Similarities and Differences Between Terrestrial and Space Logistics

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From the time of ancient civilizations up to the modern era in which we live, logistics has always played an important role. Everyday activities carried out by humans thousands of years ago, such as harvesting and gathering fruits, storing, preserving, processing, and transporting them to places of exchange or sale, were the precursors of modern-day logistical activities. Today, logistics is present and vital in all areas of human activity. Major geographical discoveries and expeditions, the Industrial Revolution, as well as numerous military campaigns and wars, required the existence of a complex logistical system. A completely new dimension emerged in the mid-twentieth century, when space exploration first took place. Since space is a complex and unstable environment, every mission requires strong logistics from start to its finish. Given that this is a relatively new area of logistics, this paper focuses on a comparative analysis, highlighting the similarities and differences between space logistics and logistics on Earth. The aim and contribution of this work is to initiate a scientific discussion on space logistics, with particular emphasis on the role of modern logistical systems and management in addressing the challenges of the space environment.

Key Words: *Logistics, Space Logistics, Management, Development, Function*

1. INTRODUCTION

The development and progress of human civilization opened the way to the next great goal: the colonization of space. This endeavor requires extensive research into a still quite unknown and potentially dangerous environment. For the successful exploration of new and unknown territories, good logistics are of great importance, and space is the ultimate example of such an environment. Any research requires careful planning and management of resources, procurement of materials, selection of storage locations, selection of supply strategy, definition of delivery quantities and schedules, consideration of return flows, and other related activities. Efficient logistics ensures the continuity of operations, reduces risks and is a key success factor in both ground flows and complex space missions.

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Although it initially emerged in an economic context, throughout its evolution logistics was primarily associated with military skills, and it became more closely linked to economic systems starting from the 1970s [1].With the development of the field, definitions also changed [2]. One of the most general and accepted one was given by [2]: Logistics encompasses all systems and processes that make the movement of material and non-material flows possible. To effectively plan, design, monitor, and manage logistics systems and processes in support of space activities, it is essential to examine the concept of space logistics. This is a challenging task, since the field is still in its early stages of development and the number of researchers remains limited [3].

A couple of authors have tried to give a definition on space logistics [4, 5, 6]. Through their analysis and with a thorough understanding of the field of logistics, [3] provided a broader, comprehensive definition. „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.“ [3]

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 [3]. By examining the characteristics of terrestrial and space logistics, it is possible to better understand the specific challenges present in both environments. This enables the development of more effective strategies for planning processes and systems, as well as for managing resources, information, and risks. It also supports the assurance of system safety and reliability, particularly under conditions of limited capacity, complex operations, and dynamic environmental changes. Planning and managing flows in space is significantly more complex than managing terrestrial flows, considering the unfavorable conditions, the distances between the origin and destination points of the flow, the frequency of the flows, the time required for their realization, limited transport and storage capacities, safety and reliability requirements, and other influencing factors. The main objective and contribution of this work are to foster scientific interest in the field of space logistics and to emphasize its vital importance for the successful execution of all space missions and operations.

The paper is organized as follows. The next section is dedicated to the development of logistics, both space and terrestrial. It provides an overview of the key stages of development and significant milestones in the field. In terrestrial logistics, this includes the evolution of logistics within military and economic spheres, while in space logistics, the development is presented through various space programs that were carried out. The third section explores the functions of logistics, taking into account its role in managing resource flows, coordinating activities, and improving the efficiency of business processes. In the fourth section given is a more detailed analysis of logistics subsystems, highlighting their key characteristics, challenges, and particularities.

Although all subsystems of logistics that exist on Earth are also present in space, certain specific requirements arise due to the extreme conditions that prevail in the space environment. Finally, the conclusion provides a brief overview of the contribution of this work, along with suggestions for future research, followed by a review of the literature.

2. DEVELOPMENT OF LOGISTICS

Logistics has been present in human daily life for thousands of years. In its early stages, it involved basic activities such as the gathering, storage, and distribution of food, which served the fundamental needs of the community. Over time, the discovery of new territories created the need to move goods from one place to another. This led to the establishment of the first transport routes, enabling the movement of goods over long distances. Thus, early global trade routes were established, such as Spice and Silk Road [7].

