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SPACE LOGISTICS – CURRENT STATUS AND PERSPECTIVES

Abstract

Space exploration has been going on for decades. Although humanity has not been able to reach further than the Moon, and the only human activity in space is currently taking place in the low Earth's orbit, technological and organizational innovations that accompanied the previous projects have contributed to significant changes in the space sector and the global economy. These changes are also visible in logistics activities, especially in transport. In this article, the author reviews the current achievements in the field of space logistics, presents its definition, principles and functions, and indicates the specifics of processes, resources and the infrastructure. Due to the reviewing nature of the paper, the author's main goal is to identify a new research problem in logistics and initiate a scientific discussion on space logistics, especially in the Polish logistics environment. The important goal of the paper is also the promotion of this topic on the basis of business practice, pointing to the space sector, as a place for the development of Polish enterprises and organizations, including logistics operators or research centers. The main method used in the work on the paper is a critical, systematic analysis of the literature of the subject and resulting from the author's interests, the observation of the global space sector. An important premise for addressing the topic is the search for an original research problem using knowledge, interests and intuition. The most important conclusion resulting from the considerations undertaken in the paper is to establish that space logistics, as a result of technological breakthroughs dedicated mainly to the perspective of manned interplanetary missions, is a field that is facing extremely rapid growth, which in turn determines the growing expectations towards the scientific community. Logistics in space considered so far as an "abstract" theme should meet with greater interest of Polish scientists. This article is an introduction to an in-depth research on the subject of setting up and managing orbital and interplanetary supply chains.

Keywords: space logistics, International Space Station, interplanetary supply chain

JEL: M0, L990, O310, F530

Introduction – premises for taking up the topic

The main reason for taking up the topic was the author's interest and the related need to popularize a futurological vision of the development of logistics in space. An important premise for addressing the topic is the search for an original research problem using knowledge, interests and intuition.

The groundbreaking events related to space exploration that have occurred over the past few years have also worked as an incentive to generate a scientific discussion on the identified issues. The most important one, from the point of view of developing logistics in space, can be the successful return of the Falcon 9 rocket. The rocket manufactured by the American company SpaceX in April 2016 was used to move Dragon spaceship to the orbit, which carried supplies and an inflatable BEAM module for the International Space Station (ISS). A component of the rocket landed successfully on a special sea platform for the first time and could be used in subsequent missions. The introduction of a "recyclable" launch rocket into the space transport system is a harbinger of significant cost reductions, thus contributing to the growing demand for transport services from both government and private entities operating in the space sector.

Widely presented projects of manned missions to the Moon and to Mars as well as the effective implementation of unmanned research expeditions, in which Polish scientists and engineers had a significant share, were also important for the topic. In the author's opinion, at this stage of the life cycle of the space sector (the stage of dynamic growth), it is not only Polish engineers or constructors but also the cooperating Polish logistics specialists that have a chance to appear as significant participants in the planned expeditions.

The ancillary (support) function is included in the idea of logistics, not differently for space projects. As the history of the conquest of space shows, the importance of logistics for its effectiveness is growing. This is associated not only with a visible large share of logistics costs and the impact of logistics on the efficiency and safety of moving in space. The importance of logistics is growing mainly due to the opportunities offered by innovative logistics systems, adapted to the extremely difficult natural conditions prevailing in space, using the laws of physics to reduce the costs of flows and adopting terrestrial concepts to the very non-standard needs of space missions.

1. Space in logistics literature

Logistics is a key element determining the effectiveness of space projects (Coogan, 1987). Until now, these projects have been coordinated mainly by government agencies of these countries, which are perceived as the source of a global economic and political advantage in space. These are: NASA – National Aeronautics and Space Administration, Russian ROSKOSMOS – Russian Federal Space Agency, European ESA – European Space Agency (which includes 20 space agencies in European countries, including the Polish Space Agency), Chinese CNSA – China National Space Administration and Japanese JAXA (Japan Aerospace Exploration Agency), and recently also Indian ISRO – Indian Space Research Organization. Of these, it is only American, Russian and Chinese agencies that have a sufficient financial and organizational potential to take up a comprehensive activity in space, with the possibility of sending manned missions. So far, the largest budgets for space programs have been allocated by NASA, but it should be emphasized that the majority of initiatives dedicated to space exploration are undertaken in international cooperation, over political divisions. The aforementioned balance of power, state and scale of rivalry and international cooperation, as well as the very history of human expansion into space, have shaped the map of scientific and research achievements, including theoretical ones (see NASA website).

