



Defining factory in space: comparative analysis of components, features, and functions[☆]

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Abstract

The current limitations imposed by traditional launch constraints – namely mass, volume, and cost – significantly restrict the potential for large payload deployment in space. Coupled with the scarcity of resources in extraterrestrial environments, it means that for a new Space Economy to prosper, there is a need for sustainable, self-sufficient systems. In response to this challenge, new research initiatives and launch vehicle advancements provide opportunities for the implementation of innovative new technologies that can be coupled with existing systems and/or used to establish a new Factory in Space (FIS). FIS represents a paradigm shift, promoting the manufacturing, servicing, refurbishing, recycling, reusing, and repairing of components directly in space, thereby mitigating conventional launch barriers and optimizing the use of in-situ resources. Initiatives such as NASA's OSAM project, SpaceX's development of the Starship, and Northrop Grumman's success on-orbit servicing demonstration missions demonstrate the early progress towards the realization of an integrated FIS ecosystem. Despite individual studies investigating various facets of FIS, a comprehensive and cohesive understanding of FIS as a single ecosystem remains absent. This study addresses this gap by systematically defining the FIS ecosystem through a detailed analysis of its associated components, features, and functions. This study applies an Expert-Informed Mixed-Method Synthesis framework, integrating a hybrid literature analysis and semi-structured expert interviews, to derive a definitional framework for FIS. The framework specifies modular technological components and their functional interdependencies within architectures designed for scalability and resilience in deep space exploration contexts. The outcomes presented not only advance the understanding of the FIS ecosystem but also lay the groundwork for future research, underscoring its pivotal role in the new Space Economy and implications for advancing in-space manufacturing capabilities.

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Keywords: Space economy; Factory in space; Manufacturing; Sustainability; Recycling; In-space manufacturing; Space logistics

Abbreviations: AM, Additive Manufacturing; AMAZE, AM Zero Waste and Efficient Production of High-Tech Metal Products; AMF, Additive Manufacturing Facility; CSS, Commercial Space Station; DARPA, Defense Advanced Research Project Agency; EFESTO, Enhanced Factory for Extraterrestrial Space Technology Operations; ESA, European Space Agency; EU, European Union; FIS, Factory in Space; GEO, Geostationary Orbit; GTO, Geostationary Transfer Orbit; HEO, Highly Elliptical Orbit; HST, Hubble Space Telescope; ISM, In-space manufacturing; ISMU, In-situ Material Utilization; ISO, In-space Operations; ISR, In-space recycling; ISS, International Space Station; LEO, Low Earth Orbit; MEO, Medium Earth Orbit; MEV, Mission Extension Vehicle; MRV, Mission Robotic Vehicle; NASA, National Aeronautics and Space Administration; OSAM, On-orbit Servicing, Assembly and Manufacturing; SL, Space Logistics

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1. Introduction

Since 1955, when the Space Race began, the sector has consistently been a crucible for disruptive solutions and innovative technologies. Today, it stands on the brink of a transformative cycle poised to effect remarkable changes across societal, economic, and industrial landscapes. In recent years, the significance of space exploration has risen dramatically, fueled by the democratization of the space market, where a shift from government-controlled high-risk programs to a new public–private partnership has taken shape. The pivotal role of advanced and digital manufacturing techniques is underscored by the growth of the unprecedented expansion of the active satellite population, which increased by roughly 74 % in 2021 alone (Ghidini et al., 2023). Coupled with this growth, the estimated revenue generated by the space economy was approximately 337 billion dollars in 2021 (Euconsult, 2022), with projections soaring to over 640 billion dollars by 2030 and over 1 trillion dollars by 2040 (OECD, 2022). This expanding interest has intensified scrutiny (Boeing Starliner, etc.) regarding the integrity of ageing space structures as well as the safety and welfare of crew, payload, and vehicles, emphasizing the paramount importance of securing life-saving supplies amidst the inherent challenges of space travel.

Launch constraints—dictated by mass, volume, and, notably, the cost of launch vehicles—pose significant challenges in ensuring the availability of essential supplies. During mission operations, the vehicle’s fairing controls the payload to be transported during a single flight, limiting the ability to prepare for all possible unforeseen events that could occur during space exploration. Nevertheless, the innovative and competitive nature of space system design has propelled continuous research efforts aimed at integrating new functionalities, advanced materials, mass and volume reduction, improved performances, and extended value across the lifespan of the system. Embracing and leveraging current cutting-edge technologies, such as additive manufacturing (AM) (Tang et al., 2022), is regarded as a vital pathway for developing scalable and adaptable engineering solutions and circular business models tailored to the diverse requirements of space economy stakeholders. The advent of these innovative technologies, particularly those driven by private sector initiatives, has significantly lowered launch costs and broadened access to space, underscoring a pivotal shift in the global paradigm of space exploration and utilization, as illustrated in Fig. 1.

The democratization of the space economy, combined with a growing human fascination beyond Earth, necessitates not only innovative capabilities on Earth but also the exploitation of in-situ resources and material processing in space (Abdulhamid et al., 2023). Traditional methods of launching fully functional and integrated systems aboard a single vehicle are increasingly seen as insufficient for the ambitious missions of the future. To this extent, engineers and researchers are exploring transformative

concepts that shift the paradigm of space exploration in a way that prioritizes sustainability while prioritizing modularity, resource optimization, and reusability.

The Factory in Space (FIS) concept, which envisions manufacturing, assembly, servicing, repurposing, repair & refurbishing, and maintenance outside the earth’s atmosphere, is one way this push for advancement can be realized. The FIS focuses on harnessing locally available materials and implementing energy-efficient waste management strategies in a space environment (lunar, Orbit, etc.). Recognizing the immense potential of on-orbit activities, various organizations have begun developing and testing technologies that facilitate these capabilities. This momentum towards in-space manufacturing and resource utilization signifies a critical advancement in our approach to space exploration. Over the years, the successes of several space programs, such as the Salyut (Uri, 2021), Skylab (NASA, 2025), and the Mir (Culbertson Jr., 1996), have led to the development of several on-orbit capabilities, such as servicing, assembly, and manufacturing. Starting from the solar maximum mission in 1984, where a repair mission was launched with the space shuttle, the development and assembly of the International Space Station (ISS) to the development of manufacturing capabilities in Orbit leading to the installation of a metal 3D printer aboard the ISS, Fig. 2 summarizes some of the activities that have been actualized in Orbit which highlights the evolving landscape of technologies and the transformative new space economy.

