriators can specify which techniques or equipment are allow for fishing in their area. Acceptance of the local agreements without interference from the central government is a great assistance for the CPRs to survive over a long time.

8) Nested enterprises

Nested enterprises refer to a multi-layer governance over a CPR. As each level of the system may faces different challenges, it needs different arrangement patterns. Regarding the irrigation systems again, a local canal serves several farmlands should be managed dissimilarly from regional scale consisting. Therefore, for a complex system, the past seven principles for a level should be examined separately and the governances in all level should perform consistently to preserve the resource.

The similarities are like a framework suggesting empirical factors that support endurance of systems. Some systems require more than the principles to stay survive without destruction. Taking the eight principles in to account is a primary step to propel a system that could confronts a tragedy of common towards sustainability

4. Results Analysis

During the First Sustainable Space Economy Workshop 2019 held in Finland, the topic of space sustainability was conveyed in roundtable discussions (Palmroth, et al., 2021). The experts from multidiscipline such as economic, legal, technological, and environmental jointly exchanged views on the agenda of sustainable use of space. From the economic aspect, Common-Pool Resource (CPR) principle was proposed as a framework to deal with finite resources in a system such as fishery, irrigation, including Earth’s orbits. The roundtable discussions applied this concept to the circumstance of the space industry intending to provide economical perspectives to reinforce sustainable management of the use of space.

The space domain is also considered that it could be challenged by the tragedy of common (Undseth, Jolly, & Olivari, 2020). From an economic aspect, Earth’s orbits are characterized as a Common-Pool Resource as it possesses attributes on high level of subtractability and high difficulty of excluding beneficiary to access and use them. The grow number of space activities is leading to overuse of the Earth’s orbits and accumulation of space debris which are treats to space environment. Then, the Earth’s orbits should be treated as a CPR by formulating appropriate rules and governance institutions to arrange usage of the resource.

The CRP concept and the eight design principles was employed by Weeden and Chow (2012). They considered near-Earth orbit as a CPR and used the design principles to derive considerations for governance framework suite to sustainability usage of near-Earth orbit in long-tern. These analyses particular aspects of the space domain that national and international formulators should concern in order to avoid the Tragedy of Common in space. The study identified gaps in current space governance needed to be addressed. The consequent study be

Johnson-Freese and Weeden (2012) also expressed concerns that the Near-Earth Orbits may be the largest-scale resource that principles considered.

The design principles can be adopted to to derive essential factors for a sustainable governance for a limited resource with the purpose to make it sustaina and can heritage value for the next generations. The Earth's orbits then can be accounted as a CPR due to their attributes on limited volume and everyone with enough competency can freely use them. The eight design principles will be used to figure out a space governance that drive the ecosystem towards sustainability. Given that the relevant perspectives of whole space sustainability are extensive, the study takes the only contribution of the In-Orbit Servicing aspect. The output will be considerations to complement recommendations of public and private entities on the formulation of policy, strategy, and business plan.

This study employs the design principles and applied it with the information provided from literature reviews and interviews, with the objective to derive a recommendation to develop a sustainable paradigm of space system. Gaps that are absence in the current scenario are addressed. The Earth's orbits are considered as a CPR. All the design principles are used except the principle 7. Minimal Recognition of Rights.

4.1 Design principle 1. clearly defined boundaries

Considering that the focused resource is finite, in the beginning, identifying who is allowed to perform any acts taking advantage of the system should be examined, to separate people who have appropriation rights from others who are not authorized to harvest the limited resource.

The Article I of the Outer Space Treaty stated that "Outer space, …, shall be free for exploration and use by all States without discrimination of any kind. (United Nations, Outer Space Treaty, 1967, Article I)" Moreover, the report from the Center for a New American Security placed space as a main global common together with maritime, air, and cyberspace, where space presents characteristics of unable to be owned or controlled by an entity, better being utilized as a whole than smaller parts, and any entities have qualified technological capabilities can access and use them (Denmark & Mulvenon, 2010; Johnson-Freese & Weeden, 2012). So, in general, space has provided value to almost all people on Earth for example, through satellite communication services for rural areas, a Global navigation satellite system for transportation, and Earth's surface imagery for disaster management. Then all people are stakeholders in space missions. But taking a look closer from the IOS aspect which play an important role to enable infrastructure for sustainable space, users who could be seen as appropriators can be categorized into two groups. The first group is a direct user, who has the capability of launching their physical assets to orbits or possessing space objects that can obtain IOS. As of now, the boundary covers satellite operators, satellite manufacturers, launch service providers, and payload owners. The second group is beneficiaries, which are a conglomerate of the mentioned actors, such as international committees, in addition to interested parties like insurance companies, non-profit organizations, and youth associations.

