Chapter 4

DIGITAL (R)EVOLUTION IN MANUFACTURING AND IN THE PRODUCTION OF SPACE SYSTEMS

This chapter examines how digitalisation is affecting the space sector, with a focus on key developments in manufacturing and production in space systems, particularly satellites and space launchers. The chapter reviews some of the new production processes and changes in supply chains; it also introduces current developments in the space launcher and satellite markets particularly the rise of small satellites; and examines possible emerging activities (space tourism, in-orbit servicing, space mining and resources extraction).

Introduction

As demonstrated by the large-scale OECD Going Digital project, all sectors of the economy are starting to be impacted by digital technologies and data flows (OECD, 2019[1]). Not only is digitalisation accelerating research and innovation cycles, but it also allows more open and collaborative innovation, while in many cases radically changing competition dynamics and business models (OECD, 2019[2]). In this context, it is not surprising that the space sector is entering a new paradigm, mainly driven by digitalisation. The impacts of the digital revolution in space manufacturing and in the production of space systems are still hard to measure, although they will probably have strong implications in the next five years on both the structure of space industry itself and on several policy-making aspects, related to space activities' research and development funding and regulations.

These rather sudden changes in the space sector are taking place against the backdrop of broader evolutions in science, technology and innovation, largely driven themselves by digitalisation (OECD, 2018[3]). The development of the space sector follows five distinct cycles, each lasting some 10-15 years and illustrating the evolutions of space technology and applications and their uptake in society (Table 4.1).

Table 4.1. Cycles of space development

Cycles	Dates	Description
Pre-space age "-1"	1926-1942	First rockets (from Goddard to the V2)
Pre-space age "0"	1943-1957	Military race for intercontinental ballistic missiles, first satellite on orbit (i.e. Sputnik)
Cycle 1	1958-1972	Space race (from Sputnik to the end of the Apollo era), beginning of military applications (e.g. spy satellites), first humans in space, robotic space exploration
Cycle 2	1973-1986	First space stations (Skylab, Salyut) and shuttles (US space shuttle, Buran), further development of military applications (GPS, Glonass), beginning of civilian and commercial applications (earth observation, telecommunications), emergence of new actors (Europe, Japan, China)
Cycle 3	1987-2002	Second generation of space stations (Mir, ISS), stronger role of space applications in militaries, further development of civilian and commercial applications (Landsat, Spot Image, satellite television), with more actors entering markets, and many space technology transfers at the end of cold war
Cycle 4	2003-2018	Ubiquitous use of space applications in various fields thanks to digitalisation (strong rise of downstream activities), new generation of space systems (small satellites) prompted by integration of breakthroughs in micro-electronics, computers, and material sciences, globalisation of space activities (large and very small national space programmes coexist, development of global value chains)
Cycle 5	2018-2033	Growing uses of satellite infrastructure outputs (signals, data) in mass-market products and possibly for global monitoring of treaties (land, ocean, climate), third generation of space stations, extensive mapping of solar system and beyond thanks to new telescopes and robotic missions, new space activities coming of age (e.g. new human-rated space launchers, in-orbit servicing)

Source: Adapted from OECD (2016[4]), *Space and Innovation, https://dx.doi.org/10.1787/9789264264014-en.*

The first two cycles of space development, during the 1960s and 1970s, were heavily dominated by public-oriented missions, with an emphasis first on defence projects followed by space exploration missions (e.g. Apollo programme), and civilian applications. The third cycle, from the 1980s onwards, saw the development of the first commercial space applications, in particular in telecommunications, with large satellite operators being privatised. From 2000 onwards, digitalisation and miniaturisation have been key drivers of new downstream space applications and new generations of (smaller) space systems, prompted by ever-increasing computing power capabilities and breakthroughs in micro-electronics, computing and material sciences. The year 2018 marked the verge of a fifth cycle of space development, where data and signals from satellites feed directly into mass-market consumer products, and are routinely used in government and commercial operations. This may also be the beginning of a new era of space exploration and in-space activities, as the sector has never seen such a diversity of actors getting involved, as funders and developers of space systems.

The drivers for this transformation are multiple and complex, and can be found in both the upstream and downstream segments of the space sector. This chapter will particularly focus on key enabling activities and developments in manufacturing and space launch. The following sections review some of the new processes for production and supply chains; discuss important developments in the space launcher and satellite markets; and look at some of the maturing technologies on the horizon. The evolutions in space exploration and in telecommunication markets that are driving much of the commercial growth in the space sector are treated separately in dedicated chapters (Chapters 5 and 6).

New production and supply chain management processes

Building on decades of research and development, much of the innovation in the space sector still originates in countries with long-standing and well-funded institutional space programmes. But new and disruptive groups of actors, production processes and digital technologies are starting to change where, what and how space systems and products are being developed as compared to less than a decade ago. The next sections review selected technical evolutions in space manufacturing, as well as ongoing adaptations in supply chain management.

Evolutions in space manufacturing

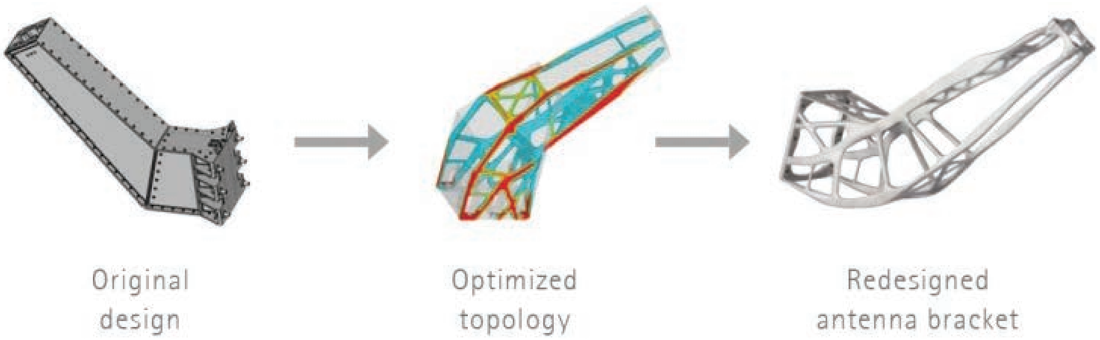
The next production revolution in manufacturing refers to the increased use of digital technologies in industrial processes (OECD, 2017[5]). It has profound impacts on productivity, on employment levels and required skill sets, on industry demographics, etc. The first mover advantages of big companies may also be reinforced by large investments in digital technology, with an increased probability of "winner-takes-most" scenarios due to the scalability of intangible digital assets (OECD, 2017[5]; 2017[6]; Haskel and Westlake, 2018[7]; OECD, 2019[2]).

In this context, where aerospace and defence industry players tend to benefit the most from large institutional space programme contracts in both OECD countries and partner economies, digital manufacturing technologies are already gradually transforming the space sector. Several incremental technologies, such as data analytics, additive manufacturing and robotics, contribute to reducing material costs and production times for many different types of missions. These missions include one-off platforms for government science missions for example, and more standardised satellite buses for commercial earth observation or telecommunications. In particular, incremental technologies pave the way for mass production of both satellites and launchers, something which is closely related to the planned broadband constellations of thousands of communications satellites in the 100-400 kg range (see chapter 6) and requiring space manufacturers to produce and assemble satellites at an unprecedented scale and speed.