1.1. Research motivation

The FIS concept emerges as a groundbreaking solution, advocating for the fabrication and assembly of systems in the extraterrestrial environment in-situ rather than utilizing pre-assembled payloads launched from Earth. By decentralizing production, FIS effectively mitigates launch constraints and reduces dependence on terrestrial supply chains. However, it is important to note that while FIS lightens some of the constraints associated with Earth-based launches, it does not eliminate the need for launch altogether. Non-terrestrial material must still be sourced and transported to FIS platforms, which introduces a different type of logistical constraints. Therefore, FIS does not eliminate launch demands but instead seeks to improve long-term sustainability and scalability of material acquisition in space operations. Despite the promise of FIS to revolutionize space operations, existing literature reveals a fragmented understanding of its component activities and functions. While elements of FIS, such as in-space manufacturing or in-space servicing, have been individually reported in literature, these elements have seldom been reported as an integrated ecosystem. Hence, a comprehensive definition that encapsulates the full scope of FIS as a unified ecosystem remains inadequately articulated. This gap underscores the necessity for further investigation into the various facets of FIS. In this paper, this gap was addressed through a comparative analysis of the compo-

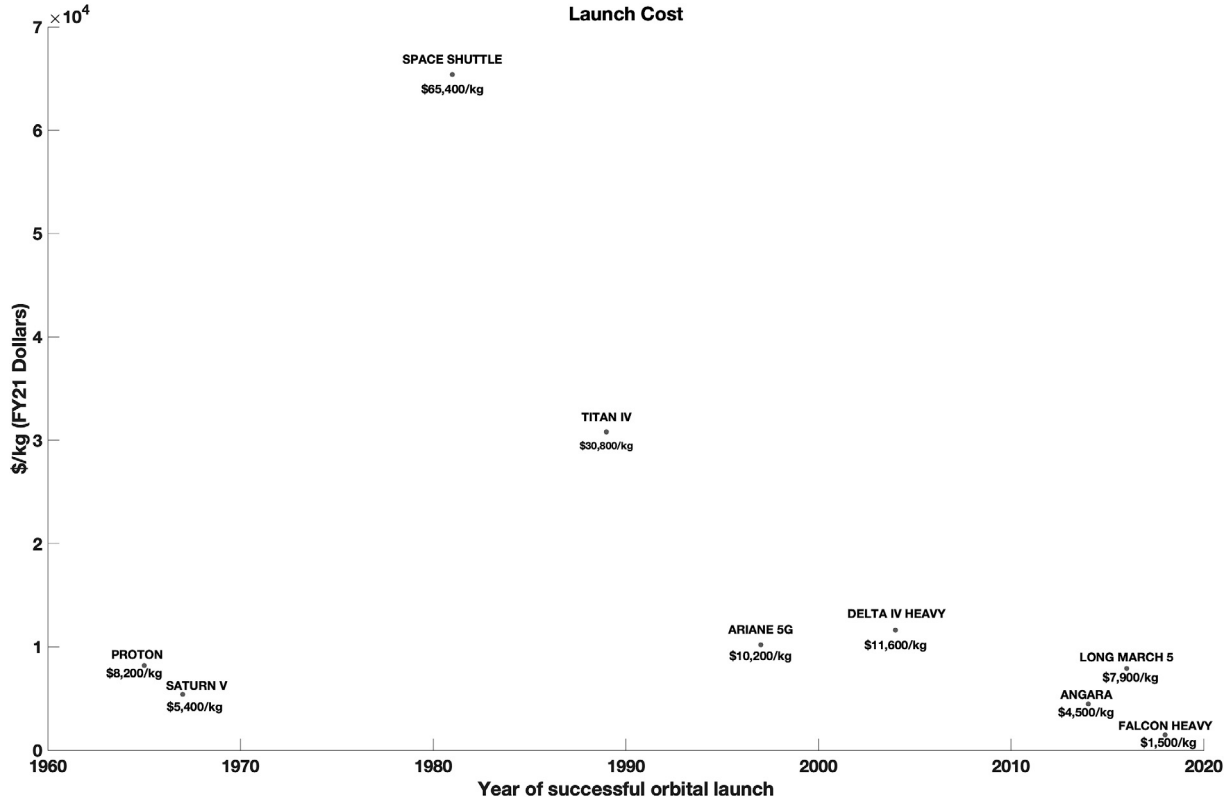


Fig. 1. Launch costs (adapted from (Roberts, 2022)).

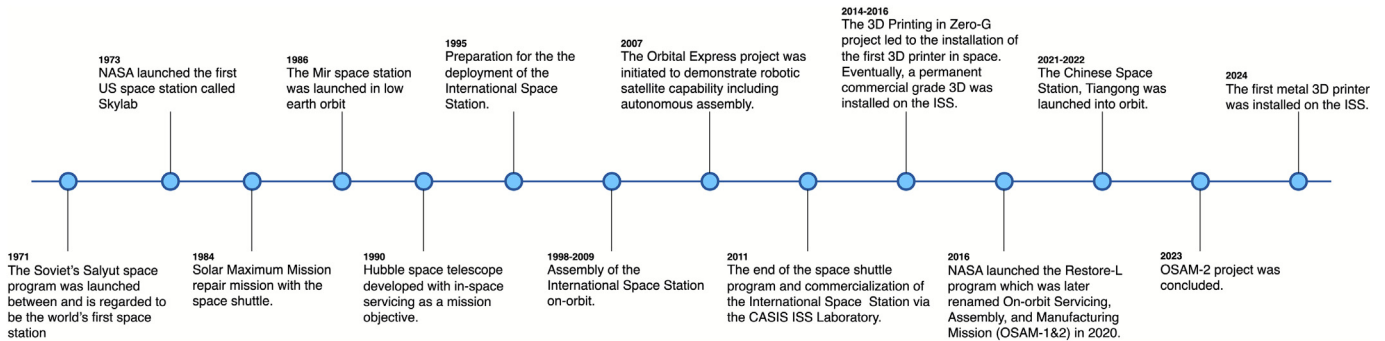


Fig. 2. Summary of some on-orbit activities.

nents, drivers, and enabling technology that define the FIS concept. The aim of this study is to propose an operational definition of FIS that entails all the elements and capabilities – such as manufacturing, assembly, servicing, recycling, and logistics – required to achieve a sustainable and scalable space-based ecosystem. The proposed definition aims to serve as a starting point for space operators and practitioners to evaluate and develop future space practices that will facilitate and contribute to the advancement of sustainable and efficient in-space manufacturing practices.

1.2. Research approach

The approach utilized in this study, as illustrated in Fig. 3, leveraged expert insights and comprehensive analysis of existing literature to construct a nuanced understand-

ing of the Factory in Space concept, thereby addressing the critical need for a coherent definition and framework encapsulating its components and functionalities. This approach was selected due to the relatively nascent and under-defined nature of the FIS concept. The combination of focus group, expert validation, and literature review ensures that the proposed definitions and terminologies are grounded in both academic and industrial domains.

The approach was divided into three phases, as shown in Fig. 3. In the first phase, highlighted in green, a focus group was utilized to develop the main research question. The functions and principles discussed and introduced in this study were developed based on interactions and responses derived from the Enhanced Factory for Extraterrestrial Space Technology Operations (EFESTO) (Sindoni et al., 2024) focus group. The EFESTO group comprised

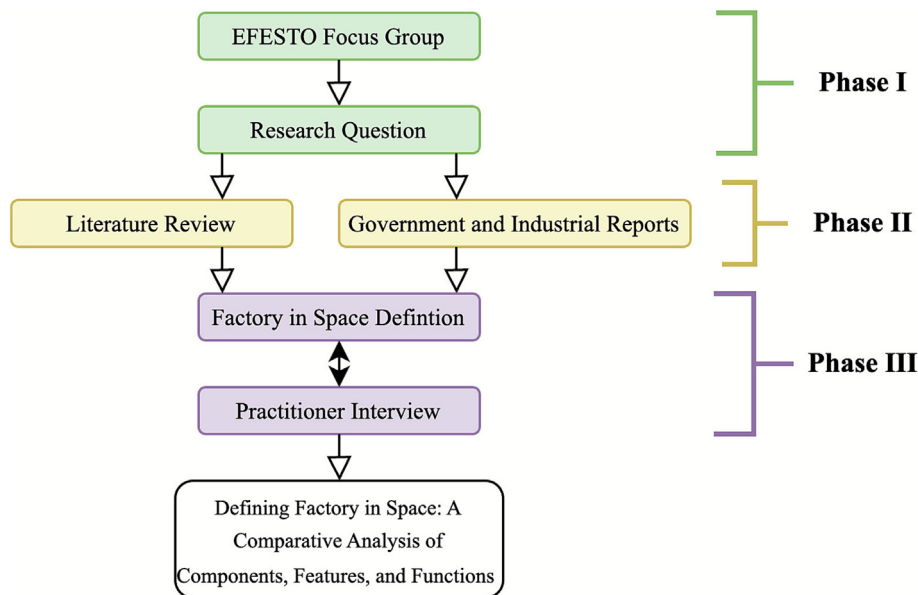


Fig. 3. Research approach.

