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THE ROLE OF LOGISTICS CENTRES IN SPACE LOGISTICS SYSTEMS

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Abstract: The development and advancement of human civilization have led it to its next great step – the exploration and colonization of outer space. Humans have had a continuous presence in outer space for more than twenty years, but until now, this was on the level of individual, isolated space missions. Reaching the cosmic level of civilization requires the planning and development of sustainable, long-lasting systems of space logistics. Previous scientific literature did not define the space logistics system adequately, nor did it identify the key elements and stakeholders/participants of such systems. The contribution of this article is in providing an encompassing definition of space logistics, the definition of space logistics system structure, and the role of different categories of logistics centres in its planning and development. The article provides a brief literature review in the domain of all types of human activities that take place in outer space and relates them with the realization of logistics processes to support those activities. Based on that, the main processes and functions that would take place in space logistics systems are defined, which dictate the emergence of diverse, specialized categories of space logistics centres. The identification and planning of appropriate space logistics cetres categories impacts the development directions and patterns of sustainable space logistics systems and enables the spatial integration of systems that cover enormous geographical dimensions and distances.

Keywords: space logistics, space logistics system, space infrastructure, logistics centres.

1. Introduction

During the entire history of humankind, humans were obsessed with sky events, so during the twentieth century, the first human spaceflight happened, and not long after that – a flight to the Moon. The thing that was considered impossible for thousands of years before was achieved. Today, a large number of national and international organizations have their own space programs. For over twenty years, humans have had a continuous presence in outer space.

During the twentieth century, space missions were experimental in nature, were planned independently of each other, generated enormous costs, and required the efforts of scientists, experts, and engineers from different fields. With technological

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advancements in the last few years and the ever-growing understanding of conditions in outer space, it can be stated with great confidence that the era of intensive human exploration of deep space is at hand. The involvement of private enterprises in space exploration has significantly disrupted the traditional balance of power where national governments were the only and most significant participants, and this accelerated space exploration (George, 2019). The advancement of science and technological innovations enabled a significant cost reduction in travelling to outer space which poses an extraordinary opportunity for its extensive exploration (Jones, 2018). A significant contribution to this was by the development and application of reusable spaceships by SpaceX company (Cahill and Hardiman, 2020). Considering the intensification of research, the expansion of research networks in the field, and the reduction of space transportation costs, NASA and SpaceX have announced that, by the year 2030, they will visit Mars (Drake, 2009; Musk, 2017).

In contrast to the pioneering projects from the twentieth century, as well as those from the beginning of this century, future tasks of the space sector are the planning of crewed missions for exploring distant parts of the Solar system, a more frequent space travels through established regular transportation lines between Earth and outer space, and permanent settlement of humans in outer space. Aside from the extreme conditions, one of the main barriers to achieving large-scale space missions is the lack of first-hand experience and the required infrastructure.

Although space exploration is a multidisciplinary field that gathers scientists and experts from different fields, engineers, physicists, biologists, the military, trading companies, industry, politics, etc., one of the key sectors in the realization of space missions is the logistics sector. There is not enough encompassing definition of space logistics and its subsystems in the existing literature body, while the significance of logistics centres in such systems is overlooked. This article tries to fulfil this gap in the literature by recognizing the significance of space logistics systems in developing large-scale, sustainable space logistics systems spanning over enormous geographical distances in outer space. The article is organized into five sections. The next section defines the system of space logistics according to the gaps in the existing definitions found in the literature, by respecting the existing, encompassing definition of the logistics on Earth. The third section presents a short literature review of space-related research. A classification of existing research is provided and the significance of logistics, as the main support for conducting space-related activities, is pointed out. In the fourth section, the main categories of logistics centres in the system of space logistics are defined. The categories are defined according to the identified functions and subsystems of space logistics. The last section presents concluding remarks and future research directions.

2. The Notion, Definition and Subsystems of Space Logistics

In the existing literature, the logistics sector is not treated adequately and recognized as the key element of space exploration. Since the 1950s, space logistics is stated to be an important element of space exploration, but its understanding and definitions were (and still are) seen as a parallel to military logistics but in outer space (Snead, 2004). There are several attempts of defining space logistics in the literature, but an encompassing and widely accepted definition is still missing. The existing definitions included only some of the elements/and aspects of space logistics:

- Space logistics is the science of planning and carrying out the movement of humans and material to, from and within space combined with the ability to maintain human and robotics operations within space (Snead, 2004).
- Space logistics addresses the aspects of space operations both on Earth and in space that deal with material, people, facilities, and services (Ishimatsu, 2013).
- Space logistics refers to activities dedicated to projects and space systems, undertaken both in space and on Earth with the ultimate goal to maximize the exploration potential derived from vehicle performance, efficiency and effectiveness of processes and infrastructure capabilities (Baraniecka, 2019).
- The theory and practice of driving space system design for operability and managing the flow of material, services, and information needed throughout the system lifecycle (AIAA SLTC, 2021).