Several of these process innovations were introduced to the sector by newcomers, but incumbents are following suit. SpaceX was one of the first companies to adapt experiences and data from high-volume industries, such as the automotive industry, to space manufacturing. Other companies are also heavily investing in new technologies and facilities. The company Thales Alenia Space is building a EUR 20 million automated production facility for photovoltaic assemblies in Belgium, with several new techniques such as robotised panel assembly, digital data management and traceability, online tests and inspections, as well as augmented reality (Mouriaux, 2017[8]; Thales Alenia Space, 2017[9]). The satellite manufacturing company OneWeb Satellites, a joint venture between the broadband satellite company OneWeb and European manufacturer Airbus, opened a new facility in Toulouse (France) in 2017 and is finalising the main production facility in the Kennedy Space Center Exploration Park in Florida, which will have two assembly lines (Bauer, 2017[10]; Richardson, 2017[11]). The estimated cost of the 10 000 m^2 Florida facility is some USD 85 million and it will employ about 250 people (Richardson, 2017[11]). The venture aims to produce up to 15 satellites per week (OneWeb Satellites, 2018[12]). The US company Blue Origin is equally investing some USD 200 million to build a new 70 000 m^2 (750 000 ft^2) production facility for its New Glenn launcher in the Kennedy Space Center Exploration Park, employing some 330 people (Richardson, 2017[13]), as well as a new facility in Alabama for its BE-4 engines, capable of producing 30 engines per year (Foust, 2017[14]). "Moving" assembly lines have also been introduced for the production of Ariane 6 first- and second-stage engines, inspired by similar practices in aeronautics manufacturing (Meddah, 2017[15]).

The uptake of additive manufacturing in space manufacturing has accelerated in the last years, especially with the advances made in metal additive manufacturing. 3D-printed metal satellite components (e.g. antenna brackets and supports) were first sent to orbit in 2015-16 (Arabsat-6B) (Russell, 2017[16]). Figure 4.1 shows the redesign process of an antenna bracket on the Sentinel satellites, with the final 3D-printed aluminium alloy bracket 25% lighter, more performant and with half the production time (down from ten weeks to four or five weeks) than the original bracket (EOS, 2016[17]). For some satellite parts, the weight gain is even higher. 3D-printed dual antenna arrays for mobile satellite communications can be up to five times lighter than more conventional products (Swissto12, 2019[18]).

Figure 4.1. Additive manufacturing of satellite antenna bracket



Source: Adapted from EOS (2016[17]), "Additive manufacturing of antenna bracket for satellite", *Customer case studies*, *https://www.eos.info/case_studies/additive-manufacturing-of-antenna-bracket-for-satellite*.

3D-printed components and parts are also increasingly used in launchers, in particular for engine components. SpaceX made its first launch with a 3D-printed engine part (the main oxidiser valve body) in 2014 (SpaceX, 2014[19]). Currently, several manufacturers are using additive manufacturing for producing engine parts. The US/New Zealand company Rocket Lab uses additive manufacturing for all "primary components" of its Rutherford engine, including the combustion chamber, injectors, pumps and propellant valves (Rocket Lab, 2015[20]). Table 4.2 summarises these findings and shows a selection of 3-D printed engine parts among space manufacturers.

Table 4.2. Selected 3D-printed parts in space launcher engines

Space vehicle	Company	Type of part	Material(s)	Main subsystem	First launched
Falcon 9 launcher	SpaceX	Main oxidiser valve body	Inconel (nickel-chromium based alloy)	Merlin 1D engine	2014
Electron launcher	Rocket Lab	All primary engine components (e.g. combustion chamber, injectors, pumps and main propellant valves)	Titanium	Rutherford engine	2018
Vulcan launcher	Blue Origin	Housing, turbine, nozzles, rotors	Aluminium; nickel-based alloy	BE-4 engine	In development
Ariane 6 launcher	ArianeGroup	Injector head (all-in-one design, 248 elements reduced to only 1)	Nickel alloy	Upper stage Vinci engine	In development
Ariane 6 launcher	ArianeGroup	Gas generator	n.a.	Vulcain 2.1 engine	In development
	Aerojet Rocketdyne	Preburner	Mondaloy 200 (nickel-based alloy)	AR-1 engine	In development

Additive manufacturing is also used in small satellite and cubesat manufacturing. While previously mainly adopted for the production of secondary structural parts, experiments are now carried out with primary structures (NASA, 2018[21]). The PrintSat picosatellite (0.1-1 kg), whose structure was entirely 3D-printed at Montana State University using a carbon-fibre reinforced composite, was lost in a launch failure in 2015 (Montana State University, 2015[22]).

Adaptations in supply chain management

The changes in space manufacturing processes and the increasing development of small satellite and cubesat constellations in low-earth orbit increasingly influence the management of space manufacturing supply chains. Several trends can be identified, such as the vertical integration of production and increased internationalisation of supply chains, with a growing reliance on off-the-shelf components. Advances in additive manufacturing (3D-printing) and autonomous systems are also making certain in-space assembly, repair and manufacturing activities increasingly feasible.

Leaning towards more vertical integration

The increased reliance on serial production and automation lowers the cost of production and reduces the need for outsourcing. It is estimated that more than 70% of each Falcon launch vehicle is manufactured at the SpaceX production facility, in Hawthorne, California (OECD, 2014[23]). This has made it possible to quickly scale up productions and to shorten research and development lead times (e.g. the rapid transformation of Falcon 9 to address the commercial geostationary market, increased reusability). Other companies, such as Blue Origin and Rocket Lab, also rely on vertically integrated, in-house production. Blue Orbital's Florida facility for its New Glenn launcher will accommodate manufacturing, processing, integration and testing (Calandrelli, 2016[24]). In a similar vein, ArianeGroup, the joint venture of Airbus and Safran, which is producing the future European Ariane 6 and the small launcher Vega-C with Arianespace, is also consolidating its production supply chain, previously spread across 25 different European industrial sites, by focusing more on site specialisation and mass production of standardised parts and components (OECD, 2016[4]; Meddah, 2017[15]).

Increased internationalisation and use of off-the-shelf components

Other manufacturers, in contrast, are spreading out their supply chain, using more affordable international suppliers to cut costs, despite higher risks of delay (US Department of Commerce, 2013[25]). As very small satellite and cubesat constellations become more efficient and commonplace, the relatively low cost and rapid satellite turnover makes technology solutions more "expendable", with increased room for experimentation with off-the-shelf technologies and components sourced from other, faster moving non-space industries (e.g. electronics).

Examples include the early adoption of technologies such as flat lithium-polymer cells for cubesat energy storage or off-the-shelf technologies used for on-board computing system (NASA, 2018[26]; 2018[27]). Table 4.3 shows a selection of battery and battery cell providers for cube- and nanosatellites identified in NASA's report *State of the Art Small Spacecraft Technology*. The list includes both specialised aerospace/defence manufacturers (ABSL/EnerSys, Clyde Space, GomSpace, EaglePicher) and electronics manufacturers such as Canon, Molicel, LG and Samsung.

Table 4.3. Selected cubesat batteries and their manufacturers

Product	Manufacturer	Energy density (Whkg-1)	Cells used	Technological readiness level (TRL)
COTS 1865 Li-ion Battery	ABSL	90-243	Sony, Molicel, LG, Sanyo, Samsung	TRL 8
BP-930s	Canon	132	Four 18650 Li-ion cells	TRL 9
Li-Polymer, 8.2 V, 1.25-20 Ah	Clyde Space	150	Clyde Space Li-Polymer	TRL 9
Li-Polymer, 32 V, 6.25 Ah	Clyde Space	150	Clyde Space Li-Polymer	TRL 8
Rechargeable space battery (NPD-002271)	EaglePicher	153.5	EaglePicher Li-ion	TRL 7
NanoPower BP4	GomSpace	160	GomSpace NanoPower Li-ion	TRL 9
NanoPower BPX	GomSpace	157-171	GomSpace NanoPower Li-ion	TRL 9
Li-ion battery block VLB-X	Vectronic	..	SAFT Li-ion	..