Referred to the interviews, the expert from CNES highlighted on including both space and non-space actors to jointly shared ideas on sustainable space paradigm from different perspectives and expertise. He also indicated that the potential future space actors for the new scenario may came from current non-space entities.

To identify the CPR that should be managed for sustainable utilization by the users, a physical criterion can be taken to distinguish space from Earth's atmosphere as the inner boundary and area beyond the orbital region as the outer boundary. The analysis from Weeden and Chow (2012) gave an explanation regarding the debate on the specification of the boundary between air and space, which resulted that a universal definition being left blank. For technical activities, Fédération Aéronautique Internationale (FAI), working on aeronautics, not space, defined the Kármán line, 100 km above Earth's mean sea level, to be the boundary between Earth's atmosphere and space (FAI, 2004).

As missions pertinent to IOS serving spacecraft orbiting around Earth, the outer boundary separated orbital regions from outer space far away and the cis-lunar region should be referred to. IADC (2021) defined geostationary altitude in a range of ±35,786 km. The farthest orbit that space objects remain could be an orbit for post-mission disposal, known as Graveyard orbit, located at an altitude a few hundred kilometers above the GEO. It is also an operation area for IOS, for instance, the case of (MEV) - 1mission provided the service for Intelsat IS-901 in 2020 occurred in the Graveyard orbit to avoid space debris that can be generated if the mission failed and interfered with operating GEO satellites (Northrop Grumman, 2021). The Graveyard orbit can also be a testbed for more missions in the future. Therefore, the outer boundary might be the edge of the Graveyard orbit that laws of Physics allow an object to orbit around the Earth. Beyond that, where area for space probes traveling, spacecraft orbit-transferring to the moon, and cis-lunar missions are excluded from the resource boundary.

4.2 Design principle 2. congruence between appropriation and provision rules and local conditions

This item refers to rules and concurrence identifying the uses of the resource by the users. From environmental conditions, the proliferation of spacecraft in finite-sized orbits leads to congestion in some regions, in particular, LEO and GEO. The obvious guidelines that make changes the on how spacecraft are designed and operated are the IADC guidelines. For instances, space objects in LEO have to be de-orbit within 25 years after decommission. Same as in GEO but re-orbiting instead of de-orbiting. These measures were drafted based on the physical conditions of Earth’s orbits. This restriction opens an opportunity for Active Debris Removal, which shares the core technology and same developers with IOS.

As of now, the number of satellites in two protected regions is not yet restricted, but there is a possibility to arise in the future if the concept of orbit capacity is accepted. The orbit capacity is related to 1) physical capacities of orbits, satellites, and existing space debris, 2) total product and value of services from those orbits (Palmroth, et al., 2021). When the finite characteristic of a resource is accounted for, there will be a maximum level of CPR units that can be used while the system still be sustain. Then a certain maximum number of satellites in each orbit can be calculated, possibly evoking a debate on whether a specific satellite should be sent to space or not, to maintain sustainable space.

IOS can be solutions to maximize the usage of satellites as it can provide versatile services as mentioned in the literature review, for instances, life extension, mission upgrade, maintenance, etc. In addition, the IOS technologies enables appropriators to designate additional environmental conditions to encourage sustainable uses through the concepts of in-orbit recycling and manufacturing, such as GEO Robotics platform and GEO city concept proposed by JAXA can reduce the launching of new items by executing recycle mission in space. In addition, CNES is also interested the idea on transforming in-situ resource, such as defunct satellites and space debris, to assist on-going satellite projects.

4.3 Design principle 3. Collective Choice Arrangements

Perusing an agreement on sustainably use of the resource among users is a necessary to set up the rules that can provide benefits for all users. Apart form the first group of direct users from the design principle 1., suggestions from Undseth, et. Al. (2020) recommended that the involvement from the third parties, the second group of beneficiaries, to jointly formulate objectives, incentives, and supportive activities could increase effectiveness of mechanisms for CPR arrangement.