With the goal of planning and optimizing logistics processes and systems in the function of various space-related activities, and the definition and application of efficient solutions, it is necessary to appropriately address the notion of space logistics. This is hardly possible since the field is still in its initial development phases with a limited number of researchers, especially those in the field of logistics. The main problem is insufficient understanding of activities that take place in outer space which at the same time define demands for logistics services. By analyzing the existing definitions and reviewing the activities and demands in outer space, but also during their preparation on the Earth, the authors of this article tried to define logistics in this area more clearly and encompassing.

Space logistics is the scientific field that refers to the planning, development, realization and management of materials, goods, people, and information flows to/from/in outer space. It includes all technologies and solutions of logistics, as in outer space so in the hinterland of space systems (on the Earth and other celestial bodies), that provide support to all participants, functions and activities in space systems, regardless of their size and number, goals, duration, location, and boundaries, but in correspondence with their individual and mutual interests and goals. Furthermore, the main goal of space logistics is the planning, development and exploitation of sustainable space systems that support the permanent human presence in outer space.

The carrier of flows realization is the logistics chain – the arranged set of logistics processes and activities (ordering, packaging, transportation, transshipment, warehousing, sorting, controlling, consolidation, etc.), while the carriers of logistics chains realizations are logistics systems (Zečević, 2006). The space logistics chains' links, processes, and systems are characterized by enormous complexity, interdependence, and rigorous physical limitations, while in their realization multiple different entities, companies, and sectors are involved (scientific sectors and research agencies, national governments, research centres, manufacturers of spaceflight vehicles, manufacturers of spare parts and components, telecommunication and information companies, the military and security sectors, food industry, textile industry, chemical industry, metal processing industry, space navigation sector, regulatory bodies, insurance companies, international partners, technology development corporations, quality management sector, logistics service providers, etc.) (Chen and Ho, 2018).

The conditions that the space logistics systems and processes are exposed to are significantly more harsh and complicated compared to the most hostile conditions found on the planet Earth. Some of the main characteristics of space logistics that separate it from the one on Earth are the exposure to extreme conditions of the outer space environment, huge distances between flow origins and destinations, the effects of temporal and physical phenomenons in puter space, enormously high logistics costs, a limited selection of transportation modes, technologies, and capacities, high demands for system reliability, and the unique function/task of space logistics – exploring of the unknown (Baraniecka, 2019). Considering all the aforementioned, the task set before space logistics is challenging and requires more intensive research and effort. As is the case on Earth, the efficiency of logistics depends on the encompassing and simultaneous analysis of all the processes, systems, and problems related to them, on all planning levels. Another great challenge, that is necessary to overcome to enable more frequent realization of space logistics activities in the future, is the establishment of a high-quality and long-lasting space logistics system. The space logistics system is not clearly defined in the existing literature. According to the general system theory and some other logistics systems (for example city logistics Tadić, 2014; Tadić and Zečević, 2016), a space logistics system is composed of stakeholders, infrastructure, and regulations, as well as their interrelationships included in the planning, development, management processes of goods, people, materials, and information flows from/to/in outer space (Figure 1). Every element of the space logistics system represents a distinctive system with a large number of elements and interrelationships.