Source: Adapted from NASA (2018[26]), "Power", in *State of the Art of Small Spacecraft Technology*, *https://sst-soa.arc.nasa.gov/03-power*.

The same mix of specialised (aerospace/system critical) and general electronics manufacturers can be found among providers of cubesat on-board electronic systems, as illustrated in Table 4.4.

Table 4.4. Selected manufacturers of cubesat on-board computing systems

Mainly system-critical and harsh environment (aerospace/defence) industries	Mainly electronics industry
BAE Systems	STMicroelectronics
BroadReach/Moog	Texas Instruments
C-MAC Microtechnology	3D Plus
Cobham (Aeroflex)	Xilinx
Intersil	Arduino
Maxwell Technologies	BeagleBone
Space Micro, Inc.	ATMEL
	Honeywell
	Intel
	Freescale/NPX
	Microsemi/Microchip

Source: Adapted from NASA (2018[26]), "Power", in *State of the Art of Small Spacecraft Technology*, *https://sst-soa.arc.nasa.gov/03-power*.

Additive manufacturing for space habitation and exploration

Additive manufacturing is a particularly interesting technology for space habitation and deep space exploration, making it possible to produce spare parts when needed in space, instead of transporting voluminous parts from Earth.

The technology, using aerospace-grade composites, has already been tested on the International Space Station since 2014, and the permanent Additive Manufacturing Facility on the station can print tools, components and other hardware. Made in Space, the same company that has developed the additive manufacturing facilities for the International Space Station, recently won a NASA grant to develop a hybrid composites/metal printer for microgravity, capable of producing precision parts of aerospace-grade metals, such as housings for life support systems, and components that consist of multiple materials (Made In Space, 2018[28]).

Another potential application of additive manufacturing is the provision of human shelter in space. NASA's printed-habitat for Mars challenge has been running for several years in separate stages, each time focusing on different aspects of the habitat, such as design and materials. The latest stage of the challenge required the digital representation of a 90 m^2 (1 000 f^2) habitat sustaining four astronauts during a year combining living space with critical life survival systems such as life support, plumbing and rover hatches (NASA, 2018[29]).

From rockets to satellites: More changes are coming

Incumbent satellite and launcher manufacturers are facing competition from a growing number of international and commercial actors. Markets are also diversifying, with new niche products such as small and inexpensive satellites for rapid technology testing and prototyping, small satellite launchers and cubesat constellations. At the same time, government and commercial large-scale launchers for lunar exploration are getting closer to completion. The following sections take a closer look at these developments.

A crowded landscape of rockets

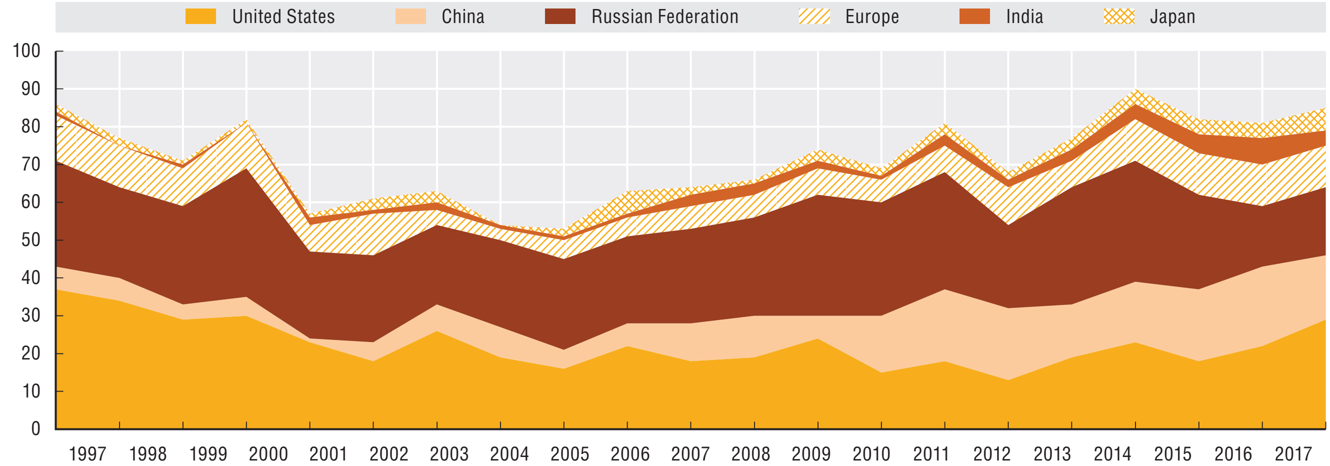
The space launch market has traditionally been closely aligned with the 10-15 year replacement cycles of telecommunication satellites, and annual launch patterns have not evolved significantly since the late 1990s (see Figure 4.2). But there have been important recent changes in the composition and type of launch providers, and more changes are coming, driven by the new manufacturing and production trends described in the previous sections, affecting particularly commercial telecommunications satellites.

The capability to carry out an orbital space launch and to manufacture and maintain a fleet of launchers remains limited to a small number of actors, which in 2019 includes ten countries (the People's Republic of China (hereafter "China"), India, the Islamic Republic of Iran, Israel, Japan, Korea, New Zealand, the Democratic People's Republic of Korea, the Russian Federation and the United States) and the European Space Agency (ESA). Six of these actors can launch to the geosynchronous orbit at some 36 000 km altitude, home to crucial telecommunications and weather satellites (China, India, Japan, the Russian Federation, ESA and the United States).

Global space launch activity has picked up since 2010, and 2018 saw the highest number of launches since the late 1990s. This growth is mainly due to significant launch activity increases in China and the United States. But launch activity has also increased in several other parts of the world (e.g. Europe, India and Japan), and with new entrants (New Zealand). Only the Russian Federation has seen a decrease in its launch activity since 2010, with launch activity in 2016-18 representing the lowest number of launches in 20 years.

In 2018, there were 111 successful space launches and 3 failed launches globally (FAA, 2018[30]). China had the highest number of successful space launches (38), followed by the United States (31), the Russian Federation (19), Europe and India (7) and Japan (6). Europe, China and the Russian Federation had one launch failure each. A small number of these launches (22), were commercial launches, e.g. privately financed or internationally competed.

Figure 4.2. Number of successful space launches for selected actors, 1997-2018



Note: This figure only counts successful or partially successful launches, i.e. the payload(s) was delivered to a usable orbit.

Source: Adapted from FAA (2018[30]), *The Annual Compendium of Commercial Space Transportation: 2018*, *https://www.faa.gov/about/office_org/headquarters_offices/ast/media/2018_AST_Compendium.pdf* and equivalent reports for previous years.