The further development of logistics is largely linked to military logistics. War is not solely a matter of tactics and strategy, it is very often a question of logistics. In the military domain, logistics encompasses the processes of supplying, moving, and sustaining military forces in both combat and non-combat periods. During the early stages of operational planning, logistics determines the deployment of forces and the pace of operations. In addition to providing material, military logistics encompasses the capabilities of national infrastructure and industry to equip, support, and sustain armed forces, as well as the ability of transportation systems to efficiently move troops and maintain their supply after redeployment [8].

Over time, logistics gradually expanded from the military sphere to the economy and modern business, keeping progress with social and technological changes. In the developed world, logistics has long been regarded as a key factor in economic development, spatial connectivity, and market integration. With the growth of global trade and the movement of goods, logistics has gained increasing importance, as it provides a competitive advantage. The fast, safe, cost-effective, and efficient execution of goods and transport flows is essential for regional prosperity and defines its ability to compete in the global economy [9].

Furthermore, logistics has become a key element that dictates the efficiency of space projects [6, 10]. As in terrestrial logistics, space logistics also involves a large number of different participants engaged in the decision-making process. The primary objective of logistics management is to achieve the optimal allocation of resources in time and space within a system where future events are often uncertain [11]. Although space logistics as a distinct field is still in its early stages of development, its importance cannot be denied. It plays a crucial role in the execution of missions in near-Earth environments, such as missions to the International Space Station (ISS), and is also essential for the planning and implementation of long-term, permanent human settlement in space.

Terrestrial logistics

Looking at most wars throughout history, it can be observed that logistics was often a decisive factor in the final outcome. Business logistics essentially originates from military logistics, making it meaningful to also consider the military aspect of this field [8]. However, in its early stages it was not primarily oriented toward war, but rather toward survival and the supply of food. Multiple key periods in the development of logistics can be identified [2, 8].

Ancient Rome and Byzantium. The term Logista referred to the management of state stocks, which included finances and the distribution of food supplies. Moreover, by effectively mobilizing soldiers and draft animals, using water transport for goods, materials and cargo, constructing and maintaining roads, and exploiting the enemy's logistical weaknesses (for example by blockading ports and rivers used by enemy supply vessels), it was possible to accelerate the military campaign. A well-developed infrastructure, including the roads constructed during the empire's expansion, was particularly important for the advancement of Roman logistics. Following the collapse of the Western Roman Empire in the fifth century AD, both the practice of warfare and the logistical systems that supported it disintegrated. The organization of soldiers and animals, along with road construction and maintenance, stands as an early example of structured management of labor and resources [2, 8].

Napoleon's age. Regardless of the time period, the challenges faced by armies remained largely the same: maintaining supply lines during military campaigns despite the emergence of new tactics, gunpowder, and railways. Inefficient logistics is considered the main reason for the failure of Napoleon's 1812 campaign in Russia. Inadequate logistics, shortages of food and medical supplies, and the failure to deliver medical care or evacuate the injured led to the collapse of Napoleon's army. Logistics proved to be a determining factor in both the successes and failures of many subsequent military campaigns and expeditions [2, 8]

20th century wars. The First World War was a turning point for military logistics. From a logistical standpoint, armies were unprepared for war. The demands for personnel, equipment, and horses exceeded the existing logistical capacities of the armies, while the need for ammunition, particularly artillery shells, was severely underestimated. Ammunition consumption averaged ten times higher than what had been anticipated in prewar forecasts. Apart from food, water, fuel, and ammunition, the start of trench warfare necessitated supplies of materials for building fortifications. However, it wasn't until the later stages of the Second World War that logistics was fully recognized as a critical component of military systems. Beyond the demands of provisioning military forces far from their home bases, consideration had to be given to their mobility and the logistical challenges of moving and supplying massive amounts of fuel, food, water, and ammunition. Railways proved indispensable, and during the war, maritime and air transport became increasingly important. The main contribution of the Second World War from a logistics perspective is the expertise in conducting operations over long distances [2, 8].

Additionally, logistics during the Vietnam War (1955–1975) is particularly significant due to the secret Ho Chi Minh route. This route served as a meticulously planned and powerful logistical network through the jungle, allowing North Vietnamese forces to move up to 20,000 troops per month and transport roughly 60 tons of supplies daily to the battlefield near Saigon in enemyheld South Vietnam. Supplies were primarily transported by porters, with occasional use of bikes and horses [8]. Modern day logistics. It represents the development of logistics as a business function. During 1950s and 1960s the planning, control, and coordination of various logistics functions were at a very low level. The focus was primarily on optimizing transport, which was carried out using the organization's own fleet [12].