academic and industrial practitioners, each with a minimum of five years of experience in the space and manufacturing industries. An extensive review of current literature and relevant governmental and industrial reports augmented their insights. The initial interviews focused on three critical areas: (a) shaping the scenario, (b) identifying technical and operational challenges, and (c) defining the components, features, and features of FIS.

Analysis of the interactions revealed a lack of agreement regarding the definition and perceived value of a FIS. Notable descriptors provided by the respondents were characterized as referring to: 1) In-space production of goods and services; 2) Extraterrestrial competency to repair; 3) The terminology FIS does not exist; 4) A manufacturing system with material harvesting capability. These descriptions, while not entirely distinct, do not collectively yield a comprehensive understanding of FIS activities, thus leading to the central research question: “What is the definition of a Factory in Space?”.

The second phase, highlighted in yellow, was the literature collection phase. The literature collection phase relied on a literature review and identifying and collecting relevant governmental reports and white papers. The literature review was carried out by performing a narrative-systematic literature review. The approach followed the systematic literature review for data gathering, and the analysis was performed using the narrative literature review technique. Data collection was done through the Scopus database. Keywords such as “manufacturing in space”, “in-orbit manufacturing”, and “factory in space” were queried on the database (Abdulhamid et al., 2025b). Both governmental and quasi-governmental documents/reports/briefs were collected in parallel. It is essential to highlight that due to the proprietary concerns that characterize the space industry, the references identified in this research

phase are not peer-reviewed but documents by internationally reputable bodies like the National Aeronautics and Space Administration (NASA). Additionally, national entities such as NASA and the European Space Agency (ESA) often restrict sensitive data to the public, while commercial firms such as SpaceX, Blue Origin, Redwire, and Boeing share even less information. Consequently, this study relies on peer-reviewed documentation and credible non-academic resources.

The third phase of this research involved the development of a working definition for FIS and validating it through another set of interviews. The two steps (definition and validation) involved in the third phase, as shown in Fig. 3, are related to a feedback loop, such that the experts refine the definitions proposed from the first two phases and then reformulate them until the experts approve. This feedback loop mechanism allows for rigorous scrutiny of any proposed definition, increasing the robustness of the research. Following the preliminary interviews and literature review phases, a working definition of in-space manufacturing was formulated and validated through a second set of interviews. This consisted of 10 individuals with an average of 10 years of experience in space and manufacturing. The respondents provided valuable feedback on the relevance of the research and the clarity of the proposed definitions, which further reinforced the proposed research question and the need for research on the components, features, and functions of FIS.

2. Shaping the scenario

Certain elements of FIS have existed since around 1984, when astronauts were dispatched on a mission to repair a faulty altitude control system on the Solar Maximum Mission aboard the space shuttle by NASA in April 1984

(Rapley et al., 2017). This led to the development of the Hubble Space Telescope (HST) (Mattice, 2008; National Aeronautics and Space Administration, 1993). The design of the HST proposed the possibility of astronauts replacing defunct/faulty components on the telescope while in Orbit to extend the functionality and mission life of the telescope. These servicing missions helped maintain and extend the overall capabilities, prolonging the lifespan of the system (Harris, 2015; Stockman, 1994). Stoor (Bradley and Col Peter Garretson, 2018) reported that the goal of reducing the associated cost was validated by the development and servicing of the HST and was an important step for future in-orbit servicing and operations.

However, it is important to note that several space programs predate the HST, but unlike with the HST, the goal of such programs was to study and establish extended human presence in outer space. NASA launched the first US space station into Orbit aboard the Saturn V rocket in 1973. The Skylab hosted three crewed missions with 171 days of occupancy and about 300 scientific and technical experiments studying human adaptability to microgravity and resource experimentation. In 1979, the Skylab was deorbited with scattered debris over the Indian Ocean (NASA, 2025). However, it is pertinent to note that the Skylab was not the first space station recorded in history. The Soviet's Salyut space program, launched between 1971 – predating the Skylab – and 1982, is regarded to be the world's first space station (Uri, 2021). The Salyut program comprised seven military and scientific missions, hosting international cosmonauts for short stays. The progress of the Salyut program spurred the actualization of the modular next-generation soviet space station called Mir (Culbertson Jr., 1996). The Mir space station was operated in Low Earth Orbit (LEO) between 1986 and 2001, spanning more than three times the planned lifespan. The success of the Salyut, Skylab, and Mir, among other space programs, led to an international collaboration between the United States, Russia, Japan, Canada, and Europe to develop the ISS (NASA, 2023a). The assembly of the ISS began around the 2000s, and new modules were added as recently as 2021. The ISS has evolved from an outpost to an advanced microgravity laboratory, capable of demonstrations and scientific research from a wide range of fields (Stockman et al., 2015). The results have seen the emergence of new benefits, such as improved spatial awareness and LEO monitoring, among others (Doran, 2025). A more recent development is the Chinese space station, Tiangong. Launched between 2021 and 2022 and located at around the same height as the ISS in LEO, the Tiangong is a permanently crewed space station that Chinese researchers have access to microgravity research, albeit at a smaller scale than the ISS (Dobrijevic and Jones, 2023). Similarly, India plans to build its own space station by 2035, with the first launch planned for 2028. The space station called the Bharatiya Antariksh Station (BAS) aims to host 6 crew at maximum capacity and foster the advancement of microgravity research. The BAS would also be

located at a similar orientation as the ISS, allowing it to cover about 90 % of Earth's inhabited areas (Express News Service, 2023). Other space stations located even further away from Earth on celestial bodies have been proposed, such as the International Lunar Research Station proposed by China and Russia (China National Space Administration, 2021), and the Lunar Gateway space station proposed in the multinational Artemis program (NASA, 2020; Williams, 2025). The advancement and achievements of the ISS and other space stations have led to the development of commercial stations such as Orbital Reef, Axiom Station, and Starlab (Starlab, 2025), which have become more prominent due to the planned deorbiting of the ISS (Benas et al., 2025). These stations promise to further the capabilities of the ISS and offer scientific research, manufacturing, tourism, education, and sustainability. The increased human activity in space further demonstrates the need to develop capabilities that reduce the dependency on Earth for services and increase autonomy in outer space.