One of the substantial rules that lead to space sustainability is the IADC guidelines, proposing practices for satellite management throughout a satellite's life cycle from the manufacturing phase to operation and disposal (IADC, 2021). It aims to relieve the accumulation of space debris in Earth's orbits. However, the committee comprises only government space agencies and inter-governmental entities from space fairing nations who own the capability of launching and rocket technology. Even some countries that their private sector developing launch systems do not be part of the forum. Therefore, the IADC guidelines, even though they have received consensus within IADC, but they were based on space fairing perspectives without official participation from emerging space countries and the private sector, who are categorized as direct appropriators from the principle 1. Moreover, some countries have adopted the guidelines and used them at the national law level to regulate space actors both public and private. To set up a soft law that affects a large group of stakeholders, comments and opinions should be aggregated as broad as they can, particularly from Newspace actors who are experimenting with state-of-art space technologies to ensure that the guidelines do not deter the development of the innovation process. The second group of users, beneficiaries, should also involve modifying the rules by leveraging their expertise. Hence, it is necessary to bring the guideline and conduct public revisions again before embedding them in other mechanisms such as the guidelines for LTS.

The case of IADC is an example in common space fora that is frequently absent of engagement from actors represented the majority of space stakeholders but have the lower technological capability.

Another important forum is COPUOS. Its members are State representatives of all countries. It has welcome observers from international bodies and private sector. The committee declared the Guidelines for LTS which have been endorsed by the members. The Guidelines for LTS is a good sample of collective measures and practices from public actor. However, the COPUOS has been criticized for their slow processes which is difficult to catch up trends of commercial space activities. Surely, geopolitics power is a significant force that intervened in the fora's altitudes and designated practices. But COPUOS is on the right track on promote of capacity building and raising awareness agendas on sustainability. COPUOS's missions and initiatives can elevate many stakeholders to have understanding and insight so they can share contributions in designing the rules that will govern themselves. Otherwise, the mechanisms will only be international-political tools instead of constructive instruments shaping cooperative norms for sustainable space. To improve agility of COPUOS can strengthen the space governance in global level.

4.4 Design principle 4. Monitoring

To conduct the space system towards sustainability, apart from some applicable rules should be considered and participation of users is required, monitoring and sanction are processes that keep the evolution on the line. E. Ostrom indicated that monitoring and sanction are mostly implemented by participants, the users of Earth's orbits. With the purpose to protect effectively usage the CPR, appropriators present the role of monitoring each other, ensuring that collective benefits are still there and not be spoiled by a violator. The process yields benefit shared among the appropriators will remain in long term.

The examination from Weeden and Chow (2012) identified that the capability of monitoring in-orbit activities relies on the advancement of Space Situation Awareness (SSA). The SSA refers to the capability of detecting and tracking objects in orbit areas to analyze risks that could endanger spacecraft or assets on the ground (PWC, 2022). Besides the precision of the sensor itself, the accuracy of SSA data depends on the geographical distribution of sensors across the globe. They are various international cooperation pertinent to SSA which promote information sharing including research and development among the members. But a key thing to have in mind is the technology is highly relevant to geopolitics and directly involves national security, which reflects the military capability of countries. For some space products, the fewer people possess the technology, the stronger competitiveness of the technology presents. The truth is only a handful of countries own the most advanced defense armament rather than the rest. Then the capability of monitoring and data are not equally accessed by all appropriators. Not to mention the competency to protect in-orbit assets, there are many countries that own satellites but lack of capability to inspect and protect their asset from aggression. Moreover, currently, as space is being accelerated by Newspace, the private sector should participate in the monitoring usage of space. The fact that today, only a small group holds almost all of valuable information and reserve a patrol role for themselves and allies while the others are incapable to monitor in return. This is a major concern for the space ecosystem leading to inefficiency of the monitoring process and making the pathway to achieve space sustainability to be obscure.

The expert from Japan shared his visions in the interview about the GEO robotic platform which is a step entering more sustainable usage of space. The concept relies a lot on the SSA technology for monitoring nearby space objects and conjunction assessment. Development of monitoring process directly assists working of the IOS platform. Additionally, undertaking of the IOS require neighborhood technologies, including in-orbit inspection, Rendezvous and Docking (RDV&D) and proximity operations. Data from SSA can assist the technology that support IOS.

Currently, many startups have seen business opportunities and jumped into the space data market providing information for satellite operators. By the way, ground infrastructure to measure high-quality SSA data needs high investment and a lot more support from the public sector. With the unique capability of IOS technology, they can deliver orbital information directly from orbits, with higher accuracy than detect from ground stations. Even though, in order to well perform IOS, SSA information remotely detected from the ground is still necessary for the mission operation. The information from the interviews expressed that all three countries aim to facilitate private companies to advance technology and offer IOS services more. Showing that, in the near future, the private sector will gain competencies and might able to collect SSA data themselves. Hopefully, when IOS technology is scaled up, the private sector will able to be SSA data providers. When commercial entities can do it, the SSA information may not be retained only within government agencies. The IOS companies can reduce the gap of acquiring SSA data among the users and hand over monitoring capability to all space users, consistent with E. Ostrom's principle that appropriators should monitor each other in the system.