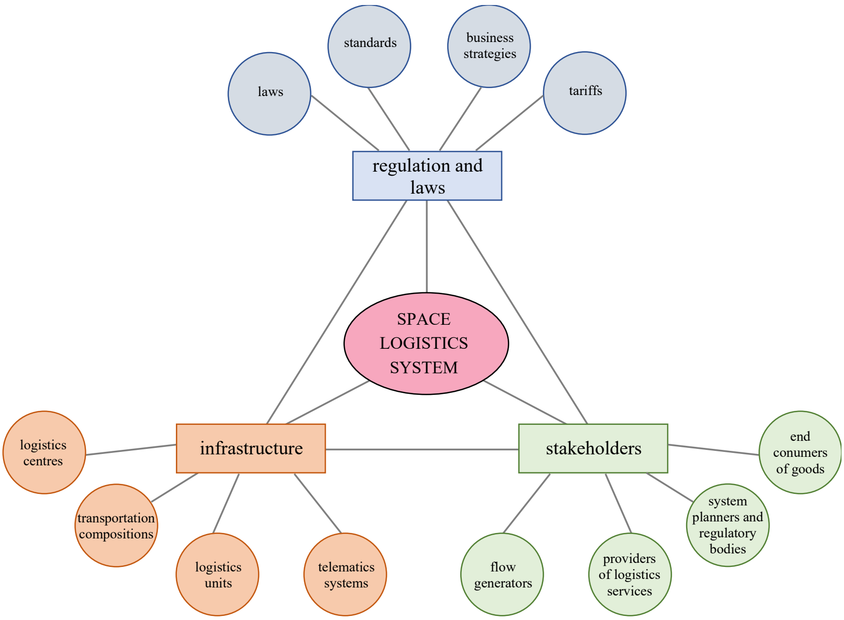

Fig. 1.
Space Logistics System
Source: defined according to (Tadić, 2014)

The subsystem of space logistics participants (stakeholders) is composed of goods flows generators (senders and receivers of goods – manufacturers of goods, raw material gatherers, research centres and missions, human colonies and settlements, trading companies, military and security agencies, etc.), logistics service providers (as well as companies that offer transportation and warehousing services in space), but also all others whom logistics is not the main activity in space – the planners of space activities and system development (national governments, international and national organizations, space associations, etc.) and end consumers of goods. In other words, this subsystem is composed of all participants of logistics chains in outer space. The infrastructure subsystem is constituted of different categories of logistics centres, terminals, transportation compositions and elements (in outer space and the system hinterland), logistics units (pallets, containers, special types of packaging, etc.) and telematics systems. The regulations subsystem refers to all law-regulatory standards, tariff systems, and business strategies that have a direct impact on the functioning of any system element and the space logistics system as a whole.

Aside from its usual support to unmanned missions into deep space and occasional crewed missions to the Earth's orbit, the task of space logistics is also to support large-scale space voyages. The development of sustainable and long-lasting space logistics systems would enable long-distance crewed missions (towards Mars and beyond the boundaries of our Solar system), space mining (Dorrington and Olsen, 2019) and resource exploitation (Starr and Muscatello, 2020), the settlement and colonization of other celestial bodies (Braddock *et al.*, 2020), and with the commercialization of space logistics, the emergence of space tourism (Spector *et al.*, 2017).

3. Literature Review

Scientific research in all fields of space exploration is in constant proliferation during the 21st century. By searching scientific articles (articles from scientific journals, review articles, conference articles, books, and book chapters) present in the *Web of Science* database, in the period between 1.1.2000 and 1.1.2022, filtered by the most common keywords[2] in space exploration articles from various fields, the growing trend is evident (Figure 2).

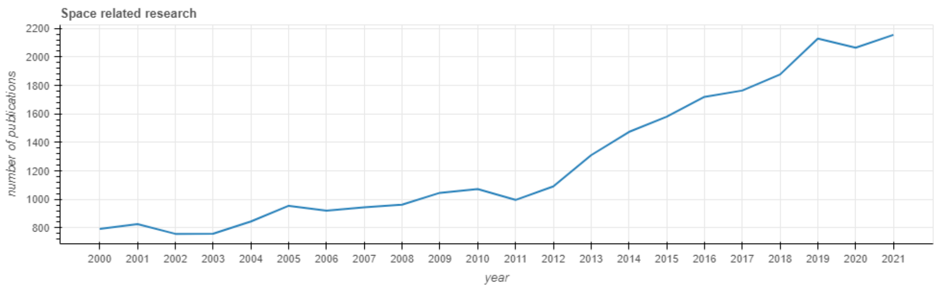

Fig. 2.
Existing Literature Body in the Fields related to Space Exploration from the Year 2000

However, only a small fraction of the research even brings space missions and logistics into connection (Figure 3). The literature is still lacking in encompassing approaches for defining and treatment of space logistics systems, clearly defined future demands for developing such systems, demands for logistics services in outer space, and the analysis of space logistics structures of the future that would represent the foundation of large-scale space logistics. Besides that, the logistics segment in the system hinterland – on the surface of the Earth, is greatly neglected and overlooked.