Notwithstanding the fact that space exploration is undertaken more or less independently by many countries in the world, the United States are leading the way in initiating and coordinating the majority of cosmic ventures. It is not surprising then that American literature is the richest and most accessible source of knowledge in the field of operational activities, including logistics operations undertaken for the needs of human activities in space. Rich achievements are also a consequence of a very fruitful cooperation of the American government agency with scientific units that has existed since the beginning of NASA. The review made by the author in scientific databases dedicated to logistics reveals that the most important are the papers written by MIT researchers – the Massachusetts Institute of Technology in cooperation with representatives of NASA (see NASA Online Directives Information System) and publications of the American Institute of Aeronautics and Astronautics (AIAA) – the world's largest technical society dedicated to the global aerospace profession (https://www.aiaa.org/about). Intense scientific activities in preparing publications in the field of space logistics is also visible at American astronomical universities, such as, e.g. the Embry-Riddle Aeronautical University, which has been organizing a conference on space conquest (Space Conference) since 1962, giving high priority to logistics (https://commons.erau.edu/space-congress-proceedings/) and training in areas related to operational activities in space (Bachelor of Science in Spaceflight Operations) (see Embry-Riddle Aeronautical University website).

An important source of knowledge about the state and perspectives of the development of cosmic logistics are publications available on the websites of space agencies, especially NASA and ESA. Many years of theoretical and practical achievements of employees of both organizations and the openness to share knowledge allow obtaining very reliable knowledge in this field.

In the Polish logistics literature, as well as in publications on astronomy or space physics, the subject of logistics activities in space is not really discussed. Individual publications are in the achievements of military academies (Borek, 2016), whereas the base of popular science sources is very rich. Magazines, such as *Astronomy* and *Urania*, have relatively many articles dealing with the logistics aspects of space exploration in their tables of contents. Interestingly, some information concerning logistics, in particular with regard to transport, appears in publications of scientists from other fields than logistics, such as, for example, law or tourism (Kułaga, 2007; Muweis, 2017; Różycki, Kruczek, 2017).

In the author's opinion, an important source of knowledge about space logistics may be the Polish Space Agency, established in 2014, as a member of the ESA. Notwithstanding a short period of operation, the agency is very actively pursuing the scientific goals of its activity. Currently (2019) the available publications are related to the subject of astronomy, and in an area close to logistics – GPS systems (polsa.gov.pl).

2. Definition, specifics and functions of space logistics

According to the definition of AIAA (American Institute of Aeronautics and Astronautics) the Space Logistics Technical Committee, space logistics is the theory and practice of driving space system design for operability, and of managing the flow of materiel, services, and information needed throughout the space system lifecycle (Snead, 2004; Goodliff, Paunescu, 2018). In the presented perspective, space logistics refers to activities dedicated to projects and space systems, undertaken both in space and on Earth. The ultimate goal of logistics in space is to maximize the exploration potential derived from vehicle performance, efficiency and effectiveness of processes and infrastructure capabilities.

Nevertheless, referring to the above approach, simplifying it, space logistics can be defined as managing the flows of people, products and information in space. The main purpose of logistics in space understood in such a way is to ensure the safety, efficiency and effectiveness of these flows. The long-term goal to which the described logistics activities contribute is the progress in space exploration.

Logistics activities in space pose a much greater challenge than those undertaken, even in the most difficult conditions, on Earth. Two main differences are significant here compared to terrestrial analogs. First, the physics of rocket propulsion provides only a minute fraction of the launch mass (typically well below 1%) for resources and items needed during exploration. This narrow margin forces careful selection of what cargo to bring and makes multi-level packing and packaging a high priority. Second, the dynamics of orbital trajectories significantly constrains the transportation schedule and duration. If a critical item fails during an exploration, it may take weeks or months to deliver a replacement with no alternatives for resupply (Grogan, 2010; Grogan et al., 2011).