Then, during the 1960s and 1970s, the interconnections between logistics functions and activities, such as transportation, warehousing, transshipment, and packaging, began to be recognized. During this period, a systems approach to logistics was developed. At the same time, a total cost perspective was introduced, aiming at more efficient management of all logistics functions and activities [12].

During the 1970s, numerous companies recognized the need to integrate logistics into the organizational management structure. Changes occurred in the structure and control of the logistics chain in goods distribution. The power of manufacturers and suppliers declined, while the influence of retailers increased. Larger retail chains developed their own distribution networks [12]. During this period, new concepts such as Just in Time (JIT) and Total Quality Management (TQM) were developed and became widely adopted, eventually giving rise to the competitive strategies used today by the most successful companies [8].

At the end of the 1980s and the beginning of the 1990s, information technologies underwent substantial advancement. Organizations began integrating an increasing number of functions. During this period, logistics evolved into a concept that combines materials management (inbound operations) with physical distribution (outbound operations), creating opportunities to enhance customer service while reducing costs [12].

During the 1990s, the concept of Supply Chain Management (SCM) developed rapidly. Companies began paying attention to other organizations involved in getting products to the market. They started to recognize the importance of cooperation among producers, suppliers, distributors, and other entities in establishing an integrated supply chain that ensures the efficient, reliable, and timely movement of products to end consumers.

From 2000 onwards, logistics has been acknowledged as a strategic area vital for achieving business success. Companies no longer regard it solely as an expense, but increasingly employ it as an instrument to create added value in their business operations. As population, consumerism, and globalization increase, along with the diversification of product assortments, shorter product lifespans, and the growth of ecommerce, logistics has become increasingly critical. The volume of goods flows is expanding, individual demands are fragmenting, and market survival depends on customer satisfaction, i.e., the quality of logistics services. At the same time, growth and new forms of trade, new business strategies, the expansion of the service sector, and the development of new urban structures impose complex demands on logistics service providers. Fulfilling these demands requires diverse supply chain structures, a large number of participants, different logistics strategies, systems and processes, and intensive flows of goods and transport across various vehicle categories. The development of new forms of trade (e-commerce) and the growing demand for home delivery bring particular challenges for future urban planners and decision-makers. Carrying out these flows according to existing patterns is becoming increasingly uneconomical and environmentally unsustainable [13]. As e-commerce continues to grow, the complexity of logistics challenges intensifies at every level, highlighting the essential role of logistics providers, freight forwarders, and shippers [9].

Logistics is not everything, but it is present in everything. It enables all human activities and economic endeavours. It can be found in households, sports, culture, journalism, tourism, healthcare, trade, and other socio-economic activities. The fact that logistics has become an independent scientific discipline is evidenced by its reliance today on a range of recognized fields and methodological approaches, including reliability, cost analysis, systems engineering, system efficiency, integrated support, cybernetics, mathematical-statistical methods, probability theory, operations research, and simulations [14, 15, 16].

The present era is considered the Fourth Industrial Revolution, commonly known as Industry 4.0. As with earlier industrial revolutions, it has been initiated and further propelled by rising competition, the foundations of which are assessed through efficiency, flexibility, speed, transformational capability, costs, and other key metrics [17]. It builds on industrial innovations and constitutes one of the central drivers of economic development for both companies and countries [18, 19].

In recent years, the concept of Logistics 4.0 has become increasingly prominent, involving the application of Industry 4.0 solutions and technologies in the field of logistics [18, 20]. The range of these solutions and technologies encompasses the Internet of Things, autonomous vehicles and automated guided vehicles, artificial intelligence, augmented and virtual reality, Big Data, data mining, blockchain, among many others [18]. By implementing these technologies, efficiency is increased, the urban environment becomes more visually attractive, and both costs and the adverse environmental effects of logistics operations and activities are mitigated [21].

Space logistics

On the other hand, conducting logistics activities in space represents an even greater challenge than performing them on Earth, even under the harshest conditions. Spacecraft and other objects in space are exposed to various hazards, including high-energy particles and electromagnetic radiation, dense plasma flows, highly reactive substances, and variable densities of neutral gases in Low Earth Orbit (LEO) [6]. As is the case with logistics on Earth, the efficiency of space logistics depends on the simultaneous analysis of all processes, systems, and the problems associated with them, at all levels of planning [3].