Significant advancements have been made in developing technologies for autonomous in-space servicing and manufacturing. A notable example is the Orbital Express program, developed by the Defense Advanced Research Projects Agency (DARPA) in 2007, which successfully demonstrated robotic satellite servicing capabilities such as autonomous assembly, refueling, and component replacement (Friend, 2008). Furthermore, the development of robotic arms based on proprietary technologies by NASA and ESA reflects a strong institutional commitment to the development of autonomous systems for in-orbit operations (Xue et al., 2021). Building on these efforts, NASA and ESA have advanced specialized robotic arm systems leveraging proprietary technologies, underscoring the sustained institutional investment in autonomy to enable in-orbit servicing, assembly, and manufacturing operations (Abdulhamid et al., 2025b; Li et al., 2019; Xue et al., 2021). AM has been identified as a key enabling technology.

Furthermore, AM has been cited as vital in transitioning from a linear to a circular economy (Cruz Sanchez et al., 2020). AM processes have progressed so that it is possible to produce ready-to-use components straight from stock (Zocca et al., 2022), allowing for enhanced resource efficiency. This has led to the proposal and utilization of AM technology for several FIS-related activities, such as the "AM in Space" initiative launched by NASA, which resulted in the 3D Printing in Zero-G project and the installation of an AM device aboard the ISS (Clinton, 2019), which resulted in the permanent installation of a commercial device in 2016 called the Additive Manufacturing Facility (AMF). Furthermore, in 2020, NASA changed the name of its Restore-L program, which was launched in 2016, to On-orbit Servicing, Assembly, and Manufacturing Mission (OSAM-1&2). Discontinued in 2024, the OSAM-1 spacecraft infrastructure was designed to create beams, refuel satellites, and construct antennas. Meanwhile,

OSAM-2, a technological demonstration mission, was completed in 2023 prior to flight, storing data and crucial lessons to utilize in subsequent missions (Abdulhamid et al., 2025b). On the other hand, the European Union (EU) has prioritized AM initiatives for space applications, with a strategic focus on sustainable and circular technologies (Jackson and Joseph, 2021). The EU primarily concentrates on technologies leading to sustainability and circularity, while the ESA works to support the ISS's continued advancement by supplying spare parts. In parallel, the ESA has concentrated on advancing in-situ manufacturing to support long-term operations, including the ISS, through on-demand production of critical components. A landmark collaboration between the EU, ESA, and the UK's Manufacturing Technology Centre (MTC) (The Manufacturing Technology Centre Limited, 2018)—the AM Zero Waste and Efficient Production of High-Tech Metal Products (AMAZE) project (2013–2018)—demonstrated the viability of AM processes for extraterrestrial environments such as lunar and asteroid surfaces. The AMAZE initiative established four pilot factories across Europe to validate large-scale, zero-waste production of aerospace-grade alloys (Mies et al., 2016). Subsequent ESA-led efforts, as outlined by Makaya (Makaya et al., 2023a), further refined space-based manufacturing capabilities. Meanwhile, China's carbon-fiber-reinforced composite AM device achieved milestone validation in LEO aboard the Long March 5B rocket (Ministry of National Defense of the People's Republic of China, 2020).

The role of private entities is another crucial element to take into account in the advancement of the FIS concept (Jackson and Joseph, 2021). This is demonstrated by the work of several private companies, including Redwire (Made in Space), which played a crucial role in the development of the AMF aboard the ISS and later in the OSAM, Northrop Grumman, which developed the Mission Robotic Vehicle (MRV) and deployed the Mission Extension Vehicle (MEV), and Thales Alenia Space, which is developing a servicer satellite with manufacturing capabilities with a 2026 demonstration launch scheduled (Thales Alenia Space, 2023).

3. Considerations and perceptions of FIS

In this section, the insights from both literature and expert interviews are presented. Several factors have been highlighted as crucial to the definition of FIS. Several terminologies and concepts associated with FIS are discussed below:

3.1. Factory in space vs in-space manufacturing

In-space manufacturing (ISM) is a common terminology constantly associated with FIS. While FIS and ISM share similarities, it is essential to note that they are two distinct concepts. Indeed, it can be stated that ISM exists under the idea of FIS, while the activities of FIS are beyond the scope

of just ISM. Indeed, the relation of FIS and ISM can be related to that of a system (FIS) and its mission (ISM) in systems engineering. While the distinction of a system and its mission is well established, within the context of FIS literature, the difference has not been clearly articulated. To clear this ambiguity in this section, an interview with experts was employed to validate how the difference between FIS and ISM (see phase III of the research approach) is perceived in practice and shape the idea of FIS and ISM within a conceptual boundary. The significant difference highlighted between FIS and ISM is that FIS is a facility similar to the ISS designated for in-space activities, while the concept of ISM is about manufacturing products in space, which can occur on any orbital/celestial system. Table 1 presents a summary of the differences between FIS and ISM according to the results of the interviews.

It is important to note that while some of the examples discussed are about orbital facilities, the scope of the FIS concept extends beyond orbital locations and may also be extended to locations such as planetary bodies, hence encompassing a broader operational environment.

3.2. Technologies and enablers

Technology has been cited as crucial to actualizing FIS activities (Abdulhamid et al., 2025a). Advancements in science and technology have led to increased accessibility to space, as illustrated in Fig. 1. However, since the actualization of FIS is enabled by the symbiosis of underlying technologies (Corbin et al., 2020), there remains a need to develop technologies that facilitate key activities in FIS operations. Some areas of technology that are critical, desired, and enabling for several FIS activities are identified below.

- **Robotics and Automation:** Several FIS activities such as assembly, manufacturing, in-space logistics, refueling, maintenance, and debris operations rely on highly robust and resilient robotic and automation systems with the ability to perform complex operations, such as an entire servicing mission, without humans in the loop while withstanding the harsh extraterrestrial conditions. The efforts to develop and adapt robotic technologies for FIS activities have been reviewed (Ma et al., 2023).
- **Material Harvesting and Processing:** A key concept in developing FIS is using locally available resources in space and on celestial bodies. To this end, there is a need to develop and adapt technologies capable of extracting and processing extraterrestrial resources such as lunar and Martian regolith. A detailed review of extraction and harvesting technologies suitable for FIS activities has been reported (Abbasi, 2023).
- **Recycling:** Recycling in microgravity conditions and developing new/extended lifecycles for by-products is paramount during FIS activities due to the lack of

Table 1
Difference between FIS and ISM.

Factory in space	In-space manufacturing
<ul style="list-style-type: none"> • FIS is a facility/location similar to the ISS. • FIS is a more defined concept, representing a fully operational, autonomous factory in space. • Designing, constructing, and operating dedicated facilities • Incorporating in-situ resource utilization into space exploration. • Establishing systems for energy, materials handling, and product transportation to support continuous manufacturing operations. • FIS is essential for the maintenance, production, and assembly of space-based systems. 	<ul style="list-style-type: none"> • ISM occurs on facilities such as FIS/ISS. • ISM is broader and includes any kind of production beyond Earth, whether in orbit or on a planetary surface. • Manufacturing items that benefit from the environmental conditions like microgravity and vacuum environments • Produces products and materials with resources from earth. • Focus is on production of material and components with little regard for establishing systems. • ISM is the manufacturing component of space-based systems

resources in isolated colonies. The value that can be obtained from space debris has been linked to manufacturing activities in the space environment (Rai et al., 2024). The recycling of space debris is closely associated with robotic and automation technology, which allows for docking and recapturing of defunct space systems; therefore, robust debris removal and retrieval technologies must be developed before recycling and refurbishing activities occur. A review of the techniques and technology for space debris removal has been reported (Svotina and Cherkasova, 2023).