The conditions that prevail in space are very important for logistics operations. Spacecraft are exposed to a range of hazards including intense particle and electromagnetic radiation, dense plasma flows, highly reactive species, and variable neutral gas densities in the low Earth orbit (LEO). Additionally, spacecraft communications and radio navigation must account for the propagation of electromagnetic waves through the ionospheric plasma in the uppermost layer of the Earth's atmosphere (Anderson, Mitchell, 2005).

If we want to look for links with terrestrial logistics, then space logistics in its ideas, principles and features is closer to military than civilian logistics. It results from enormous requirements regarding the safety of undertaken activities, their design-related nature and very high requirements as to the standards of logistics services. An important feature combining cosmic logistics with logistics for military operations, including martial activities are high requirements regarding the level of synchronization and integration of physical and information flows.

Summarizing the above considerations, the specificity of the space logistics against the background of logistics undertaken on the surface of the Earth consists of:
- functioning in extremely difficult conditions of space (Bothmer, Daglis, 2007);
- very large distances between the starting and end points and the impact on the time and manner of moving phenomena in space (Anderson, Mitchell, 2005);
- very high transport costs;
- quantitatively limited means of transport and low capacity;
- very large and uncompromising reliability requirements;
- space logistics defined and characterized in this way fulfills unique functions. Studying reports of government organizations coordinating space exploration projects, including the documentation of space missions, one can find a statement about the key importance of logistics for the success of such expeditions. The strategic participation of logistics manifests itself in its dominating share in the costs of space missions and a significant impact on their effectiveness.

NASA has defined the functions of space logistics through the prism of the life cycle of the space system known as: Life Cycle Logistics Support (LCLS) (NASA, 2012). LCLS comprises the planning, development, implementation, and management of a comprehensive, affordable, and effective systems support strategy. LCLS encompasses the entire life cycle including acquisition (concept studies, concept and technology development, preliminary design and technology completion, final design and fabrication), final production, support (system assembly, integration and test, launch, operations and sustainment), and closeout.

The principal objectives of LCLS are:
- Ensure Life Cycle Cost (LCC) is considered along with key design and performance parameters[1];
- influence product design so that the system can affordably attain required operational availability;
- design, develop, and implement a cost-effective support system;
- maintain and improve availability, improve affordability, and minimize the logistics footprint.

[1] In the case of a system such as a space vehicle that is used multiple times or is in continuous operation for an extended period, the majority of the system's life cycle costs (typically 60–70%) can be attributed directly to operations and support costs, while in the case of a system such as a launch vehicle the majority of life cycle costs may be in design and production (NASA, 2012).

3. Systems of space logistics

The areas of the use of logistics in space are related to the directions and objectives of space projects. Currently, logistics activities support mainly the transportation and servicing of telecommunication and research equipment (satellites, probes, telescopes) and the service of the International Space Station (ISS). However, in the future, on the basis of the observation of the plans of major space agencies, as well as private companies interested in space, the use of logistics will expand to support unmanned and manned interplanetary missions and to support space sectors such as space mining, space tourism and waste management activities. Each of the mentioned areas of logistics in space requires an individual, "tailor-made" logistics support system. These systems differ in the goals and scale of logistics activities, the degree of their complexity and recurrence, as well as, and perhaps above all, the cost of maintenance.

Current and future cosmic logistics systems include:

– a system of transport and service of objects on a low and geostationary orbit of the Earth (e.g., satellites, telescopes);
– a space objects service system: purchasing, transporting people, redistribution and servicing (e.g., International Space Station (ISS), objects of the space tourism sector, space mining and ecologistics);
– a system for interplanetary unmanned missions (e.g. probes);
– a system for manned interplanetary crew missions (e.g. planned expeditions to the Moon or Mars).