Every successful space flight is preceded by complex and carefully planned logistics [11]. However, in the existing literature, the logistics sector has not been adequately addressed, nor has it been recognized as a key element in space research. Since the mid-20th century, space logistics has begun to emerge as a distinct segment of space exploration. Yet, its understanding and definition at that time (and to some extent even today) largely mirrored military logistics, albeit adapted to the conditions of the space environment [3, 4]. This is a result of the stringent requirements related to the safety of operations, their complexity, and very high standards. The similarity between space and military logistics lies in the need for a high level of synchronization and integration of both physical and information flows [6].

During the 20th century, space missions were largely experimental in nature, planned independently of one another, incurred enormous costs, and required the involvement of scientists, specialists, and engineers from various fields [22]. During the 1960s and 1970s, logistics did not occupy a central role in the planning of space exploration. National Aeronautics and Space Administration (NASA) managers, much like Napoleon, were accustomed to quick victories, particularly during the Apollo program. Missions were carried out at a rapid pace, and the goal of sending humans to the Moon was achieved, yet the program was still discontinued to make room for new objectives. It was then that NASA transitioned to the Space Shuttle program [23].

The reusability of the Space Shuttle enabled more frequent missions and made them more cost-effective. This, in turn, paved the way for the construction and regular resupply of the ISS. The ISS, as a result of international collaboration, represents a significant milestone in space logistics, as it requires continuous supply missions to maintain a permanent human presence in LEO [24]. Between 1981 and 2011, when the Space Shuttle was retired, a total of 135 Space Shuttle missions were conducted [25].

A huge part of the knowledge in space logistics has been gained through missions to the ISS, given its proximity to Earth. However, prior to the launch of the ISS, other space stations had already been deployed. By considering their earlier successes and failures, it is possible to trace the development of technologies and logistical solutions that preceded the ISS and shaped its design and functionality.

Based on the experiences gained during this period, NASA identified and systematized the key challenges in the field of logistics. The most frequently mentioned logistics subsystem in databases is storage. Problems that may arise due to the lack of standards and regulations for goods storage include additional crew involvement during loading and unloading operations, absence of accountability, restricted access to operational areas, difficulties in maintaining cleanliness, low crew morale, increased need for stock replenishment, and other related issues. In addition, the defined challenges also included those related to inventory management, standardization, maintenance, and reverse logistics. The use of a shared system for labeling and tracking goods across multiple organizations would reduce duplication and overall inventory levels, thereby lowering logistics costs while increasing product availability [26].

The idea of introducing a code, or identifier, was motivated by the need to eliminate ambiguities, vagueness, and multiple interpretations of language when describing items. An organized list of all products assigned such codes forms a catalog or nomenclature. The establishment of a unified product codification system under centralized management can generate substantial improvements in the planning, execution, and oversight of logistics processes such as procurement, ordering, transportation, inventory control, warehousing, and packaging. These improvements are diverse, covering technical, organizational, economic, and other dimensions, and they enhance the quality of business processes, the logistics system, and all organizational units supported by the inventory system [27]. Furthermore, standardization applies to packaging, logistics units, handling equipment, astronaut gear, life support systems, communication procedures, as well as procedures that ensure the safe execution of missions. In addition, incorporating maintenance considerations already at the design stage is a key criterion for reducing overall resource requirements. Project documentation should also include reverse logistics flows. It is essential to understand and define in advance the requirements for packaging, repair, or disposal of items in the event of their return or destructive reentry into Earth's atmosphere [26]. In addition to controlled reentries from space into Earth's atmosphere, there are also uncontrolled ones. Uncontrolled re-entries of objects still pose a relatively low risk to the population compared to other common risks encountered in everyday life, related to lifestyle, the workplace, or household safety. Nevertheless, the possibility that uncontrolled re-entries of larger spacecraft and objects may become a significant problem in the coming decades cannot be ignored, due to the synergistic effect of increasingly intensive space exploitation and global population growth [28].