4.5 Design principle 5. Graduated Sanctions

This design principle 5. On graduated sanction is a consequence of design principle 4. monitoring. After the monitoring process works, in case of any deviation or violation the rules are found, a sanction will be performed to maintain the established rules. Currently, the space treaties and international space law are at the level of recommendation, with no consequence for noncompliance. Even though, the guidelines for LTS and IADC guidelines do not mention punishments for breaking the rules. Enforcement of the mechanisms starts to apply when a country adopts the guidelines in its national space law. The substantial sanctions occur in a country through penalties on the domestic private sector, banning of foreign products and services, including restriction of specific technology export, etc. In addition, a country can action through official announcements in reacting to irresponsible behaviors polluting the orbital environment. In the situation of Russia's direct-ascent anti-satellite test creating at least 1,500 pieces of fragment debris in 2021, Australia, the European Union, France, Germany, Japan, NATO, and South Korea released statements blaming this action expressing their disagreement the such of the action (Raju, 2021).

At the level of international space fora, some processes open the floor to conduct soft sanctions. For instance, through the COPUOS mechanism, if an action intended or risk to violate the guidelines takes place, a State can circulate a proposal asking for support from the Member States on decisions or actions in the name of the committee, or revise some arguments in the measures or guidelines to prevent future misbehaviors. However, the actions mostly have political-purpose rather than a serious sactions aiming to keep sustainable space.

Even no rigid punishments, sanctions at the national level can disturb the supply chain of spacecraft, reduce number of customers, and be an obstacle to the development of standardization of satellites, which many IOS providers such as iBOSS project from DLR aims to achieve (Kreisel, Schervan, & Schroeder, 2019).

4.6 Design principle 6. Conflict Resolution Mechanisms

When the rules or regulations are enforced, some conflicts regarding compliance with the rules may arise. With the purpose to support the system to endure over a long-time, mechanisms to solve conflicts are one of the pillars for sustainability. In this regard, Optional Rules for Arbitration of Disputes Relating to Outer Space Activities (2011), a voluntary, binding dispute regulation proposed by the Permanent Court of Arbitration, has been released serving conflicts in the space industry among States, international organizations, and private entities. However, after 10 years, according to Rosenberg and Dadwal (2021), the rules have never been used to dispute any conflicts. People avoided this choice and selected other mechanisms that were not directly dedicated to the space industry to solve the conflicts.

Advancement of IOS increase the complexity of space activities and may cause more disputes. Generally, conducting IOS has a certain risk of failure due to technology limitations. When the number of missions grows up, the possibility of collision during proximity operations or explosion from refueling may generate space debris. These negative consequences contrast with the concept that the technology will enable space sustainability. Furthermore, a failure during performing IOS could create a difficulty to determine who is wrong for the damage. It is hard to prove whether the servicer or the target satellite is malfunctioning and cause the error. Also, more difficult to find out who is the owner of a space debris (Wright, 2020). The sake of circumstance escalates more conflicts from the technology. The mechanisms aiming to deal with these conflicts should keep up with the progress of the technology and could be revised easily to suit the rapidly changing industry.

4.7 Design principle 8. Nested Enterprises

Space is a common global, mutually utilized by all nations. The governance of space as a whole has been organized into three main levels consisting of international, regional, and national.

At the national level, the governance structures vary from country to country depending on the political regime and size of the space economy in the country. Space fairing countries normally have many domestic organizations in charge of policy, regulation, operator, and facilitator. In some countries, space activities are under defense entities such as Russia and China. While in many countries, civil space affairs have been divided from the military sector, for instance, Unites States, France, and Italy. The expert interviews reflected those national policies play the most important role to support IOS capability in the countries. The policies determine whether to establish a standard for space industry or not. They also guide public agencies to facilitate budget and technical expertise to private sector. Some agencies, such as JAXA, are first customers for the companies and can be actuators for commercial activities. In addition, a government is the entity who adopt guidelines and decide level of enforcement in the country. Therefore, the national level governance is an important mechanism to implement actions for space sustainability.