Each of these systems uses specific processes, resources and logistics infrastructure. These elements do not differ from their earthly counterparts in terms of type. Therefore, all major logistics processes are carried out in space systems such as locating, transporting, storing, controlling stocks, managing information. These processes use appropriate means of transport (rockets and spacecraft), storage facilities (logistics modules, ground storage centers), information and IT systems (control and control centers), and are organized according to appropriate concepts or methods. And thus, for example, the satellites and orbiting systems around the Earth use terrestrial devices to monitor and control satellites, equipment to exploit the capabilities of satellites in orbit (terminals), carrier vehicles that carry satellites into orbit and take-off systems. The planning and implementation of logistics activities is of key importance for the efficiency of the functioning of the discussed system. It also affects its costs, and thus the profitability of public and private investments in the satellite system (the cost of putting into use and maintaining one satellite ranges from several hundred million to one billion dollars) (Breidenbach, 2011).

In addition to operating a satellite system, the highest logistics activity in space is recorded in the service of the International Space Station. This, by far the most important and expensive space project (project and construction cost of about $ 10 billion), is also the most complex organizational space exploration program ever undertaken. Thus, it is an excellent testing ground for innovative logistics solutions.

The main ISS coordinators are the space agencies of the United States, Russia, Europe, Japan and Canada. The ISS Program of the International Space Station brings together international flight crews, a fleet of carrier rockets, equipment and infrastructure for takeoffs deployed around the world, operations, training, engineering and development. Communication networks and the international research community are a key element of the program.

The assembly of the ISS was by far the most ambitious project of man in space. Station elements delivered from different countries and continents were assembled in space, and merged with each other only after reaching the orbit.

Space station support is even more complicated than other space flights because it is an international program. Each partner has a basic responsibility to manage and run the provided equipment. The construction, assembly and operation of the International Space Station requires the support of facilities on Earth managed by all international partner agencies and countries involved in the program. These include the construction of objects, take-off and processing support facilities, mission support facilities, equipment for the research and development of technologies and communication devices. Such a complex project requires perfect coordination, integration and synchronization of coordination, integration and synchronization activities.

Supply missions to the International Space Station (ISS) are still the most complicated logistics operations. The need to maintain a balance between the security of astronauts, maximizing the effects of scientific research and the effectiveness of logistics operations means that although it seems to be a simple process on the surface of the Earth, it is actually highly diverse and labor intensive, requiring reliable management of goals and changing priorities.

The specifics in the ISS supplies are primarily:
– limited capacity of logistics and crew modules;
– limited size of the admission area (docking compartments);
– low frequency of deliveries associated with very high costs;
– high versatility of supply vehicles that can be used for other purposes in the ISS, e.g. as a residential module, tugboat leveling the orbit of the station and a vehicle for transporting waste from the ISS to Earth (Rarick, 2016; NASA, 2015).

The ISS has been supplied over the years using various spacecraft, including those constructed and built by international partners, i.e. government space organizations cooperating within the ISS project, as well as private partners. The ISS has served several spacecraft belonging to countries leading in the station project, but from the point of view of the development of space logistics, the ISS involvement of the spaceship DRAGON owned by SpaceX is extremely important (Rarick, 2016).

We read in the guide to the ISS that SpaceX missions are launched on Falcon 9 from Launch Complex 40 at the Cape Canaveral Air Force Station, Florida. The first stage is powered by nine SpaceX Merlin engines, and the second stage is also a single SpaceX Merlin engine. The spacecraft that launches on Falcon 9 is called the Dragon. The Dragon spacecraft is an automated logistical resupply vehicle designed to rendezvous with the ISS and is grappled and berthed using the Space Station Remote Manipulator System (SSRMS). The Dragon has a capsule section for delivering pressurized cargo, and another section called the "trunk" is used to deliver unpressurized cargo to the ISS. Once the mission is complete, the Dragon unberths from the ISS. The trunk is jettisoned and destroyed during reentry into the atmosphere, whereas the Dragon capsule, with its valuable pressurized return cargo, reenters the Earth's atmosphere and lands in the ocean with the use of parachutes. The Dragon capsule is recovered by SpaceX and it is transported back to their facility for return cargo processing (NASA, 2015).