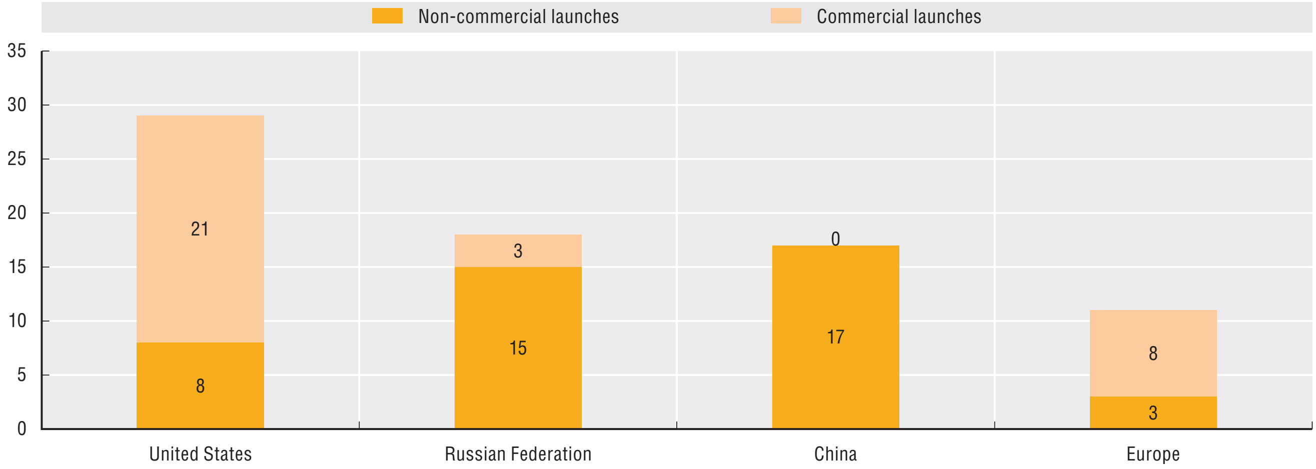
The majority of commercial launches were carried out in the United States (14 launches), followed by Europe (six launches), and New Zealand (two launches), as shown in Figure 4.3. China is seeing a considerable growth in launcher start-ups targeting commercial markets, and in October 2018, the private company Landspace made the first private (commercial) orbital launch attempt with its Zhuque-1 launcher.

Commercial launch revenues accounted for some estimated USD 3 billion in 2017 and were mainly generated from the launch of telecommunications satellites for the geostationary and low-earth orbit, as well as commercial resupply missions to the International Space Station. The launch of many small and very small commercial satellites that are launched as secondary payloads will not necessarily be recorded under this definition, if the primary payload is non-commercial. Revenues were divided between the United States (57%), Europe (36%) and the Russian Federation (6%), as shown in Figure 4.4 (FAA, 2018[30]).

Commercial launch revenues are starting to be affected by the looming crisis in satellite telecommunications, which will be further described in Chapter 6.

Figure 4.3. Commercial and non-commercial space launches in 2018

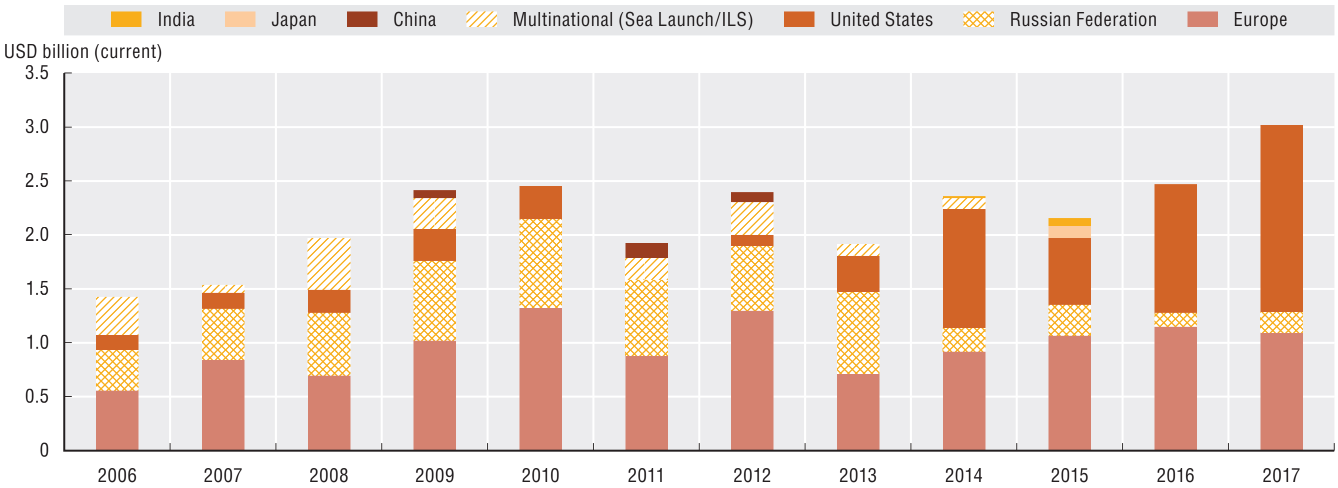
Number of successful and failed launches



Note: This figure counts both successful and failed launches and include three launch failures for China (commercial launch), Europe (commercial launch) and the Russian Federation (non-commercial launch).

Sources: Adapted from FAA (2018[30]), *The Annual Compendium of Commercial Space Transportation: 2018*, *https://www.faa.gov/about/office_org/headquarters_offices/ast/media/2018_AST_Compendium.pdf* and equivalent reports for previous years.

Figure 4.4. Launch industry revenues estimates



Note: Estimated revenues generated from "commercial" launches, according to the US Federal Aviation Administration definition. See Box 4.1.

Source: Adapted from FAA (2018[30]), *The Annual Compendium of Commercial Space Transportation: 2018*, *https://www.faa.gov/about/office_org/headquarters_offices/ast/media/2018_AST_Compendium.pdf*.

From the (re)emergence of small launchers to super-heavy launchers for interplanetary exploration

The number of launches of very small satellites, e.g. cubesats with a spacecraft mass of some 1-10 kg has grown exponentially in the last five years. Further future demand for launch services is expected from the multiple planned mega-constellations, consisting of several hundreds of small satellites in the low-earth orbit (see Box 4.1). Meanwhile, affordable launch opportunities remain limited.

Box 4.1. Ever smaller satellites

The last ten years have witnessed a revolution in the design, manufacture and deployment of satellites. Satellites vary in mass from a couple of kilogrammes or less for a small cubesat to several metric tonnes for a geostationary telecommunications satellite. A satellite with a mass of 500 kg and less is generally considered 'small'. The satellites in many of the planned satellite broadband mega-constellations are much bigger than cubesats but still much smaller than traditional telecommunications satellites, ranging from about 150 kg for the planned OneWeb constellations to 400 kg for satellites in the SpaceX Starlink constellations.

Small satellites, weighing less than 500 kg, have become very popular and cost-efficient as commercial off-the-shelf components and consumer electronics are now commonly used to build satellite platforms and instruments at the lower end of the cost range. Small satellites are making space technology more affordable and accessible to new types of users. Increasingly popular are also nano- and microsatellites (weighing between 1 kg and 50 kg), but they come with much more limited functionalities and a very short mission life (1-2 years):

- small satellite, 100-500 kg
- minisatellite, 100-180 kg
- microsatellite, 10-100 kg
- nanosatellite, 1-10 kg (e.g. cubesats)
- picosatellite, 0.01-1 kg
- femtosatellite, 0.001-0.01 kg (e.g. pocketqubes, suncubes, mainly used for educational purposes).

Cubesats are a class of nanosatellites that use a standard size and form factor, originally developed in 1999 by California Polytechnic State University at San Luis Obispo (Cal Poly) and Stanford University to provide a platform for education and space exploration. The standard cubesat size is "one unit" or "1U", measuring 10x10x10 cm, and is extendable to larger sizes stacked lengthwise; 1.5, 2, 3, 6, etc.