[2] **Keywords used for article selection**: *space exploration; space colony; space travel; interstellar travel; space mission; human spaceflight; space mining; asteroid mining; in-situ resource utilization; in-situ resources; space manufacturing; space law; space systems; space infrastructure; orbital warehouse; space tethered satellite; space launch vehicle; propellant depot; space station; space transportation; interplanetary supply chain; space debris; orbital debris; space tourism; interstellar trade; space farming; space cultivation; space nutrition; Mars habitat, Lunar habitat; worldship; terraforming; planet colonization; private activities in space; interplanetary species*

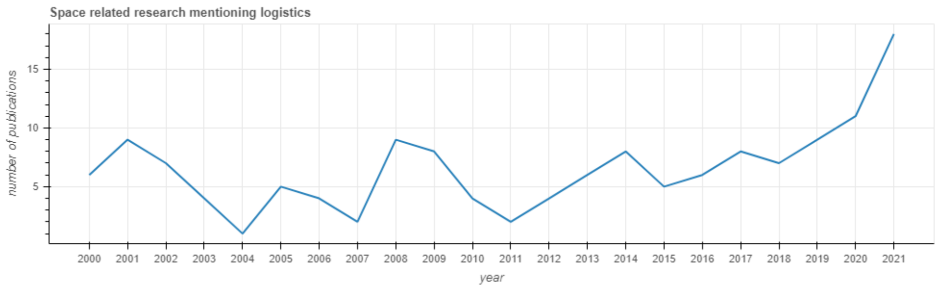

Fig. 3.
Scientific Articles that bring Space Exploration and Logistics into Connection

Most of the conducted research in the field of logistics focused on technologies/approaches to space transportation. Researchers in physics mostly focused on the conditions and phenomena that space missions are exposed to, or on the phenomena that could be exploited in the realization of space missions (Tartaglia *et al.,* 2018). Research in the field of biology and medicine focuses on the biological and health aspects of space travel (Cohen, 2021; Landry *et al.,* 2020). The exploration of space, aside from the technical problems, faces also regulatory and ethical issues that should be overcome to make the cooperation of different entities possible. The article (Pražák, 2021) states that it is necessary to define appropriate international norms that refer to future space systems in order to direct their development toward space exploration instead of the military supremacy of current global actors. The literature emphasizes also establishing international agreements and the enactment of laws that refer to resource extraction (Anderson *et al.,* 2019) and establishing human colonies (Szocik *et al.,* 2016) in outer space. The research that focuses on the planning problems, mainly tactical and operative, is limited to individual space missions. Some of the problems solved in the literature refer to location routing in the function of network modelling for asteroid mining (Dorrington and Olsen, 2019) and planning space missions by considering some individual elements of logistics infrastructure (Chen *et al.,* 2020), spaceship design (Chen and Ho, 2017), stochastic nature of the environment (Chen *et al.,* 2021), etc.

The existing literature in the field of space exploration could be classified in numerous different ways. However, one of the main common characteristics of most of the research is the fact that they are in some way, more or less, directly or indirectly, related to the realization of logistics activities in outer space. Having in mind that the subject of many research articles has a deep connection with logistics, its role and context in that research could be noticed effortlessly.

3.1. Supplying Space Missions

Supplying space missions with necessary goods, materials, equipment, etc., is of vital importance for its existence (Blue *et al.,* 2019; Douglas *et al.,* 2021). As such it represents a distinctive challenge during the planning and realization of space missions due to limited spaceship capacities, characteristics of goods and materials, capacity limitations of warehouses in outer space, etc. Numerous physical constraints and high launching costs of spaceships force space missions to maximize the utilization of spaceship storage space. This requires detailed planning of what goods, equipment, and materials, and in what quantities, should be transported for supporting the space mission. In other words, the main issue when supplying space missions is the demand for the planning of a complete chain and the attributes of all related processes and activities.