- **Manufacturing Processes:** An essential aspect of FIS is the capability to manufacture robust, high-quality products in space that can replace components and products produced on Earth. Moreover, to improve manufacturing efficiency for automated repair and restoration, it is crucial to optimize the core design. Hence, extra effort must be directed toward the development of innovative processes to enhance existing manufacturing systems so they can withstand the severe conditions of outer space. To this extent, there is a push for research and development of manufacturing processes that work in, or are improved by, the space environment. Furthermore, unlike traditional manufacturing processes where material wastage is rampant, FIS requires processes that lead to continued reduction of waste/byproduct production in chemical and manufacturing processes. For this reason, AM manufacturing systems have been identified as a key technology for FIS activities. To better understand manufacturing processes suitable for FIS, an overview of the proposed systems has been reported (Abdulhamid et al., 2025b).
- **Modularity:** Modularity and the FIS concept are intrinsically linked due to their foundational characteristics. Modular space systems are designed to be adaptable and refueled, allowing launches with fewer components and limited fuel initially, which enhances mission flexibility. By utilizing standardized elements such as modular robotics, plug-and-play parts, and 3D-printed

components, these systems significantly increase the scalability and versatility of in-space manufacturing. Modular architectures also simplify maintenance, as damaged modules can be easily replaced (Abdulhamid et al., 2025a). Therefore, to fully harness the potential of FIS, it is essential to explore and advance enabling technologies like modular spacecraft.

3.3. Environments and missions

The environment outside the Earth's atmosphere is complex and strongly influences space exploration in different aspects. Several components of the space environment, such as radiation, temperature, and solar activities, can affect extraterrestrial activities depending on the altitude outside of the atmosphere. To define FIS, it is paramount to understand the type and behavior of environments suitable for FIS operations. In this section, the environment reported in the literature for FIS activities is reviewed, mainly focusing on the orbits, Martian, and lunar environments.

3.3.1. Orbits

Generally, the locations outside the Earth's atmosphere can be classified in terms of orbits based on their altitudes (Lu et al., 2019). Orbits are curved paths in which objects in space move about with the aid of gravity. In the solar system, the moon orbits Earth, and the Earth-Moon system orbits the Sun. The Orbit analysis holds even more strategic importance when considering the in-situ material utilization (ISMU), including debris and orbiting objects. Several orbits have already been introduced (European Space Agency, 2020), and their challenges and conditions are discussed in this section and summarized in Table 2. The **Low Earth Orbit (LEO)** is between 160 and 2000 km above Earth (commercial airplanes fly 14 km above Earth). The routes in LEO do not always follow a particular path and can be tilted as desired. Hence, many routes are avail-

Table 2
Orbit characteristics.

Parameter	LEO	MEO	HEO	GEO
Path	No significant path limitation		Elliptical	Travel is along the equator
Distance	Easier to reach due to proximity to earth		–	Need to travel to GTO
Payload	Up to 45 ton	Up to 25 ton	Up to 1.3 ton	Up to 6.5 ton
Launch cost (Roberts, 2022)	About 1,500 USD/kg		About 47,000 USD/kg	About 13,000 USD/kg
Coverage	A lot of effort is required to cover whole earth		2 satellites are enough	3 satellites are enough
Orbiting objects	>20,000	>600	>1300	<1000
Active devices	>3000	>130	>50	>560

able for space systems situated in LEO. The ISS is also located in LEO. Several FIS-related activities have been reported in LEO aboard the ISS, such as the installation of commercial-grade manufacturing devices (Prater et al., 2019) and mission extension demonstrations (Pyrak and Anderson, 2021). Furthermore, the feasibility of FIS activities has been previously studied (Abdulhamid et al., 2024). Located a bit above LEO is the **Medium Earth Orbit (MEO)**, which has similar characteristics to LEO and is placed between 8000 and 20,000 km above the Earth. Indeed, the OSAM project (Arney et al., 2021) explored both LEO and MEO as possible environments for on-orbit activities. Further away is the **Geostationary Orbit (GEO)**, situated at around an altitude of 36,000 km above Earth. Unlike the routes in LEO and MEO, the travel path of GEO follows Earth's rotation (from east to west). Space systems in GEO travel at about the same rate as Earth (about 23 h and 56 min). This allows GEO systems to appear 'stationary' over a fixed position. Activities to advance in-orbit operations have been explored through several studies, such as the Robotic Servicing of Geosynchronous Satellites project (Hall, 2024), which aims to advance in-orbit satellite inspection, repair, and refurbishing capabilities in GEO. Another Orbit of significance is the **Highly Elliptical Orbit (HEO)**. HEO is located between an altitude of 1000 km at the perigee and 36,000 km above Earth at the apogee. The travel path is highly elliptical. The rate of travel differs when close to Earth (similar to LEO) and when further away from Earth (similar to GEO). Some Orbits, such as the **Geostationary Transfer Orbit (GTO)**, are used to move from one Orbit to another with less power/energy than is usually required. GTO is a gateway for far-away orbits, such as GEO, without launching the vehicle directly to the target destination. A summary of the orbital characteristics is presented in Table 2.

3.3.1.1. Orbital debris. A subject of significance in the discourse on orbits is that of orbital debris. Generally, orbital debris is a class of space debris that only includes artificial items that have been launched into space (United Nations Office for Outer Space Affairs, 2019). Murtaza et al. (Murtaza et al., 2020) reported on the threat posed by the accumulation of orbital debris by concluding that the

threat of a catastrophic occurrence increases if the population of orbital debris is not reduced. Moreover, Clormann et al. (2022) argue that space debris is anything but a distant outer space phenomenon; rather, it is a subject of responsibility and sustainability. However, Leonard and Williams (Leonard and Williams, 2023) have reported while the increasing presence of debris in Orbit poses a catastrophic threat, it is a valuable untapped source of resources to support space activities. The thousands of objects and defunct space systems floating around Orbit have been cited as possible materials to be used for FIS activities (Abdulhamid et al., 2023). Indeed, a recent report from NASA (Colvin et al., 2023) concluded that “*recycling space debris may also contribute revenue to nascent markets for in-space manufacturing and assembly if debris can be gainfully reused in space.*” This perspective aligns with Hobbs (Hobbs et al., 2019), who identified functional overlaps between specific FIS components and orbital debris mitigation systems, emphasizing shared technical and operational challenges in both domains. The action of “*gainfully*” establishing FIS necessitates a thorough comprehension of the definition and value proposition of FIS activities.

3.3.2. Planetary bodies

In addition to orbital locations, planetary bodies have also been proposed for FIS initiatives. De Francesco et al. (Francesco et al., 2024) introduced the concept of a **lunar-based** manufacturing facility aimed at transforming space exploration through ISM. Moreover, several international efforts have studied the technological requirements for sustaining human presence on the moon. One such example is NASA's Gateway project, which, as part of the Artemis program, seeks to establish a permanent lunar Orbit station to support future **Mars** missions (NASA, 2023b). The Artemis mission also aims to explore the lunar environment for technological innovation and scientific research, contributing to NASA's broader Moon to Mars Architecture (Taveau, 2024). Anticipating these missions, scientists have assessed lunar and Martian materials. ESA researchers discovered that adding binders to lunar regolith improves its performance (Makaya et al., 2023b), and Cesaretti et al. (2014) confirmed the structural viability of

a mixture of magnesium chloride and regolith for producing habitat bricks. Similarly, Buchner et al. (Buchner et al., 2018) identified phosphoric acid as a promising regolith binder. Castelein et al. (2021) showed that iron could be microbially extracted from untreated lunar and Martian soils, highlighting ISMU's promise for sustainable infrastructure. Basalt, widely present on Mars, is under study for its mechanical reinforcement properties (Coughlin et al., 2019) and its potential as a radiation shield (Hedayati and Stulova, 2023), reducing dependence on Earth-based materials for building protective structures.