Source: NASA (2015[32]), *What are smallsats and cubesats?*, *https://www.nasa.gov/content/what-are-smallsats-and-cubesats*.

A comparatively low-cost option is to launch as a so-called "piggyback" payload, a secondary payload on a launch carrying a much larger satellite (FAA, 2018[30]). For instance, in 2017 the Indian Polar Satellite Launch Vehicle launched 104 satellites in one single launch: the primary payload (a government earth observation satellite, Cartosat-2), two Indian technology nanosatellites and 101 satellites (96 from the United States; and one each from Israel, Kazakhstan, the Netherlands, Switzerland and the United Arab Emirates) (ISRO, 2017[33]). For educational and non-profit cubesats, several governments also propose similar free services (e.g. NASA's Cubesat Launch Initiative, the European Space Agency's Fly Your Satellite). However, launching as a secondary payload may entail significant disadvantages both in terms of launch schedule and destination orbit, and may not be a viable option for commercial companies, which are looking for a fast access to space.

In response, both governments and private companies are investing in dedicated small launchers, i.e. those with a low-earth orbit payload capacity of less than 2 268 kg according to FAA definitions (FAA, 2018[30]). Several dozens of small launchers are being developed around the world, with many receiving venture capital funding (see Chapter 1 on private funding). As illustrated in Table 4.5, at least half a dozen small launchers have had their first orbital launch in the last five years, and more than ten launchers are in different stages of development for launch within the next three to five years (FAA, 2018[30]). Some of the most advanced launchers are Electron from the US/New Zealand company Rocket Lab, or LauncherOne from Virgin Orbit. Electron had its first orbital launch attempt in 2017 from the Mahia commercial spaceport in New Zealand, followed by a successful launch in early 2018. LauncherOne, which launches horizontally from a 747 aircraft at 10 000 metres in altitude, is expected to carry out its first orbital launch attempt in 2019. The Chinese government and private companies are also developing small launchers, both for domestic use and commercialisation, with companies such as One Space, Land Space and Linkspace (FAA, 2018[30]). After a scarcity of launch opportunities for small satellites, the next two years should see the emergence of a very competitive landscape for small launchers.

Table 4.5. Selected recent and planned small launchers for the low-earth orbit

Launcher	Year of first orbital launch	Country	Manufacturer/launch provider	Low-earth orbit capacity (kg)
Kuaizhou 1/1A	2013	China	CASIC/Expace	300
Long March 11/ LandSpace-1	2015	China	CALT/LandSpace	530
Long March 6	2015	China	SAST/CALT (CASC)/ Great Wall Industries Corp.	1 500
SS-520-5	2017	Japan	Canon/JAXA	4
Electron	2017	United States/New Zealand	Rocket Lab	225
Kaitouzhe 2	2017	China	CASIC/Expace	350
Vector R	2019 (planned)	United States	Vector	66
LauncherOne	2019 (planned)	United States	Virgin Orbit	500
Stratolaunch	2019 (planned)	United States	Scaled Composites/Dynetics	1 350
Kuaizhou 11	2019 (planned)	China	CASIC/Expace	1 500
Vector H	2019 (planned)	United States	Vector	160
OS-M1	2019 (planned)	China	One Space	205
Black Arrow 2	2019 (planned)	United Kingdom	Horizon Space Technologies	500
Alpha 1.0	2019 (planned)	United States	Firefly	1 000
Arion 2	2020 (planned)	Spain	PLD Space	150
XS-1	2020 (planned)	United States	Boeing/DARPA	1 361
NewLine-1	2020 (planned)	China	Linkspace	200

Note: First launches include launch failures.

Source: Adapted from FAA (2018[30]), *The Annual Compendium of Commercial Space Transportation: 2018*, *https://www.faa.gov/about/office_org/headquarters_offices/ast/media/2018_AST_Compendium.pdf*.

Governments are also (re)turning their attention to the manned exploration of the moon and Mars, large-scale missions that require the development of launchers capable of lifting a minimum of some 50 000 kg to the low-earth orbit. In parallel, privately-funded projects of interplanetary travel and habitation are underway (see Chapter 5 on space exploration trends).

Four large launchers, from China, the Russian Federation and the United States, are currently under development, with the US Space Launch System (SLS) the most advanced, scheduled for its first launch in the early 2020s (Table 4.6). Both SLS and the planned Russian launcher are intended to play a role in the deployment of the *Gateway* in the 2020s and 2030s, a manned "outpost" orbiting the moon (NASA, 2018[34]). The Chinese launcher Long March 9 will reportedly be used for a sample return mission to Mars as well as manned and unmanned lunar missions. It could also be used to launch a space-based solar power system, which is under consideration (Jones, 2018[35]).

Table 4.6. Selected planned super-heavy launchers

Launcher	Manufacturer / launch service provider	Country	Length (m)	Diameter (m)	LEO capacity (kg)	Planned launch year	Reusable
Space Launch System (SLS)¹	Boeing–ULA–Orbital ATK / NASA	United States	111.3	8.4	70 000-130 000	2020-21	No
Big Falcon Rocket (BFR)	SpaceX	United States	106	9	250 000	2022	Yes
Super-Heavy Space Launch Vehicle System (SH SLVS)	RSC Energia / Roscosmos	Russian Federation	n.a.	n.a.	90 000	2028	n.a.
Long March 9	CALT / People's Liberation Army	China	93	10	140 000	2030	n.a.

Note: 1. SLS is designed to evolve into more powerful configurations using the same core stage. Block 1 has a maximum launch capacity of 70 000 kg to low-earth orbit, block 1B 105 000 kg and block 2 130 000 kg.

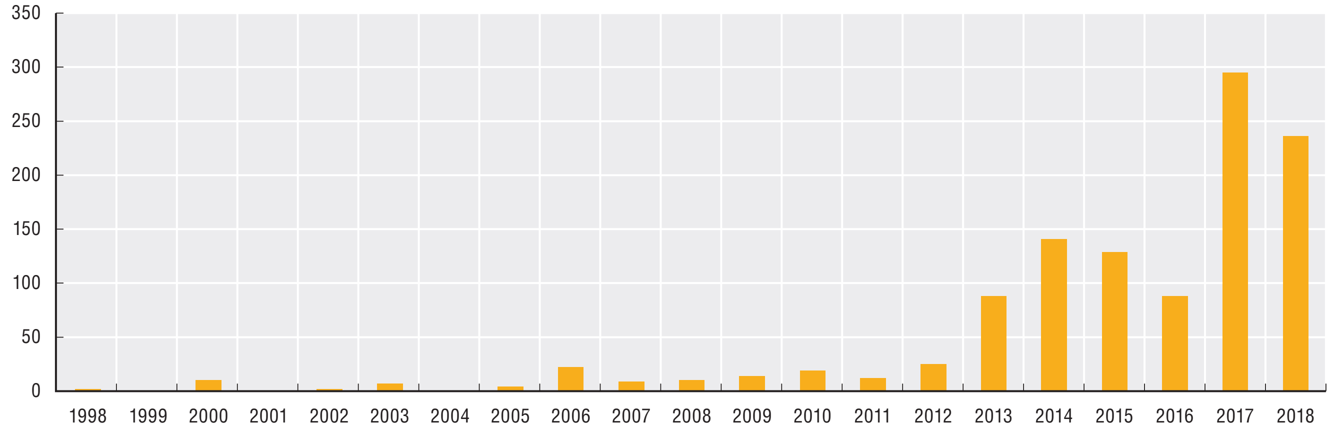
The fourth launcher, the Big Falcon Rocket (BFR), is the most powerful if measured by low-earth orbit launch capacity. While it is not a government project, BFR is being developed by SpaceX with human colonisation of Mars as the end objective (SpaceX, 2017[36]). The current design of BFR foresees a single system, one booster and one ship, that will be fully reusable and that will eventually replace the Falcon 9 and Falcon Heavy launchers and the Dragon capsule. It should be able to launch payloads to all earth orbits as well as the moon and Mars. The first launch has been set to 2022, but this could change (SpaceX, 2017[36]). The BFR, as well as the biggest configuration of SLS and the Long March 9, will all have a higher launch capacity to the low-earth orbit than Saturn V, the mythical launcher used in the US Apollo programme in 1960s, and one of the biggest space rockets ever constructed.