At a regional level, an example of model for a successful entity can be European Space Agency (ESA). With a strong establishment of the European Union providing the foundation for the initiation of the agency, ESA has been an effective space agency organizing large-scale space programs by the members working together to define the strategy, sharing funding resources, and utilizing space infrastructure in the countries. The entity allows European countries to strengthen their negotiation power in the global space industry amid the United States, China, Russia, and the others. ESA also has strong partnerships outside the region such as Canada. And for the case of the United Kingdom, even they decided to leave the European Union but firmly stated that they continue to be a member of the ESA. In addition, there is more multilateral cooperation in space set up based on region, for instance, Asia-Pacific Regional Space Agency Forum promoted by Japan and Asia-Pacific Space Cooperation Organization backed up by China. The bodies are at the cooperation level and not firmly tight as ESA. Even within APSCO there is finance pooling, but some countries have dominant role over the rest making the group is at a beginning stage to become regional space entity. At this level, regional agencies can establish norms or standards used among their member countries. For regulation aspect, they can create a treaty with legal obligations to the members to implement collective agreements. On the other hand, for technology perspective, the regional program such as PERASPERA In-Orbit Demonstration (PERIOD) undertaking by European organizations is an example of leveraging regional cooperation to set up standards for space technology (PERIOD partners, 2021). It is possible that the participants in the program could adopt the standards and use it in their countries. It also easy as well to expand the European standards for IOS to other regions when many of European countries has already adopted it, increasing competitiveness of the European companies in the program who led the technological standards. Having the role in dissemination of norms for sustainability, the regional entities can enlarge the sustainability from a country to the international domain.

At the international level, there is no truly rigid governance or regulation protocol on this floor. UNCOPUOS has been presented as a cooperative forum for all member States to exchange views and creates cooperation. The committee has been subdivided into the Scientific and Technical Subcommittee and the Legal subcommittee. But in fact, each country has its authorization to regulate and conduct space missions in the country where external sanctions have less influence than an internal political force. There are guidelines, agendas, and practices with the purpose to promote peaceful and sustainable space. But the level of adoption to regulate at the national level depends on voluntary.

By the way, the international mechanism can have a more proactive role to create space sustainability. The model from the Climate Change action can be used as an instance for the space domain (Tirole, 2017). The establishment of funding to support space projects that are on the track to sustainability can be a constructive tool to promote sustainable space. Space activities undertaken whether by public or private entities should be examined for their consistency with sustainable criteria or ruin the rules. Space projects that balance the maximization of space objects' capability and preserve the orbital environment should be highlighted, setting new norms to conduct space missions with the responsibility to the limited resource. Among these things, technologies related to space sustainability such as Active Debris Removal and In-Orbit Servicing are stand out of the line and reasonable to gain more support not only at the national level but internationally as well.

5. Conclusion

The design principles are good framework to observe aspects of space governance that should be improved for transforming towards sustainable ecosystem. The principle 7. 'Minimal Recognition of Rights' is not applied to the case as space activities are mostly initiated or strongly supported by a government and Earth's orbits are a strategic CPR. Therefore, it is hard to avoid intervention from governments.

Besides the concept of using IOS, many aspects are indispensable to contribute to the paradigm, for instance, Active Debris Removal, Space Situation Awareness, Space Traffic Management, satellite constellations, cybersecurity, weaponization of space, Moon mission, and in-situ resource utilization, which should be explored further. A single technology cannot solely be a whole solution for sustainability. The goal requires the unity of current actors and potential stakeholders in the future to jointly design a scenario that can sustain a finite resource like Earth's orbits.

From initiatives founded by international cooperative bodies, technology and innovation relentlessly developed by the research sector, creative value propositions figured out by private companies, governmental, including reflection from the economic principles, all that mentioned in this report are imperative building blocks to create a bridge towards a better future of the industry.

Among the competitive atmosphere in the global space ecosystem, the tension between countries accelerating them to protect nations, in addition to the scramble from private companies to catch the market, there is still awareness in space sustainability from actors who recognized that space is mutual assets, not only for all nations but for all generations. We all are standing at the beginning phase of Newspace which going to ramp up promptly. The concept of space sustainability should be imprinted in directions, attitudes, and core values of all space projects. Maybe, the presence of public and private actors will be triple in the next two years, thousands of satellites will be launched in the next few weeks, or a million space debris fragments are going to be added to the space debris catalog in the next few hours. The action to push forward the sustainable concept should be done now or never. The stories presented in the study can be a part that articulates some aspects that can sustainably maintain space which is the biggest home of all of us.

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