With technological advancements in recent years and a growing understanding of space conditions, as well as the importance of logistics, it can be said that the era of intensive human exploration of deep space has arrived. The involvement of private companies in space exploration has significantly disrupted the traditional balance of power, in which national governments were the sole and most important participants, thereby accelerating space research [22]. Thanks to industrial development and the expansion of commercial space activities, the cost of accessing space has decreased. A major contribution to this progress has been the development and deployment of reusable spacecraft by SpaceX [3, 29]. The next steps in the development of space logistics involve the use of reusable launch systems, such as SpaceX's Falcon 9 and Blue Origin's New Shepard. These systems have revolutionized space transportation by reducing launch costs and increasing mission frequency. The reusability of spacecraft further enhances the economic sustainability of missions, enabling more frequent launches and expanding the scope of commercial and scientific activities in space [24].

3. FUNCTIONS AND IMPORTANCE OF LOGISTICS

Globalization, specialization, urbanization, demographic changes, the internationalization of supply chains, rising consumption, shorter product lifecycles, new business strategies, product personalization, and other trends are increasing the complexity of logistics processes and the importance of logistics itself. In addition to growth, consumer demands are becoming less predictable, with consumption becoming more individualized, personalized, and hedonistic. Expanding trade, evolving business strategies, and growing urban and service sectors pose complex challenges for logistics providers, demanding flexible supply chains, numerous participants, and high-volume transport flows [9, 13, 30, 31].

In space, efficient and reliable logistics is both a prerequisite for system operation and a critical factor for crew survival and the successful execution of missions. Space logistics systems and processes operate under conditions far more complex and hazardous than any extreme environment on Earth [6]. Various organizations and agencies play a key role in shaping and managing space missions. These institutions contribute to the development and implementation of logistics solutions that enable successful space operations. Although space logistics is not explicitly mentioned in their objectives, all conducted activities require substantial logistical support.

Terresrtial logistics

Since the end of the last century, logistics functions have expanded significantly, with logistics systems increasingly focused on managing complex flows and supply chains. Logistics now extends beyond the boundaries of a single company or region, with supply chains integrating various macro, meta, and micro-logistics systems. These systems carry out a wide range of logistics processes and activities (such as ordering, packaging, storage, handling, inventory management, and transportation) both in forward flows aimed at supplying end customers and in reverse flows involving returned materials, i.e., reverse logistics.

Today, integration takes place within global logistics networks that bring together various manufacturing, trading, service, and logistics companies, different categories of logistics centers, terminals, transport exchanges, telematics systems, and more. These entities belong to different networks, are geographically dispersed, and have their own specific characteristics, requirements, interests, goals, and business strategies. All of this points to potential conflicts and a high level of complexity in the planning and execution of logistics processes and activities. To respond effectively to the complex demands and tasks of the economy and market, logistics systems apply various concepts and strategies, such as JIT, make-or-buy, insourcing, outsourcing, different city logistics models, last-mile delivery, and others. Depending on the adopted strategy, logistics systems develop diverse structures of functions, tasks, and objectives, and implement different technologies, management and marketing concepts, value and knowledge systems, and procedures. However, several common features characterize all logistics strategies and trends: integration, concentration, cooperation, coordination, and specialization of logistics functions, tasks, and subsystems.

The noticeable shift from mass production to personalized or made-to-order production has been enabled by efficient logistics, better integration of logistics systems and supply chain participants, and the application of new technologies. However, a large part of terrestrial logistics still relies on push-based flows, centered on inventory, with a growing share of pull-based logistics, which focuses on replenishment. In practice, push and pull strategies are most often combined. In the initial stages of supply chains, flows are predominantly push-based, while in the final stages, supply chain execution aligns with a pull-based strategy[1]. The boundary between push and pull flows, as well as the choice of a logistics strategy, depends on several factors, such as the type of goods, specific delivery requirements, and market and environmental conditions. Conversely, the chosen strategy affects operational costs, order fulfillment time, and the readiness and flexibility to respond to changing demands. The primary function of logistics in supplying end consumers is to meet market requirements in terms of delivery location and timing, order size and frequency, product quality, and other factors, while minimizing costs. In the execution of these supply chains, alongside costs, speed (meaning lead time) and predictability are becoming increasingly important.