3.2. Transportation

Transportation is the most visible activity in every logistics system. It is possible to notice a few different transportation relations in space systems. The first one is between the space logistics system hinterland and the orbit. This segment represents the most expensive and problematic transportation part in the context of operational costs and physical constraints (Stahl *et al.,* 2009), but also the emission of air-polluting gases (Spector *et al.,* 2020). The second transportation relation is in outer space – between two distant locations (celestial bodies for example). Large distances between the Earth and other celestial bodies are a great challenge from the aspect of travelling time and pose one of the main barriers that need to be overcome in the future. Another distinctive issue in this segment is the limited fuel amounts available to the spaceships, which forced the application of other approaches for generating energy for space transportation – solar energy (Dachwald, 2004; Peloni *et al.,* 2018), gel propellants (Padwal *et al.,* 2021), nuclear energy (Gustafson, 2021), photonic radiation (Levchenko *et al.,* 2018), etc., as well as additional infrastructure that makes the transportation process easier, such as space tethers (Liu and McInnes, 2019; Shi *et al.,* 2020). The third relation of space logistics transportation is on short distances – between orbital space stations, or between subsystems on other celestial bodies. Transportation within space logistics systems is recognized in the existing literature as an important subsystem however, scientific and expert articles treat transportation as the only important element of space systems. It is necessary to recognize the transportation subsystem as a part of a series of important elements of a more complex system – the system of space logistics, where transportation would establish linkages between infrastructural and organizational elements – space logistics centres.

3.3. Warehousing

Warehousing of goods, equipment, materials, and resources is an important function in space logistics systems which takes place in logistics centres. It enables efficient planning and realization of space missions and logistics chains in outer space. Resources in outer space are fairly limited so their timely availability is of great significance for the realization of space missions. Aside from warehousing goods that originate from Earth, it is necessary to provide warehousing capacities for all resources extracted in outer space, as well as for all the goods and equipment manufactured in outer space (when they are not utilized immediately after their production). To improve the realization efficiency of space missions, orbital fuel depots and warehouses for other resources play a significant role. These warehouses provide supply for space missions in later phases of chain realization. This eliminates the need for transporting the whole required quantity of propellants and resources at the same time (Ho *et al.,* 2014; Smitherman and Woodcock, 2011).

Aside from orbital fuel depots, in the existing literature, warehousing is treated along the way, as an accompanying process that follows some specific types of goods whose warehousing in outer space represents a distinctive challenge. Warehousing should be recognized as one of the main subsystems of space logistics which supports the physical realization of flows (flows of goods, resources, materials, and even people).

3.4. Manufacturing in Outer Space

One of the ways for rationalizing space operations (and so the processes of space logistics as well) is manufacturing in outer space. Space manufacturing would significantly unburden the already limited capacities of space transportation vehicles and warehouses, and it would provide major support for all future space missions. Special attention in this domain is focused on additive manufacturing (3D printing) because its application enables the rationalization of space logistics activities, especially those in the subsystems of transportation, warehousing, and supplies. When applying additive manufacturing, only the raw materials are transported from Earth to outer space, from which the necessary goods and equipment could be manufactured (Sacco and Moon, 2019). Of course, raw materials extracted in space could also be used for additive manufacturing (Isachenkov *et al.,* 2021). The manufactured goods could be recycled and used again for manufacturing new goods (Fateri *et al.,* 2018), which reduces the demand for raw materials but requires more detailed planning. The application of 3D printing greatly improves the utilization rate of vehicle loading space, reduces their mass, and therefore the operational costs as well (especially the launching costs of spaceships). Manufacturing in space greatly dictates the characteristics of space logistics systems' elements and makes the realization of space logistics chains more efficient and simple. Aside from that, it provides additional flexibility when planning the supplying of space missions. The existing literature even analyzed the possibility of manufacturing spaceships in outer space with 3D printing (Sacco and Moon, 2019). Of course, physical phenomena in outer space impact this segment as well, so additive manufacturing in outer space is not as simple as its Earth counterpart. This requires additional research, testing, standardization, etc. (Williams and Butler-Jones, 2019).

3.5. Resource Extraction in Outer Space

The sustainability of space missions, aside from the resources and goods originating from Earth (system hinterland), greatly depends on the resource extraction in outer space and on other celestial bodies (In-Situ Resource-Utilization - ISRU). The idea is to utilize resources available in space to reduce the dependency of the space logistics system on Earth-based supplying, whose realization is in terms of costs and operational challenges one of the most complex planning elements. Outer space (planets, asteroids, natural satellites, etc.) is abundant with materials that could serve the purpose of space manufacturing necessary goods and equipment. So, for example, on the Moon and Mars, all prerequisites for space manufacturing exist – H_2O, O_2, H_2 и CH_4 (Chen *et al.,* 2020). This topic is analyzed in many research articles (Chen *et al.,* 2020; Dreyer *et al.,* 2018; Linne *et al.,* 2017; du Jonchay *et al.,* 2020; Volger *et al.,* 2020). ISRU systems represent the foundation for a permanent human settlement and colonization of other celestial bodies. Despite its obvious significance, the literature does not treat ISRU systems and their role in the space logistics system adequately. ISRU systems should be observed through the prism of the roles and functions of space logistics system elements, and the connections with other subsystems should be identified and defined.