Cubesats as the new Swiss knife of the space sector

With growing digitalisation of all segments of space activities, cubesat constellations have shown a remarkable growth in the last five years, as illustrated in Figure 4.5. Cubesats are a class of standardised very small satellites that have low mass (mostly less than 10kg) compared with standard satellites and that are relatively low-cost to produce (OECD, 2014[23]). They consist of one or several units of 10 cm × 10 cm × 10 cm (Box 4.1). They were originally developed in 1999 by California Polytechnic State University at San Luis Obispo and Stanford University to provide a platform for education and space exploration. In the beginning they were mainly used at universities as technology demonstrators, but in the last five years they have become increasingly popular with commercial firms.

Figure 4.5. Annual launches of very small satellites

Includes successful and failed launches



Note: Includes all cubesats (0.25U to 27U), nanosatellites (1-10 kg), picosatellites (100 g-1 kg), pocketqubes, tubesats and suncubes (see Box 4.1 for more information).

Source: Nanosatellite Database (2019[37]), *Nanosatellite and cubesat database*, Version 19 January 2019, *https://www.nanosats.eu/*.

For cubesat constellation operation alone, unofficial industry statistics (e.g. the comprehensive *Nanosatellite Database*) list more than 30 start-ups either already operating or in different stages of development, headquartered in a dozen different countries on four continents (Table 4.7). There is great variation not only in the planned size of the constellation (from a couple of dozen to several hundred satellites) but also the size of the cubesat, ranging from 2U to 16U (see Box 4.1). These constellations also have an increasing variety of sensor technologies for a growing range of applications, including optical, multispectral, infrared and synthetic aperture radar for earth observations applications; GPS-radio occultation and microwave radar for weather observations; automatic identification system receivers for maritime tracking; and (mainly) narrow-band receivers for machine-to-machine communications and the Internet of Things (IoT) (Nanosatellite Database, 2019[37]).

Finally, this rush to test and develop commercial systems is bringing new challenges, as newcomers to the space industry, including start-ups, still have to follow national and international rules to launch and operate satellites in orbit. Spectrum, for instance, is a rare commodity and needs to be allocated via a well-established, although at times lengthy, regulatory process, so as to avoid dangerous interferences. Also, even very small satellites need to be tracked from the ground to avoid collision risks with other satellites in orbit. In January 2018, the first case of "rogue small satellites" was reported, as the Californian start-up Swarm Technologies, specialised in autonomous robots and the IoT, launched four nanosatellites on-board an Indian rocket, despite having had its launch license request rejected by the US Federal Communications Commission. The accumulation of space debris is another concern (see chapter 5).

Table 4.7. Selected existing and planned cubesat constellations

Company	Country	Number of launched satellites/ planned constellation size	Launch of first satellite	Cubesat size	Application/technology
ExactEarth	Canada	67/67	2008	Nanosat/hosted	AIS
Planet	United States	355/150+	2013	3U	Earth observation
Spire	United States	103/150+	2013	3U	Weather/AIS/ADS-B
Planetary Resources	United States	3/10	2014	12U	Earth observation
Astro Digital (Aquila)	United States	6/25	2014	6U/16U	Earth observation
Sky and Space Global	United Kingdom	3/200	2017	3U	Internet of Things (IoT)
GeoOptics	United States	7/?	2017	6U	Weather (GPS-RO)
Helios Wire/SIRION	Canada	2/30	2017	6U, 16U	IoT/machine-to-machine
Dauria/SatByul	Russian Federation	2/8	2017	6U	Earth observation
Swarm Technologies	United States	7/150	2018	0.25U, 1U	IoT/machine-to-machine
Kepler Communications	Canada	2/140	2018	3U	IoT
Analytical Space	United States	1/?	2018	6U	IoT
Hiber (Magnitude Space)	Netherlands	2/48	2018	6U	IoT
Astrocast (ELSE)	Switzerland/United States	1/64	2018	3U	IoT
Fleet Space	Australia	4/100	2018	12U	IoT
Reaktor Space	Finland	1/36	2018	6U	Earth observation (hyperspectral)
AISTech	Spain	1/150	2018	2U/6U	IoT/AIS/earth observation (IR)/ADS-B
Myriota	Australia	1/?	2018	n.a.	IoT/machine-to-machine
PlanetiQ	United States	0/18	2019	6U	Weather (GPS-RO)
Lacuna Space	United Kingdom	0/32	2019	6U	IoT
Blink Astro	United States	0/?	2019	3U	
NSLComm (SkyFi)	Israel	0/60	2019	6U	Internet
Aerial & Maritime (partially GomSpace)	Sweden/Denmark/Mauritius	0/?	2019	n.a.	AIS/ADS-B
Hera Systems	United States	0/48	2019	12U	Earth observation
Bluefield	United States	0/22	2019	16U	Methane emissions
Kleos Space	Luxembourg	0/20	2019	Cubesat	AIS, geolocation, orbital data
SatRevolution	Poland	0/66	2019	2U	Earth observation
Karten Space	Spain	0/14	2019	6U	Earth observation/AIS
UnSeenLabs	France	0/?	2019	6U	RF spectrum monitoring
Orbital Micro Systems	United States/ United Kingdom	0/40	2019	3U	Weather (microwave radar)

Note: Includes all cubesats (0.25U to 27U), see Box 4.1 for more information.

Source: Adapted from Nanosatellite database (2019[37]), *Nanosatellite and cubesat database*, Version 29 January 2019, *https://www.nanosats.eu*.

Looking ahead to emerging space activities

Projecting possible developments of any economic sector is a difficult exercise. Almost fifteen years ago, the OECD conducted its first two-year project in co-operation with the space community to investigate which contributions space applications could make to meet five major societal challenges up to 2030 (the environment, the use of natural resources, the increasing mobility of people and goods, growing security threats, and the move towards the information society) (OECD, 2004[38]; 2005[39]). The project included alternative future scenarios to model possible trajectories of space activities, the drawing of technology maps that proved to be quite accurate more than fourteen years later (Table 4.8), and the elaboration of key recommendations to make the sector more sustainable.

Many of these policy guidelines are still valid today. They aimed at implementing a sustainable space infrastructure; encouraging public use of that infrastructure; and encouraging private sector participation.

The project furthermore identified some of the most promising space systems and applications by 2030, which are listed in Box 4.2. The majority of the main contender applications (e.g. precision farming, traffic management, location-based services) have matured and turned into full-fletched commercial services thanks to advances in space systems, data analytics and machine learning.