Climate, socio-economic, and geopolitical changes, as well as natural phenomena, contribute to an increase in humanitarian problems and crises worldwide. Human life, health, safety, rights, and property are threatened by natural disasters such as earthquakes, floods, droughts, and landslides, as well as by diseases, epidemics, inequalities, poverty, wars, and terrorism. In such conditions, humanitarian efforts become increasingly important, with one of the key segments being Humanitarian Logistics (HL). HL encompasses the planning, implementation, and control of the efficiency of material and non-material flows from their origin to the end user, with the goal of alleviating the suffering of the most vulnerable [32]. The goal of humanitarian logistics is to ensure that people affected by disasters or prolonged crises receive the right services or the delivery of appropriate goods and materials, of suitable quality, in the right quantity, at the right time, and in the right place [33, 34]. Humanitarian efforts rely most heavily on logistics during the response phase, as this is when affected populations and the injured are evacuated, and food, medical supplies, and other essential items are delivered. Lives depend on the speed of logistics operations.

Event and exhibition logistics serve specific functions, tasks, and objectives for activities such as sports competitions, concerts, art festivals, trade fairs, and similar events. Logistics for these events encompasses a wide range of services, including the setup and dismantling of venues, security, medical and healthcare services, equipment procurement, site provisioning, accommodation, technical support, transportation of people, goods, and supplies, communication and media equipment, waste removal, and more. The primary goals of an event logistics system are to minimize costs, ensure timely fulfillment of requirements, maintain safety, and enable rapid response to changing demands.

Based on all of the above, the functions and importance of logistics are clearly evident in every segment of human activity. It plays a central role in the efficient management of resources and the timely delivery of goods. Whether in daily tasks, industrial processes, event organization, humanitarian missions, or space expeditions, logistics ensures the coordination of activities and the stability of processes.

Space logistics

Logistical requirements in space exploration are largely predetermined, meaning that most space logistics operates as pull-based flows. Depending on the mission's objectives and duration, the structure of goods and materials, cargo space requirements of spacecraft, necessary supplies, storage capacities, and the allocation and use of resources during the mission are clearly defined. Each mission has its specific characteristics, but from the perspective of logistics system functions and goals, the focus is on maximizing cargo space utilization, ensuring timely resupply, and achieving safe and reliable delivery, while maintaining as much flexibility as possible and minimizing costs. However, unlike terrestrial logistics, where new concepts emphasize integration and cooperation, these aspects are almost entirely absent in space missions.

Due to its immense potential, space logistics has attracted the interest of various industries. While the essence of logistics remains the same, whether on Earth or in space, stricter constraints and extreme conditions necessitate a secure system for the transport, storage, inventory management, and delivery of essential materials beyond Earth's atmosphere [35]. Interest in deep space (which includes Mars and other distant celestial bodies) is growing, along with existing activities such as space mining, space tourism, and space debris management. All of these endeavors require highly careful logistics planning and management. The production of goods and resource exploitation in space paves the way for establishing commercial relationships among entities operating in this domain [36].

The sustainability of space missions, in addition to relying on resources and goods sourced from Earth (systemic supplies), largely depends on the exploitation of resources in space and on other celestial bodies (ISRU, In-Situ Resource Utilization). The application of ISRU reduces the dependence of space logistics systems on Earth-based supply. Supplying space missions with goods from Earth remains one of the most complex elements of planning, both in terms of costs and operational challenges. Importantly, space, including planets, asteroids, natural satellites, and other celestial bodies, is rich in materials that could be used to produce necessary goods and equipment [3]. These materials can be used for the production of rocket fuel, development of life support systems, agriculture, metallurgy, semiconductors, and precious metals. For example, hydrogen and methane can be converted into rocket fuel, enabling travel between space stations, Earth, the Moon, asteroids, and other distant destinations. Processing materials on a celestial body and in its surrounding space will require significant research efforts [37].

The storage of goods, equipment, materials, and resources represents a crucial function within space logistics systems and is carried out in logistics centers. It enables efficient planning and execution of space missions and logistics chains. In addition to storing goods sourced from Earth, it is necessary to provide storage capacities for all resources extracted in space, as well as for any goods and equipment produced in space (if not used immediately after production). ISRU systems form the foundation for permanent habitation and colonization of other celestial bodies.

Despite their evident importance, the literature does not adequately address ISRU systems and their role within the space logistics system. These systems should be considered across the spectrum of roles and functions of space logistics elements, with their connections to other subsystems clearly identified and defined [3].

To enhance the efficiency of space mission execution, orbital storage facilities for fuel, as well as for other resources, play a significant role [3]. Orbital fuel depots are envisioned to function like gas stations on Earth, allowing rockets and spacecraft to begin their missions with less onboard fuel, thereby increasing the payload capacity for other cargo. These depots can be positioned in LEO, between Earth and the Moon, or at other locations, depending on the available infrastructure in a given region of space [38].