3.6. Space Trade

Manufacturing goods and extracting resources in outer space paves the way for establishing trading relations between entities engaged in the field (Ahadi *et al.,* 2020). This drives serious demands for developing space logistics systems. The development of space logistics systems causes the emergence of new markets for goods and services and it attracts different stakeholders from the private and public sectors (Tkatchova, 2018). Although it is natural to develop trading entities in the field of trading goods and services in outer space, the existing literature does not recognize the significance of space logistics systems that would enable those exchanges.

3.7. Colonization

The literature has long ago pointed out the possibility of human settlement on Mars (Lordos and Lordos, 2019) and the Moon (Sherwood, 2017). The colonization of other celestial bodies is, logically, possible only if the conditions for human stay are met. This refers to the previous delivery of goods and equipment that would support the forming of permanent human settlements (Smith and Jonckers, 2020). Aside from the delivery of manufactured infrastructural elements, it is possible to use local materials for infrastructure manufacturing (Kalapodis *et al.,* 2020; Meurisse *et al.,* 2018). The sustainability of human settlements is directly dependent on the availability of essential life-supporting resources (water, oxygen, and food), necessary energy, and the possibility of adapting to extreme conditions in outer space. Providing periodical supplies from Earth is possible, but the colonies could not entirely rely only on that. Instead, the colonies must be capable of local production (Perchonok *et al.,* 2012) to become self-efficient. Aside from food manufacturing in human settlements (Medina, 2020), the literature examined also the concepts of space farms whose task would be the production of food in outer space and to supply human settlements with it (Garden, 2022; Monje *et al.,* 2003).

3.8. Space Tourism

Companies, such as SpaceX, Virgin Galactic, Blue Origin, Orion Span, etc., are pushing initiatives that would enable new chapters in space-related activities – space tourism, available to the wider public (Yazici and Tiwari, 2021). Besides suborbital and orbital touristic tours, it is expected that space tourism would reach other celestial bodies and stimulate the development of space hotels (Chang, 2015). To make the idea of space tourism and recreational activities in outer space possible, it is necessary to achieve a high safety degree for space exploration tours (Spector, 2020), and the prerequisite for that is the development of sustainable, spatially integrated logistics systems which would also support the realization of space tourist activities.

3.9. Collecting and Treating Space Debris and Waste

The presence of space debris in celestial bodies' orbits can endanger any space-related operation (therefore the safety of space logistics systems as well) so its collection and treatment represent important activities (Adushkin *et al.,* 2020; Jakhu *et al.,* 2017). The exponential growth of space debris amount equally poses a threat to space logistics systems and the safety of Earth itself (Haroun *et al.,* 2021). The scientific community is interested in solving the problems of space debris, so a wide set of technologies for its collection and treatment is examined (Raguraman *et al.,* 2020). The auxiliary role of space logistics systems would be in supporting the debris removal activities, as is the case with reverse logistics on Earth.

4. Logistics Centres in the System of Space Logistics

Infrastructural elements of space logistics systems compose its physical structure. Current literature examined individual infrastructural elements and functions of space logistics systems, such as satellites (Jacob *et al.,* 2019), tethers (Liu and McInnes, 2019; Shi *et al.,* 2020), ISRU systems (Chen *et al.,* 2020; du Jonchay *et al.,* 2020), orbital warehouses (Chari *et al.,* 2013), orbital space stations (Thirsk *et al.,* 2009), permanent space bases located on other celestial bodies (Kalapodis *et al.,* 2020), permanent human settlements (such as the Moon Village concept) (Sherwood, 2017), etc. The research treated these infrastructural elements as independent units, separately from their functions in the forming of the system.

Logistics centres (terminals) represent the main elements of the infrastructural subsystem of space logistics, and as such, they are the main link in the realization of logistics activities and chains. They enable spatial and organizational integration of complex logistics systems. Logistics centres could be classified according to their function, size, catchment area, position in logistics networks, strategies, organization and technology, proprietorship, types of goods, etc. (Notteboom *et al.,* 2017; Zečević, 2006). Analogous to this, space logistics centres are the main physical component of the system, but at the same time, they represent the core of its organizational structure. To make the expansion of space logistics systems possible, it is necessary to develop different and appropriate categories of logistics centres (Do *et al.,* 2019). No existing research had adequately treated and structured space logistics centres.