The participation of a private company in space programs has become a milestone in increasing the efficiency of cosmic logistics. The NASA programs focused on the development of public-private partnerships, including Commercial Orbital Transportation Services (COTS) or Commercial Resupply Services (CRS). Commercial Orbital Transportation Services was a NASA program to coordinate the delivery of crew and cargo to the International Space Station by private companies. The program was announced on January 18, 2006 and successfully flew all cargo demonstration flights by September 2013. COTS are related but separate from the Commercial Resupply Services (CRS) program. COTS relate to the development of vehicles, CRS to the actual deliveries (NASA, 2014, 2018).

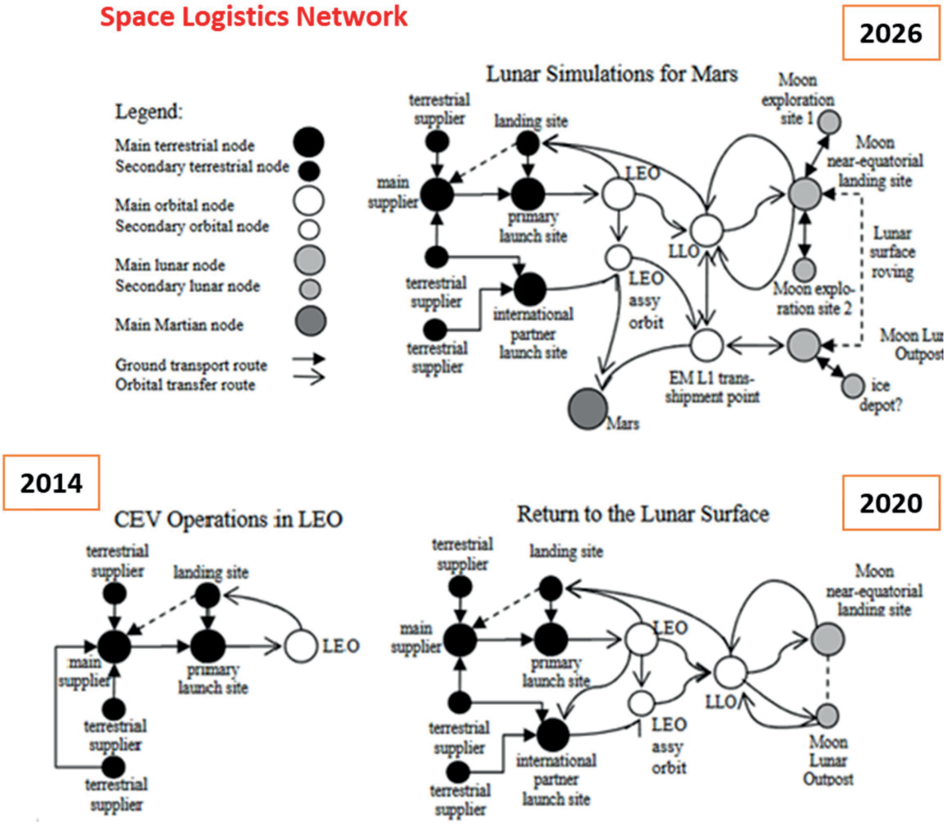
The support for telecommunications or ISS systems have provided a starting point for developing further more advanced space projects. These are definitely manned interplanetary missions, to the Moon and to Mars (Shull et al., 2006). Researchers from NASA and MIT have been preparing for new challenges for many years. At the inception of the Exploration Systems Research and Technology study entitled Interplanetary Supply Chain Management and Logistics Architectures, the investigators determined that there should be a set of studies on terrestrial analogs for space exploration. The decision to undertake projects improving space logistics based on NASA's experience results from a very serious challenge which is a human flight to the Moon and to Mars, and the future of regular traveling on these space routes.

The study, assigned to United Space Alliance LLC in Houston, TX, was to review as many sources of Logistics Lessons Learned as were available, and to attempt to draw some conclusions about the current state of NASA's logistics architecture and any challenges to developing an interplanetary supply chain (see Figure 1).