The region of space near Earth represents an open market for various commercial activities, which are currently dominated primarily by companies in the telecommunications sector. However, in an effort to expand its influence in space, Starlink, well known for its satellites, has entered the space tourism market. In addition to SpaceX, companies such as Virgin Galactic and Blue Origin also have programs in space tourism, offering trips within the LEO region. The expected increase in competition in space tourism is likely to expand the number of destinations available, potentially reducing costs for users and making space travel accessible to a wider audience. Equally important is that spacecraft used for space tourism are equipped with all necessary systems to maximize the safety of both crew and passengers [38]. A key requirement is the development of sustainable and efficient logistics systems that ensure the safe execution of space tours and support space tourism activities. These systems must be well-integrated and capable of supporting all aspects of space operations [3].

Another area that requires a robust logistics system is space debris management. Space debris refers to all human-made objects, along with their fragments and parts, irrespective of whether the responsible parties can be identified. These objects are located in Earth's orbit or re-enter the denser layers of the atmosphere. They are characterized by non-functionality, with no realistic expectation of performing their original functions again. The issue of space debris has been known to experts in the space community for more than three decades. Despite increasing pressures for the sustainable use of space, little progress has been made in addressing this problem [39]. The exponential growth of space debris poses a significant threat both to space logistics systems and to the safety of Earth itself [40]. The supportive role of space logistics systems is reflected in their assistance with space debris removal activities, similar to the role of reverse logistics on Earth [3].

4. SUBSYSTEMS OF TERRESTRIAL AND SPACE LOGISTICS

The end goal of space logistics is to maximize the research potential by enhancing spacecraft performance, as well as the efficiency and effectiveness of processes and infrastructure capacities. On the other hand, the specific characteristics of space logistics compared to terrestrial logistics include[6]:

- Operation under extremely harsh conditions [41];
- Very long distances between origin and destination points, affecting travel time and modes of transportation [42];
- Extremely high logistics costs;
- Limited logistics infrastructure;
- Lack of cooperation and other logistics strategies;
- Partial development of logistics subsystems;
- Logistical resources limited in quantity and capacity;
- Extremely high requirements for the reliability of systems, procedures, and equipment;
- Requirements for the safety of crew, spacecraft, power and life support systems, as well as all other systems that ensure the continuous and secure execution of the mission.

Quantitative constraints refer to transport resources, available storage capacities, the quantity and type of research equipment, crew necessities (food, water, clothing, personal hygiene items), fuel and other consumables, mission duration, the number of crew members, and similar factors. Additionally, reliability implies that the system will remain functional and resilient to malfunctions or unforeseen events, which does not necessarily guarantee crew safety. Furthermore, it is important to highlight the requirements for precise mission planning, efficient resource utilization, system autonomy, and coordination of all subsystems.

Logistics subsystems that exist on Earth are also present in space. Every logistical flow begins with an order, which arises from the need for a specific good or resource. The order serves as the initial source of information, defining the quantity and type of goods, delivery time and location, special packaging requirements, and other characteristics, enabling efficient planning and coordination of logistics flows. The primary tasks of ordering include transmitting and processing the order, analyzing it as an information source, and forwarding it appropriately [2]. On Earth, the ordering process is more frequent and flexible, as it can utilize various communication and ordering methods, such as in-person visits, phone calls, emails, online platforms, mobile applications, and other digital tools. A wide range of products, a large number of suppliers, and a developed infrastructure allow greater flexibility in supply, faster delivery, and adaptability to changes in demand. In space logistics, the ordering subsystem includes not only orders between space and Earth but also coordination between suppliers and launch centers on Earth. These flows involve synchronizing production, suppliers, logistics providers, and all other stakeholders to ensure timely delivery of resources to launch centers, thereby guaranteeing the efficiency, continuity, and safety of space missions. Missions have strictly defined timeframes that must be met, and every kilogram of cargo launched into space requires careful planning and justification due to limited spacecraft capacity and high launch costs. Therefore, it is crucial that goods reach launch centers on time, in the correct quantity, condition, and packaging, with minimal delivery costs. The efficiency of space logistics flows largely depends on the efficiency of logistics flows on Earth.