The system of space logistics is still in its embryonal phase (as in the physical so in the organizational and development sense). Nevertheless, it is important to predict and define different structures and roles of space logistics centres to better understand the possibilities, opportunities, limitations, and weaknesses of future space logistics system development directions. A common characteristic of all logistics centres, therefore also of those in outer space, is that they enable different goods flow transformations: spatial, temporal, quantitative, qualitative, structural, dynamic, informational, proprietary, value transformation, definiteness transformation, and the dependency transformation (Zečević, 2006). By reviewing the existing literature in the context of the infrastructural elements that would compose space logistics systems, and the main, accompanying, or auxiliary activities of space exploration, it is possible to define several distinctive categories of space logistics centres and their role in the space logistics system (Figure 4). As is the case in terrestrial logistics centres on Earth, by establishing adequate transportation connections (links) between space logistics centres (terminals, nodes), a space logistics network is formed.

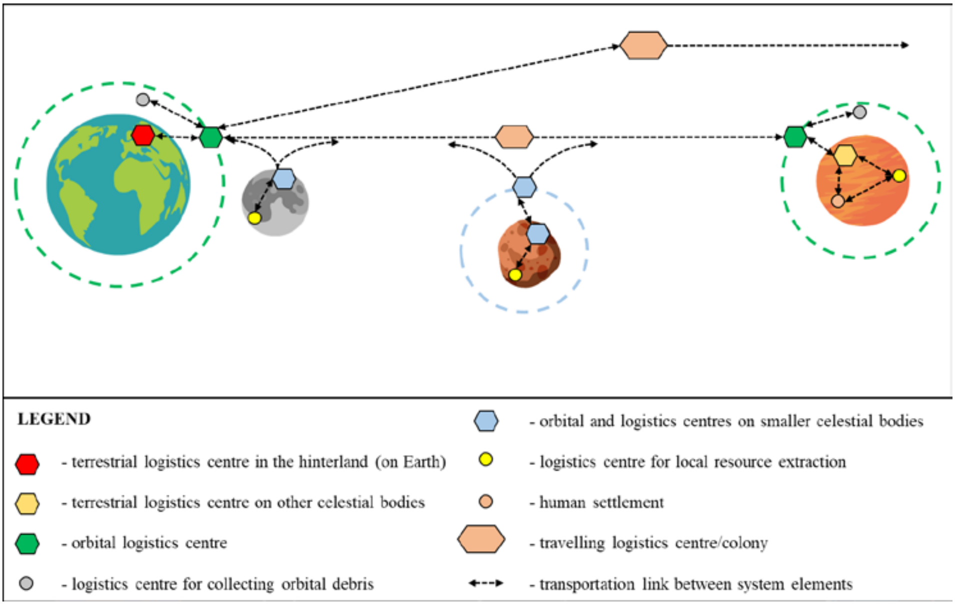

Fig. 4.
A Schematic Representation of a Space Logistics Network with Different Categories of Logistics Centres

Terrestrial logistics centres in the system hinterland have a leading role in the planning, development, and expansion of space logistics networks. The functions of a terrestrial terminal are the consolidation of flows that have to be shipped to outer space, and the distributive function for flows arriving from outer space into the hinterland, and as such represents the main connection of the terrestrial logistics system with the orbital system. This type of logistics centres enable the greatest integration degree of all terrestrial participants in space logistics chains. They represent the place of the greatest concentration of terrestrial logistics services.

Orbital logistics centres are the first logistics pass-through nodes for flows leaving the terrestrial system. They represent the main connection between the remaining space logistics system with logistics systems in the hinterland. The functions of this type of logistics centres are the consolidation of flows originating in the system hinterland, warehousing function (orbital warehouses), manufacturing function, and the supporting function for orbital debris retrieval systems. Flow consolidation in orbital logistics centres is important because it uses the time windows between voyages to other celestial bodies for the preparation and planning of those ventures. They also enable the manufacturing of the required equipment and spaceships in the orbit to significantly relieve the realization of logistics chains on the tactical and operational levels. The centres also consolidate the return flows from the debris retrieval systems and support the processing of the collected waste if possible. Aside from the consolidation of flows on the relation hinterland-outer space, these logistics nodes enable the consolidation of all flows in the opposite direction and have transportation links with orbital logistics centres of other celestial bodies. The role of orbital and local warehouses is to secure resources, goods, and equipment supplies along space transportation corridors to enable a more efficient realization of space missions. They can also serve for mitigating risks along transportation corridors by providing reserves in cases of unexpected disruptions in mission realization. Orbital logistics centres have also an important role in enabling space tourism by providing adequate support to all local tourist tours (supplying with resources and equipment, accommodation of tourists, hubs for tourist flows towards other celestial bodies).