The overall objective of this project is to develop an integrated capability for guiding the development of an interplanetary supply chain that will be required to enable sustainable space exploration of the Earth-Moon-Mars system and beyond.

The goals of this project are as follows:

– find analogies of terrestrial supply-chains for both high-risk, capital intensive projects, as well as those servicing remote environments. Define and apply criteria as to the applicability of terrestrial SCM models and methods to space logistics;
– build a flexible network-based modeling environment for capturing nodes and arcs of both the ground and space based segments of the future interplanetary supply chain. This network model must capture both energy requirements and time dependencies in the network;



LEO – Low Earth Orbit, LLO – Low Lunar Orbit, EM L1 – the first Earth-Moon Lagrange point

Figure 1. The growing complexity of the NASA logistics network architecture
Source: (own elaboration based on: Evans et al., 2006)

– develop probabilistic supply/demand models by class of supply to predict likely manifests for space exploration with emphasis on small quantity logistics under uncertainty and robust sparing strategies;
– wrap these models into a user friendly and effective simulation and planning tool for NASA and the contractor community. This tool can be used to evaluate competing mission architectures in terms of their supply chain impact and sustainability and will be integrated with the agency's planned simulation-based acquisition strategy;
– carry out trade studies to highlight the implications of major architectural options of the interplanetary supply chain in terms of intermediate buffers, redundant transportation modes and push-pull boundaries. This objective includes modeling a variety of historical and planned future missions and campaign scenarios, including some with refueling and other non-traditional operations;
– actively engage the space logistics community at NASA, the contractors and academia in the challenge of creating a sustainable supply chain for interplanetary

exploration via a series of workshops, short courses as well as model development and validation efforts;
- impact the education of future explorers and engineers by involving students at MIT and affiliated institutions in the interplanetary supply chain problem by developing additional modules and assignments for existing supply chain and logistics courses. Make these educational materials easily accessible to the public (de Weck et al., 2006; de Weck et al., 2007).

The overall objective of this project is to develop an integrated capability for guiding the development of the interplanetary supply chain that will be required to enable sustainable space exploration of the Earth-Moon-Mars system and beyond.

Many research projects are dedicated to the configuration of interplanetary supply chains (Ho, 2015). Apart from technological projects, one of the most interesting projects in the author's opinion is the use of gravity fields and gravity assistance, and Lagrangedo nodes for planning very long space travels. Lagrange nodes represent the libration points (zones of no net gravitational acceleration from the celestial bodies) (Grogan, 2010). Though a current use of Lagrange points for logistics is limited to observational satellites, future missions may use them to maintain fuel or other supply depots.

Scientists from NASA and their scientific partners create maps of gravitational tracts (gravity highways) that allow space vehicles to move almost with minimal fuel consumption. In the future such projects will contribute to the construction of an "interplanetary transport system" that uses, like ships from wind power, the gravitational interaction of planets (Mazarico et al., 2011).

Conclusions

The exploration of space changes our civilization, gives previously unknown perspectives and satisfies the cognitive ambitions of man. Logistics is a very important element of this phenomenon. This pleases but also obliges. On the basis of a review and critical analysis of the literature, including industry reports and materials from governmental space agencies, in the course of the discussion undertaken in the paper, the author is convinced that the practice and the theory of cosmic logistics do not develop at the same pace. And although these differences seem typical of logistics itself, the gap is much more noticeable in the case of its space part. The real practical achievements in the field of space logistics are the result of several decades of cooperation between government organizations and research centers, as well as the ambitions and operativeness of private enterprises. This exceptionally efficient and effective cooperation on the basis of practice confirms that progress is much greater when we combine knowledge and experience on the foundation of a shared vision and mutual trust. According to the author, such a model of cooperation is needed in the theoretical trend of the development of cosmic logistics. Greater involvement of logisticians in Poland in research projects dedicated to space exploration, can support Polish engineering projects in real terms, as well as build the image of Poland in the international scientific space. The author intends to undertake such efforts in the field of configuring interplanetary supply chains.

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