Table 4.8. Possible space innovations by 2030 (anticipated in 2004)

Innovations anticipated in 2004	Situation in 2018
Increases in processing power will enhance the capacity to process masses of data collected by remote sensing satellites usefully. Combined with insights derived from biotechnology, it will be possible to develop, among other things, macro-models of environmental processes. Remote sensing, possibly combined with artificial intelligence, will be used to monitor a variety of international treaties.	Advances in computer processing power (including in-satellite orbit processing), big data analytics, development of the cloud, and the combination of drones and satellites, are leading to a strong institutional and commercial uptake of geospatial information, improved weather and climate models (which now rely for many of their variables on satellite data series). New satellite data will be increasingly used for global monitoring, as space agencies elaborate together standards to allow better uptake by policy-makers (e.g. tracking pollution on land and at sea, Co2 emissions).
Radio frequency identification (RFID) tags will use a hybrid of ground and space systems to provide "smart transport" services, keeping track not only of inventory, but possibly of people as well.	The inclusion of active and passive RFID tags in retail, healthcare, manufacturing and other sectors has become the norm, with more growth expected as electronic sensors become ever-smaller and even 3-D printed (a few million in 2003 to around 10 billion in 2016, with active RFID systems linked to GPS). Advances in processing power and electronic miniaturisation are contributing to ever more location-based services using satellite signals and data.
Manufacture of pico- or nanosatellites in low-earth orbit, as opposed to a handful of large satellites in geosynchronous orbit, to serve future telecommunications needs. Large numbers of these satellites could be put into orbit very cost-effectively because of their low mass (tens of kilograms down to hundreds of grams) and because the globe can be spanned with low- orbit devices if there are enough of them in orbit.	Cubesats have already become very common, and further fractionated mission architectures are studied in several countries. This involves research in networked systems of distributed, co-operating small-satellites, away from the current traditional, large, multifunctional satellites. Some experts see this as an evolution similar to computers, i.e. large mainframe computers of the 1970s have evolved into networks of small computers connected via Internet. This is leading to new commercial ventures (constellations of very small satellites).

Source: Adapted from OECD (2004[38]), *Exploring the Future of Space Applications*.

Box 4.2. Promising space systems and applications by 2030

On the basis of three scenarios developed in 2002-04, a list was established of possible promising space applications that could become fully operational by 2030:

Main contenders:

- Entertainment (digital radio, TV, data and multimedia broadcasting to fixed and mobile assets, high bandwidth to the home / convergence of different media);
- Meteorology and climate change (meteorological and sea condition forecasting for commercial sea shippers, pollution maps with evolution in time, monitoring of the application of treaties, standards and policies);
- Distance learning and telemedicine (broadcasting to remote areas and across national borders, medical remote surveillance);
- E-commerce (enabling changing work patterns due to mobile workforce / home working and economic consequences, HDTV teleconferencing);

Box 4.2. Promising space systems and applications by 2030 *(cont.)*

- Location-based consumer services (driver assistance and navigation aids, insurance based on real-time usage data, vehicle fleet management, asset tracking (especially high-value) and road repair management);
- Traffic management (location and positioning of aircraft and ships, optimisation of airport traffic management, optimisation of traffic management – road pricing - driver behaviour logging);
- Precision farming and natural resources management (precision agriculture for maximal efficiency in equipment and application of fertilizer, deforestation and forestry management);
- Urban planning (plans, maps and numerical terrain models, precise positioning of engineering structures and buildings, automatic control of job site vehicles, management and optimisation of job site vehicle routes);
- Disaster prevention and management (telecom capability in absence of ground infrastructure, remote assessment of damage and pollution for insurance claims).

Outsiders:

- Adventure space tourism (suborbital then orbital);
- In-orbit servicing;
- Power relay satellites.

Source: Adapted from OECD (2004[38]), *Exploring the Future of Space Applications*.

The following applications were listed as ‘outsiders’: adventure space tourism (suborbital then orbital), in-orbit servicing and power relay satellites. Examining today’s situation, in-orbit servicing and space tourism are in the most advanced stages of development.

Adventure space tourism

Adventure space tourism operators are getting closer to opening commercial operations after years of development and testing and millions of dollars in investments. Table 4.9 shows some of the most advanced projects to date, including the only existing space tourism service, offered by Roscosmos, to travel to the International Space Station.

The planned offerings for suborbital space tourism involves 2-3 days of training and preparations for a trip that lasts about 10-20 minutes, reaching the 100 km altitude border of space and returning to Earth either horizontally or vertically.

- In December 2018, the Virgin Galactic SpaceShipTwo spacecraft reached a peak altitude of 83 kilometres, making it the first human commercial suborbital spaceflight since 2004.
- The other current suborbital space tourism contender, the New Shepard launcher programme from Blue Origin, had by the end of 2018 completed nine unmanned test flights and is expected to start manned flights in 2019-20.

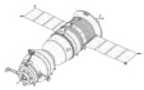
Virgin Galactic and Blue Origin, which are both backed by billionaire entrepreneurs (Richard Branson and Jeff Bezos), also intend to launch commercial and government microgravity payloads and are already part of NASA’s Flight Opportunities programme providing flights for technology demonstration payloads.

Orbital space tourism services aim to typically offer a 7-11 day stay in space and costs tens of millions of dollars. Seven paying customers travelled to the International Space Station on the Russian Soyuz spacecraft between 2001 and 2009 (one customer travelled twice) and another two customers have signed up for a flight in 2021 (Space Adventures, 2019[40]). There will soon also be seats available on Boeing and SpaceX spacecraft, at undisclosed prices. The US start-up Axiom Aerospace will further be offering tourist stays on the International Space Station starting from 2020, for a price of about USD 55 million (Axiom Space, 2019[41]).

- Manned test flights have been scheduled in mid-2019 for the Boeing and SpaceX crew capsules to the International Space Station, with the first operational flights scheduled end 2019/early 2020. The Boeing CST-100 capsule has one additional seat that is intended for paying customers.
- In September 2018, a Japanese billionaire signed up for a circumlunar trip with the SpaceX Big Falcon Spaceship, to be launched on the BFR rocket. The trip has been tentatively scheduled for 2023.

Concerning stays in orbit, several companies are developing modules that would be first connected to the International Space Station and then made fully autonomous once the ISS is retired. While the primary objective would be to offer affordable solutions to governments and corporations for microgravity research, tourism would be a secondary source of income. Axiom Space plans to have their own private space stations ready for launch in 2022, while Bigelow Aerospace, which built the inflatable BEAM module that has been connected to the International Space Station since 2016, is developing two autonomous modules, B330-1 and B330-2, planned for launch in 2021 (Axiom Space, 2019[41]).

Table 4.9. Overview of existing and planned space tourism services

Distance from Earth	Destination	Company	Vehicle		First flight	Available seats for paying customers	Signed up customers (end 2018)	Price per seat
300 000 km	Deep space	SpaceX	Big Falcon Starship (BFS), launched on the BFR rocket		ca. 2023	n.a.	1	n.a.
		Blue Origin	New Glenn		ca. 2023	TBD	n.a.	TBD
400 km	Low-earth orbit	Roscosmos	Soyuz capsule		2001	1	7 (2001-09), 2 signed up for 2021 flight	USD 20-40 million
		Boeing	CST-100 Starliner crew capsule		Expected 2019-20	1	n.a.	USD 58 million (for NASA)
		SpaceX	Crew Dragon capsule		Expected 2019-20	1-3	n.a.	USD 58 million (for NASA)
		Axiom Aerospace	Tourist stay on the International Space Station. Unspecified vehicle		2020	n.a.	n.a.	USD 55 million
		Sierra Nevada	Dream Chaser, vertical launch and horizontal landing vehicle		In development	7	n.a.	n.a.
100 km	Suborbital travel	Virgin Galactic	SpaceShipTwo, airborne horizontal launch and landing vehicle		Expected 2019	6	600	USD 250 000
		Blue Origin	New Shepard, vertical launch and landing vehicle		Expected 2019	6	Ticket sale to start in 2019	TBD