Another aspect of the operational environment to be considered is the destination of the products and services obtained through FIS activities. By taking advantage of the unique conditions in outer space, products and services could be manufactured in space and brought back to Earth. Commercial companies such as Varda Space Industries (VARDA, 2025) process materials and pharmaceuticals in microgravity and return them to Earth. On the other hand, FIS activities could be used in space to enhance and support space operations. While traditionally, space systems are rigorously designed to anticipate and mitigate most failures, the complex and unpredictable nature of space exploration means that it is impossible to anticipate all potential system/component malfunctions and accidents that could happen, and it becomes challenging to predict and prepare for such situations. In this aspect, a promising resolution could be incorporating servicing and manufacturing systems into space missions for a rapid and flexible response to support and enhance space operations. However, the incorporation of FIS systems could lead to increased complexity that must be carefully balanced, as these systems could introduce new challenges and failures.

3.4. Challenges of FIS

While several milestones have been achieved in establishing an extraterrestrial factory, significant hurdles remain associated with establishing FIS. Some of the challenges identified in this study are discussed as follows:

- **Characterization and qualification (Quality control):** In the space sector, characterization and qualification are critical and costly aspects of product development. The qualities required of space materials, particularly those associated with FIS, can be identified. While there are well established characterization and qualification methods on Earth, these methods have not been proven to be directly adaptable to FIS applications. Furthermore, the novel nature of FIS activities means that the properties of several materials used in space in not yet completely understood (Zocca et al., 2022) and hence no standard has been established to characterize and qualify FIS-related processes and products. Additionally, studies should concentrate on exploring materials and technology that are transferable and dependable enough to withstand extreme interplanetary conditions.
- **Guidelines for qualification** must be developed so that materials and components are only deemed demonstrated when they can function in the specified space circumstances.
- **Supply chain and logistics:** Successful and efficient FIS operations necessitate streamlined logistics, including orbital transportation, storage, and waste handling. Such activities demand minimal human intervention and require a robust support architecture. This includes planning for material transfer, mining processes, and identifying end-users. Properly outlining the FIS ecosystem and its logistical demands is crucial for choosing appropriate manufacturing and operation techniques.
- **Energy:** The sources of energy and demands of FIS have yet to be established. While solar power is a favored option in positions with sufficient solar flux due to its local availability (ISMU), nuclear and hydrogen alternatives may serve as supplementary sources, especially in locations with low irradiance. Furthermore, in addition to energy sources, there is a need to assess how to harvest and store energy to be used for space-based manufacturing, as those currently proposed, such as batteries and regolith storage, are either too expensive or of low efficiency (Zhang et al., 2024). As a result, a detailed characterization of energy production must be developed with long-term functionality.
- **Physics:** The space environment's dynamic nature complicates the direct application of Earth-based technologies. For example, manufacturing processes in space face challenges such as vacuum conditions, temperature fluctuations, radiation, and microgravity. These variables differ significantly from Earth's stable environment and must be integrated into design and manufacturing processes.
- **Setup and Iteration:** Developing accurate space-deployable structures is as vital as selecting suitable platforms. Most configurations are experimental and not yet scalable for full commercial use. Microgravity environments require extensive testing, often restricted by limited mission durations, necessitating strategies to address iteration constraints.
- **Regulatory framework:** Legal compliance is essential to ensuring safe and effective space operations. Existing international regulations, like those from the United Nations Office for Outer Space Affairs space law (CSU LAW, 2014) and the Artemis Accords (NASA, 2020), do not fully address the modern realities of orbital debris and in-orbit activities, especially those related to intellectual property rights (Li, 2024). Updated frameworks are needed to incorporate private sector roles and formalize FIS within the broader space ecosystem.
- **Raw Materials:** Sources of raw material for FIS manufacturing activities are extremely scarce and vary based on the local environment in space, as discussed in section 3.3. The scarcity and variability of raw materials in space pose a significant challenge. Local materials such as lunar regolith or even space debris could be utilized to reduce reliance on Earth-launched resources.

However, using these materials requires the development of new processing technologies capable of handling a broad spectrum of materials.

- **Human-Robotic Collaboration:** The continuous development and demonstrations of autonomous technology for FIS, such as the MEV (Pyrak and Anderson, 2021), mean that the boundary of the association between machines and humans would affect the security and robustness of autonomous systems. Autonomy has taken prominence in FIS research. Autonomous platforms can function independently of external controls in dynamic environments, leading to improved feedback and performance, a lesser personnel burden, and cost reduction. Nevertheless, completely autonomous platforms are still not fault-free and could experience decision-making errors or ethical problems due to data traps. As such, it is paramount that the level of autonomy should be controlled, and the system's risk/security procedures should be under the supervision of humans. Since both machines and humans are prone to decision-making mistakes, the mutual error correction complementarity of humans and machines can be implemented as a check and balance.

The challenges associated with the development of FIS are wide-ranging and complex, spanning multiple domains. Addressing these challenges requires multidisciplinary interaction among experts and significant investment in research activities. Addressing these challenges could establish a self-sufficient space system supporting long-term human space exploration and infrastructure development.

4. Defining FIS

Given the varied interpretations of FIS within the space sector, this section synthesizes a unified descriptive framework to guide the development of interoperable space platforms. These platforms aim to extend the operational lifespan of space infrastructure and advance the new space economy by addressing two critical dimensions: (1) system requirements-enhanced performance, reduced launch costs, improved safety, and component reliability—and (2) technical barriers to realizing autonomous, interconnected in-space manufacturing systems. Drawing on insights from interviews with academic and industry experts (Phase I research findings), FIS is defined as:

- A permanent or semi-permanent platform where in-space activities such as servicing and ISM occur.
- The establishment of manufacturing and production facilities in space.
- The processing of locally available resources.
- A fully operational, autonomous center, essentially a factory, but orbiting around Earth.
- Promoting the adoption of modular technologies in the design, manufacturing, and operation phases of space activities.

- Minimizing environmental impacts associated with production, operations, and the disposal of space debris, including emissions and material consumption.
- Ensuring that space missions remain economically viable and environmentally sustainable.

The appeal of FIS stems from the evolution of the new space economy, which is characterized by highly innovative practices and digitalization both in reality and perception. In this section, the principles of the new space economy (Weinzierl, 2018) merge FIS with extraterrestrial activities to create a descriptive definition of FIS (see research phase III) such that it advances and supports the design and development of space systems.

4.1. Descriptive view of FIS

As the new space economy gains prominence, the development of a comprehensive definition that integrates the needs of multiple domains within the sector is pertinent. In the scope of this study, FIS is defined as a multipurpose space facility that integrates technologies and solutions – such as in-space manufacturing, assembly servicing, and logistics – into a cohesive operational architecture to support and enhance the performance of missions across sectors in the space economy and leveraging the unique environmental conditions of space to create a sustainable industrial ecosystem beyond Earth. The range of technologies and solutions proposed by FIS should have the ability to autonomously support task executions through all phases of operation in the space economy. Based on this definition of FIS, the strong symbiosis between FIS and the new space economy is apparent, particularly regarding the integration of technologies or solutions. Although the difference resides in the fact that the new space economy was introduced to support and facilitate the next generation of advancement in the space sector, such as the concept of FIS, which represents a shift from the traditional space economy's paradigm of launch-use-waste to a more sustainable solution to the needs of the industry.