Terrestrial logistics centres on other celestial bodies are similar to terrestrial logistics centres on Earth, but the main difference between them is that these are the embryos for forming logistics systems on other celestial bodies. Forming an efficient local logistics system on other celestial bodies is a prerequisite for their colonization. This category of logistics centres plays a key role in forming logistics systems because they represent hubs of future logistics networks on those celestial bodies. The functions of this logistics centre category are the consolidation of flows on the relation terrestrial system – outer space system, distributive function for flows in the opposite direction of previously mentioned, manufacturing function, consolidation of flows from local ISRU systems, and the support function for human settlements on the colonizing celestial body. These logistics centres could be located also on smaller celestial bodies (asteroids and natural satellites) to fulfil the function of consolidating the extracted resources by ISRU systems and their perseverance until they are collected by their users.

Logistics centres with an orbital debris retrieval system contribute to the safety of space systems by removing dangerous orbital debris. The collected waste could be sent back to Earth, disposed of in special safety orbits (graveyard orbits) (Patel and Tikhonov, 2021) or sent to orbital logistics centres for preprocessing, recycling, or disposal.

Systems for local resource extraction represent important elements in the initial phases of space logistics network development. They enable the utilization of local resources required for the realization of space missions. They can be dominant subsystems of smaller, local logistics centres on other celestial bodies, or a subsystem of larger logistics centres with multiple functions and subsystems.

Many outer space destinations are beyond the reach of current technologies, even in the case of voyages with extremely high velocities. Despite that they could not be visited in a considerably acceptable timespan from the aspect of the current generation, this does not mean that those locations would remain unvisited/uncolonized in the future. An interesting concept of space travel present in the literature is the concept of worldships. A **worldship** (travelling colony) is a spaceship of huge dimensions that transports a large-sized crew – several tens or even hundreds of thousands of people, and it is self-sufficient (Hein *et al.,* 2012). The self-sufficiency of such systems provides the necessary conditions for forming an isolated ecosystem with succeeding generations over time aiming to reach distant destinations away tens, hundreds or even thousands of years (Mahon, 2020). The sustainability of such systems depends on a wide set of biological, physical, social, cultural, economic, etc. factors (Hein *et al.,* 2020). Having in mind the size and numbers of the crew, a worldship could be treated as an individual **travelling logistics system/colony** in which adequate planning and managing are of vital importance for the survival of the colony. From the logistics aspect, the dominant activities that are realized are energy and resource production, warehousing, transportation within the colony, supplying of all sectors, the movement of the system through space, etc. With the arrival of worldships at the destined celestial bodies begins their colonization. These systems represent the core of developing human settlements on those celestial bodies, as well as the core for developing local logistics systems.

5. Conclusion

Logistics centres in the systems of space logistics play an equally important role as their traditional, terrestrial counterparts. Logistics centres are the main physical component of space logistics systems, but also represent the core of their organizational structure. It is important to predict and define all functions and roles of logistics in space and, analogous to that, to define different categories of logistics centres that will give shape and definition to future space logistics systems. This article provides a detailed definition of space logistics and its subsystems, which fulfils the scientific gap in the existing literature body and definitions. A short literature review in the domain of all the activities that take (or will take) place in outer space, and the significance of the realization of logistics activities and processes as the support for space exploration activities is highlighted. Based on those activities, the main functions of logistics are defined, as well as the typical categories of logistics centres that a sustainable, long-lasting space logistics system requires to be developed. This represents the second scientific contribution of the article.

The directions of future research are in more detailed analysis and development of existing logistics centres' ideas and the definition of specific planning and development directions of permanent space logistics systems. Special attention should be directed to the system hinterland as well because it represents the initial development segment of space logistics systems. It is necessary to further classify and dissect goods flows that are realized in space logistics systems. This would help identify future demands for logistics services in outer space, which undoubtedly affect the direction of the systems' development. Adequate planning models for space logistics systems, that appropriately treat the multicriterial nature of problems and consider the goals of all stakeholders, should be developed. Only through encompassing, multidisciplinary approaches sustainable development directions of space logistics systems could be identified.

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