Market studies base their assumptions on the global availability and preferences of high net worth individuals, with a household income of at least USD 200-250 000 or a net worth of a minimum USD 1 million. A 2002 survey found then that 19% of respondents were definitely or very likely interested in undertaking suborbital space travel, and 16% were willing to pay the maximum suggested price of USD 250 000 (the current price of a seat on Virgin Galactic's SpaceShipTwo) (Futron, 2002[42]). In a more recent market study, based on more than 1 000 interviews in 11 countries, Astrium (Airbus Defence and Space) modelled demand according to different price scenarios and projected a very rapid increase in customer demand, growing from some 600 passengers in the second year of operations to more than 40 000 in the seventeenth year (in the conservative high-price scenario) (Le Goff and Moreau, 2013[43]). Depending on the degree of optimism, annual global revenue estimates after ten years of operations range from USD 200 million to 800 million (UK Satellite Applications Catapult, 2014[44]). The most conservative of these estimates is based on a relatively limited customer base (some 1 500 customers in the tenth year of operations).

These forecasts are also driving developments for commercial spaceports, often supported by regional administrations. In the United States, the Federal Aviation Administration issued ten licences for commercial spaceports in eight federal states in 2018 (Alaska, California, Colorado, Florida, New Mexico, Oklahoma, Texas and Virginia) (FAA, 2018[45]). Commercial spaceport projects are also being considered in other countries (e.g. Italy, Sweden, the United Kingdom). The UK government has awarded funding to a vertical spaceport development in northern Scotland, while several spaceports sites for horizontal launch are under evaluation (UK Space Agency, 2018[46]). In Italy, Virgin Galactic has partnered with the Italian Space Agency and Italian companies to launch from a future spaceport in southern Italy (ASI, 2018[47]).

In-orbit servicing

Several governmental agencies and commercial companies have developed, or are in the process of acquiring, some capabilities for in-orbit servicing (Table 4.10). In-orbit servicing involves a number of complex operations in space: the servicing of space platforms (e.g. satellite, space station) to replenish consumables and degradables (e.g. propellants, batteries, solar array); replacing failed functionality (e.g. payload and bus electronics, mechanical components); and/or enhancing the mission (e.g. software and hardware upgrades). This is a major challenge as, when in orbit, space platforms can move at speeds of several kilometres a minute depending on their altitude, and it is quite challenging to have several spacecraft "flying" very close to each other.

One important step includes automated and autonomous rendezvous and docking capabilities, mastered today by organisations in Canada, China, Europe, United States, and the Russian Federation. The first International Docking System Standard is now being used on the International Space Station, to allow a diversity of spacecraft from different countries and companies to dock. Recent developments include the next generation of in-orbit habitation modules, including for example the docking of Bigelow Aerospace's first experimental inflatable module to the ISS in 2016.

Table 4.10. Selected proposed commercial in-orbit servicing services

Space vehicle	Manufacturer	Clients	Estimated launch/start of operations	Orbit	Services
MEV-1 and MEV-2	Northrop Grumman (formerly Orbital ATK)	Intelsat	2019 and 2020	Geostationary	Station keeping, incline reductions, relocations, inspections
Restore-L	MDA/SSL	NASA, to service Landsat-7	2020	Low-earth orbit	Satellite refuelling, relocations
Spacetug	Airbus Defence and Space	n.a.	In development. Several technologies tested on RemoveDEBRIS satellite in 2018.	Geostationary	Satellite servicing and refuelling, debris removal
Robotic Servicing of Geosynchronous Satellites (RSGS)	MDA/SSL	DARPA, SES	2021	Geostationary	Inspection, anomaly correction, upgrades, relocations
Space START	Thales Alenia Space	n.a.	Demonstration flight in 2022	Geostationary	Satellite servicing and refuelling, inspections, satellite deorbits and debris removal
Mission Extension Pods (MEPS)	Lockheed Martin/ Orbital ATK	n.a.	In development	Geostationary	5-year satellite life extension 'pod'

The first commercial in-orbit servicing mission is expected in 2019, by a MEV-1 spacecraft developed by Orbital ATK for an Intelsat geostationary satellite. Services will include inspections and relocations, such as station keeping and incline reductions (Shephard, 2018[48]).

In terms of in-orbit refuelling, some long-term R&D programmes are underway, increasingly supported by satellite communication operators as final customers. They have an interest in extending the commercial life of future commercial spacecraft, which would allow postponing the sizeable investment needed each time to completely replace satellites in orbit (SES Global, 2017[49]). In-orbit servicing also requires, by definition, the capacity to conduct proximity operations. This not only involves robots able to perform the required tasks technically, but also the capability of remaining close enough to the spacecraft to be effectively serviced or repaired.

Some of these planned services also include debris removal. The first successful in-orbit debris removal technology demonstrations took place in 2018. They were carried out by the RemoveDEBRIS satellite, a collaborative active debris removal project involving organisations and companies from France, Germany, the Netherlands, Switzerland and the United Kingdom and co-funded by the European Union's seventh framework programme (FP7) (Surrey Space Centre, 2019[50]). Tests have included the use of nets and harpoons to capture dummy cubesats.

Advances in this area are promising for future commercial in-orbit servicing ventures and orbital space debris cleaning initiatives. The main short-term market is seen in the life extension of geostationary satellites, with some 300 potential candidates, at least in theory (Kennedy, 2018[51]). There are still several limiting factors, including national security concerns and intellectual property and design issues. However, the key benefits of in-orbit servicing are expected in the future. Satellite design is currently heavily restricted by extreme launch conditions, but the possibility of servicing could enable a much more flexible and modular satellite design, able to take advantage of the latest advances in materials and electronics, beyond software upgrades (Jaffart, 2018[52]).

Market forecasts estimate a USD 3 billion market for in-orbit servicing over the 2017-27 period, mainly driven by life extension services (Northern Sky Research, 2018[53]).

Space mining and resources extraction

Space mining and resources extraction is missing from the 2005 promising list of commercial applications (Box 4.2). Fifteen years ago, this activity was considered far too complex and technologically challenging to be included.

In the meantime, there have been several successful scientific missions to asteroids, including two landings (on the asteroids 67P/Churyumov-Gerasimenko and Ryugu) and the sample return missions Hayabusa and Hayabusa-2 (see chapter 5 on space exploration). NASA is also supporting the development of commercial incremental technologies for space exploration, .e.g. for lunar landers in the NASA Small Commercial Lander Initiative (Tawney, 2018[54]).

There are other public and private developments in this area. The United States and Luxembourg have adapted their legal framework in preparation of commercial exploitation of space resources. Luxembourg has also launched the initiative Spaceresources.lu, in partnership with companies from Japan, the United States and the United Kingdom (Luxembourg Space Agency, 2019[55]). One of the partners, the US company Planetary Resources, which has also benefited from NASA contracts and is backed by Google co-founder Larry Page, is currently testing water detection technologies in space on cubesat platforms (Planetary Resources, 2018[56]).

A socio-economic impact assessment on space resources utilisation conducted by the Luxembourg Space Agency foresees as a possible market revenue of EUR 70-170 billion over the 2018-45 period. Resources extraction for rocket and space vehicle propellant is identified as the most economically viable short-term activity in the study, due to high confidence in demand and availability of water on the moon, Mars and other celestial bodies (Luxembourg Space Agency, 2018[57]).

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