4.1.1. Drivers of FIS

The drivers of FIS presented in this section represent external sociotechnical factors influencing the FIS paradigm. Considering the insights of the focus group, interviews, literature, and reports, some of the major drivers of FIS were identified as follows:

- **Cost Reduction:** The new space economy has been characterized by increased access to space due to decreased launch costs, as shown in Fig. 1. The proposed Star Ship would further reduce costs and increase accessibility (Benas et al., 2025). Additionally, during space missions, it is impossible to prepare for all possible scenarios, such as accidents and failure; therefore, the ability to produce and assemble components on demand without relying on Earth for a launch and its associated cost makes

FIS a promising concept to reduce further the cost related to space activities and increase accessibility. Furthermore, activities such as servicing and refueling promise to extend the lifespan of space platforms such as satellites (Pyrak and Anderson, 2021), saving the cost of launching new systems upon failure of existing components.

- **Sustainability:** An important area of space travel is the development of sustainable solutions to the accumulation of waste and debris. Murtaza et al. (2020) warned of potential catastrophic risks if orbital debris continues to increase. Clormann et al. (2022) emphasized the urgent responsibility of addressing this threat. FIS contributes to sustainability not only by reducing launch frequencies but also by repurposing in-orbit waste and defunct systems as resources for in-space manufacturing (Abdulhamid et al., 2025c; Reddy, 2018). Thus, FIS fosters a more circular and resilient space economy.
- **Technology Advancement:** To comply with specific customer and market demands, it is necessary to adapt the systems to new technologies effectively. Technology impacts all facets of the system and is an enabler for new and sophisticated systems. Extreme changes have taken place in the field of technology throughout the last 20 years. As demonstrated in the development of reusable boosters (Reddy, 2018), several robotic technologies for in-space activities (Ma et al., 2023), demonstration of on-orbit servicing and refueling (Pyrak and Anderson, 2021), and material processing and manufacturing efforts on the ISS (Abdulhamid et al., 2025b). The demand for enhanced efficiency and sustainability has led to the development of new materials and propulsion technologies to meet the needs of an evolving industry. As a result, novel technological solutions are being investigated, such as integrating machine learning into space systems, novel propulsion technologies, human lunar exploration (NASA's Artemis mission), and SpaceX's starship (Space X, 2025), among others. These new advancements enhance some facets of efficiency whilst increasing complexity, fostering the establishment of FIS.
- **Development of Space Infrastructure:** NASA's plan to de-orbit the ISS has prompted the rise of commercial space stations (CSS) like Orbital Reef, Axiom Station, and Starlab. These CSS platforms aim to support research, manufacturing, tourism, and education (Benas et al., 2025). These platforms aim to draw inspiration from the modular nature of the ISS – the size of a football field – which was built incrementally after launch. This can allow for the development of an ecosystem in space similar to traditional ecosystems that exist on Earth, further reducing the dependency of space systems on Earth. Similarly, the push by the space industry to have sustained human presence on celestial bodies such as the moon and Mars has seen the testing and development of structures that could contain human activities while shielding from harsh conditions such as

radiation and temperature (Sun et al., 2024). The need and subsequent development of these space infrastructures would gradually lead to the realization of the FIS concept.

4.1.2. Component of FIS

In this context, FIS components represent industry aspects (elements) that operate together to address and respond to the primary drivers. FIS is built around the elements that respond and intersect to create an integrated architecture, as illustrated in Fig. 4. FIS can be defined through the following components:

- **Space Logistics (SL):** This component of FIS is responsible for the logistics operations in space, including surface mobility, space tug, and transportation (launches and inter-orbit movement). This factory facet envisions reusable launch vehicles to deliver payload, cargo, components, and finished products to their destinations or hubs. The ESA anticipates SL as “the Android of space transportation: various companies can plug into a common framework to ensure interoperability for their missions.” (European Space Agency, 2025).
- **In-space Manufacturing (ISM):** This component of FIS designs and produces new components, habitats, and assembles the produced components. Furthermore, ISM also assembles recycled and refurbished components and systems, readying them to be deployed to their final destination through SL. Indeed, ISM is one of the budding elements of FIS, with public–private manufacturing experiments onboard the ISS, especially with the adoption of AM and 3D printers (Abdulhamid et al., 2025b). Several materials, such as polymers, ceramics, and metal, have been produced and tested on the ISS, demonstrating that it is indeed possible to manufacture in space.
- **In-space Operations (ISO):** This unit of FIS, also sometimes known as in-space servicing or in-space operations and servicing, aims to enhance the performance, resilience, adaptability, and sustainability of space systems through in-space operations such as refueling, repair and maintenance, provision of space utilities such as energy supply among other activities. The concept of ISO has existed in some form since the 1980s (Rapley et al., 2017), and more recently, the demonstration of the MEV (Pyrak and Anderson, 2021) to extend the lifespan of satellites provides a glimpse into how ISO could support and enhance human space presence.
- **In-situ Material Utilization (ISMU):** This FIS component exploits locally established materials to support/enhance space missions. Raw materials in this context are readily available in extraterrestrial environments, such as lunar and Martian regolith and space junk. Types of materials locally available for FIS activities have been highlighted previously (Abdulhamid et al., 2025b). The scarcity of resources in the extraterrestrial environment

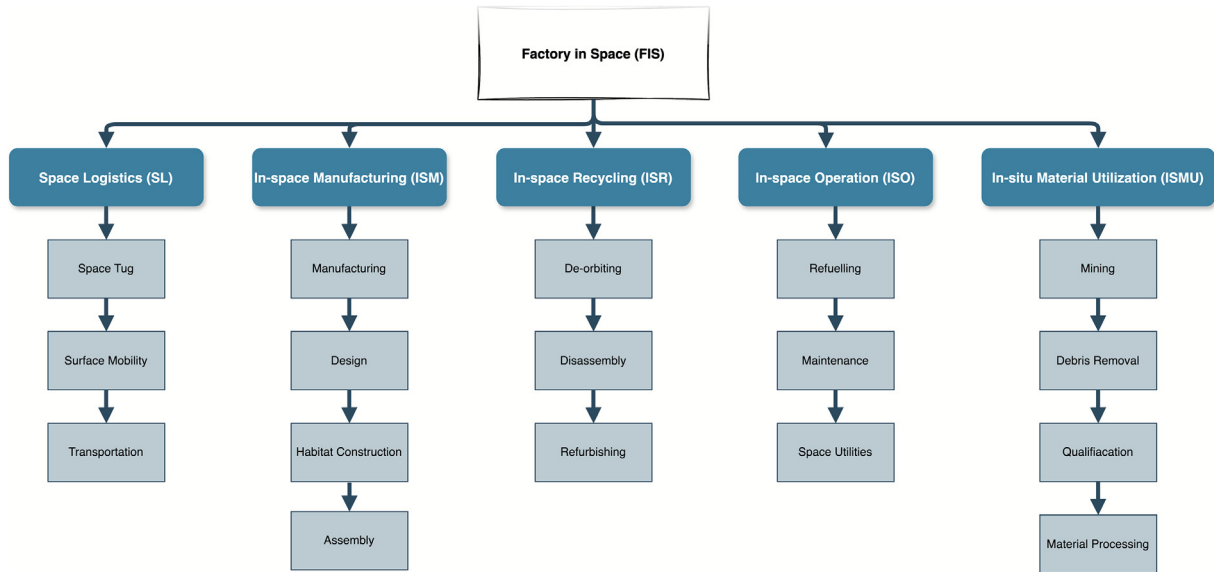


Fig. 4. Components of FIS.

means alternate sources must be established to support human life and activities in space. ISMU also involves processing resources to be used as input material in ISM and ISO.

- **In-space recycling (ISR):** This component of FIS is responsible for recycling material found in space. Recycled raw materials are generated from this unit and used as input for manufacturing in ISM. The end-of-life (EOL) strategies for defunct space systems captured through debris removal and space tug are identified in ISR. The continuous increase in the amount of human-made defunct objects in space indicates that, in theory, a potential value could be gained from these objects (Leonard and Williams, 2023). Furthermore, governmental agencies' push for debris neutrality and long-term orbital sustainability dictates the need for a solution to the accumulated orbital debris. ISR proposes a successful and sustainable method of disposing of debris while recycling valuable and critical raw materials already in Orbit.

Once the components of FIS were established, their criticality to the development of the FIS ecosystem was explored. Considering the insight from the literature and the focus group (see research phases I & II), the experts were asked to rank the importance of the identified components in developing FIS (see research phase III). The results of the responses indicated that SL was the most crucial component in actualizing any FIS facility. SL, as discussed above, entails robotic maneuvers such as space tug and surface mobility to capture and deliver products to designated positions. This highlights the foundational function of SL in coordinating operations such as manufacturing, assembly, and material transport or harvesting. SL encompasses the movement of materials, products, and services within and between FIS facilities and their target destinations. It can be stated that without SL, other key components of

FIS cannot be integrated into a fully functional and scalable ecosystem. In other words, SL can be referred to as the connector of the FIS ecosystem. Therefore, it is of paramount importance to develop robotic and mobility technology such that products and materials produced by ISM, ISMU, and ISR can be efficiently incorporated to the desired platforms. Hence, the foundation of FIS is built on the capability to overcome the logistical constraints associated with FIS successfully.

Furthermore, the components ISO, ISR, ISMU, and ISM were highlighted as equally crucial to establishing FIS. Indeed, several national agencies and commercial entities have expressed the symbiosis between the technologies required for manufacturing, repairing, servicing, and recycling products, materials, and components. For instance, the Cornerstone Research Group (CRG), together with NASA, developed a system to process Polyethylene-based thermally reversible foam into recycled 3D printing filament that could be used with fused filament fabrication (FFF) systems similar to those aboard the ISS to manufacture new components (Marshall Space Flight Center, 2019). Similarly, the versatility of robotic arms has streamlined several activities, such as in the MEV demonstration mission, where the arm was used for refilling and welding operations (Pyrak and Anderson, 2021). Similar robotic arm technology has been adopted in manufacturing and assembly systems to improve efficiency and quality and reduce lead times (Keshvarparast et al., 2024). This further highlights the need for developed space systems to be versatile and adaptable to various operations in multiple situations.

Overall, the definition proposed in this section emphasizes the need for integration in order for a system to be considered an FIS. Unlike previous and current ISS-based operations, such as the AMF, FIS systems have

capability integration by combining at least two of the components illustrated in Fig. 4. Furthermore, FIS systems are flexible, adaptable, scalable and sustainability-oriented, such that they foster resource optimization and are capable of cross-sector operations across the space economy.

5. Conclusion

The growing ambition for deep and long-duration space exploration dictates that space infrastructure must be highly resilient and adaptable. In response, the Factory in Space (FIS) concept was proposed to enable in-situ manufacturing, repair, refurbishment, recycling, and reuse, thereby alleviating reliance on Earth-based supply chains. Existing studies have individually explored these facets. However, there is still a lack of a comparative definition of FIS as a single ecosystem. This study aims to provide an operational definition of the FIS ecosystem by analyzing its components, features, and functions. Section 2 of this paper establishes the context of FIS and the milestones achieved so far in orbital operations, as summarized in Fig. 2. The role of governmental bodies in the development of FIS was highlighted. The National Aeronautics and Space Administration's (NASA) Additive Manufacturing Facility (AMF) installation aboard the International Space Station (ISS) and the On-orbit Servicing, Assembly, and Manufacturing Mission (OSAM) project have been elaborated. Furthermore, efforts from the European Space Agency (ESA) to develop sustainability and circularity in the space economy have been cited. At the same time, China's autonomous manufacturing unit, which is capable of printing carbon fiber in space, has also been highlighted. Additionally, private companies play a crucial role in this evolution. Redwire was instrumental in executing the AMF and contributed to OSAM. Similarly, Northrop Grumman's development of the Mission Extension Vehicle (MEV) and Mission Robotic Vehicle (MRV), along with SpaceX's advances in spacecraft technology, highlight the growing private sector engagement in FIS initiatives.

Considering the context of FIS, insights from this study were discussed in section 3, where the insights from both literature and expert interviews were discussed (see research phases I & II). One terminology frequently associated and interchanged with FIS is in-space manufacturing (ISM). While FIS and ISM share similarities, it is essential to note that they are two distinct concepts. Indeed, it can be stated that ISM exists under the idea of FIS, while the activities of FIS are beyond the scope of just ISM. Table 1 presents a summary of the differences between FIS and ISM. Furthermore, technology's role was cited as crucial to the actualization of FIS. Some areas of technology that are critical, desired, and enabling for FIS, such as robotics, automation, material processing, recycling, manufacturing, and modularity, were identified. Similarly, some significant hurdles associated with establishing FIS, such as quality control, supply chain, energy sources, funding, environment, and regulation, were discussed. Considering these insights,

section 4 provides a descriptive definition of FIS by outlining the drivers and components of FIS (see research phase III). FIS is defined as a space facility that integrates technologies and solutions – such as in-space manufacturing, assembly servicing, and logistics – into a cohesive operational architecture to support and enhance the performance of missions across sectors in the space economy and leveraging the unique environmental conditions of space to create a sustainable industrial ecosystem beyond Earth. Factors such as cost reduction, sustainability, and space infrastructure development were cited as the main drivers of FIS. Five components of FIS were identified as space logistics (SL), in-space manufacturing (ISM), in-space recycling (ISR), in-space operations (ISO), and in-situ material utilization (ISMU). SL was identified by the experts as the most crucial component in the actualization of FIS. SL entails robotic maneuvers such as space tug and surface mobility to capture and deliver products to designated positions. Therefore, it can be referred to as the connector of the FIS ecosystem, and therefore, it is of paramount importance to develop robotic and mobility technology such that products and materials produced by ISM, ISMU, and ISR can be efficiently incorporated into the desired platforms.

Although FIS advocates a wide range of benefits, issues such as energy, funding, and material sources remain to be resolved, as discussed in section 3. One major limitation of this study is that while it defines FIS through functional components, it does not present a complete physical architecture of the FIS ecosystem. Defining the internal and external interface of the FIS ecosystem would be an important step in advancing the concept of FIS, especially from a system engineering perspective. Future work could build on the definitions proposed in this study to develop a physical architecture with accompanying relationship identifying the links between subsystems, resources, and external interfaces.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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