In space, there are no stores or home repair centers. Trash trucks don't arrive as they do on Earth, washing and drying machines don't exist, and clean clothing may take weeks or even months to be available. Oxygen and drinking water must be supplied from Earth. In case of inventory shortages, crew members cannot simply order replacements online. Instead, they contact mission control, submit a request, and wait for it to be processed [43].

In space, the role of inventory is far more critical than on Earth. A shortage of supplies in space can have far more severe consequences. While on Earth, inventories primarily ensure continuity of production and supply, in space, the success of an entire mission often depends on carefully planned and readily available stock. Due to infrequent deliveries, especially on crewed missions, it is essential to maintain a precisely defined list of items and quantities. Supplies must cover a wide range of products, from research equipment, food, and water for the crew to personal hygiene items, but with a limited number of units per item. For long-duration missions, inventory planning may need to extend up to two years in advance. Space missions require a high level of control, as incorrect replacement of items or premature consumption of stock can have catastrophic consequences. Most short-term missions do not include resupply, so reverse logistics is practically non-existent. Nevertheless, proper initial provisioning and careful monitoring of inventory remain critically important. Additionally, reserves must be maintained to account for unforeseen events affecting mission completion or return. For long-duration missions, resupply processes involve complex and demanding operations, which significantly impact overall mission costs [44].

On Earth, it is possible to store inventory at multiple locations, using warehouses of various sizes and purposes. Warehouses can employ a wide range of storage and handling technologies. In space, however, the situation is quite different. Available storage capacity is extremely limited, as is the case on the ISS. In just a few square meters, or at most several dozen, a wide range of products must be stored. Additionally, careful attention must be paid to the compatibility of stored goods, which presents a significant challenge. In such an environment, standardization of packaging and handling equipment is of critical importance.

The concept of orbital storage facilities is currently under consideration [45]. It would be located in one of Earth's orbits (most commonly in LEO) and could serve as an effective solution for fuel storage. Currently, spacecraft carry the full amount of fuel needed to reach a point in space and return to Earth. With orbital storage facilities, spacecraft could use only a portion of their fuel to reach a designated location, then refuel at the orbital station for the journey back to Earth. This approach increases the payload capacity per launch, directly reducing the number of launches required and overall costs. Such orbital stations could become key hubs in future space logistics networks.

When it comes to packaging, its planning requires close collaboration between logistics specialists and engineers or scientists working with materials [26]. Packaging must be designed to withstand the extreme conditions of space and protect the contents of the products. On Earth, a wide variety of materials can be used for packaging, such as paper, plastic, wood, metal, glass, textiles, biodegradable materials, and more. In space, packaging options include ziploc bags, protective foam, and other containers that ensure the safe transport of goods [44].

Transport is the most visible activity and subsystem of logistics [46], which on Earth generally generates the highest costs and environmental impacts. In the space environment, it involves the movement of people, cargo, and satellites beyond Earth's atmosphere, primarily using spacecraft and rockets as propulsion. It includes various types of vehicles, such as crewed spacecraft, cargo vehicles, and satellites, and relies on infrastructure such as launch pads, spaceports, and mission control centers. This mode of transport has evolved from early experimental launches to modern, technologically advanced systems, playing a crucial role in scientific research, global communications, and economic activities. It represents an indispensable part of the overall transport system (which includes all forms of Earth-bound transport) due to its unique ability to operate beyond Earth's atmosphere. This makes it a key link in global communication networks, satellite services, and space exploration. Space transport also acts as an enabler for other types of transport, allowing the deployment and maintenance of satellites that support global positioning systems (GPS), weather forecasting, and telecommunications networks. For example, communication satellites launched into orbit provide worldwide signal broadcasting and internet services, while scientific instruments positioned in space rely on space transport for precise placement and operation [47]. Space transport vehicles are spacecraft, which assume the functions of all types and technologies of transport. They must be launched into space, with the cost of the launch system encompassing both fixed and variable expenses. Fixed costs include the terrestrial infrastructure required for the production, launch, and management of the spacecraft, as well as the costs of maintaining the minimal „intellectual capital" necessary for operating the launch system. Variable costs cover all expenses that increase proportionally with the number of rockets and spacecraft produced [48]. At the same time, they have a significant impact on the total costs of the entire space transportation system.

The transport of resources into space also has an environmental dimension. The share of space transport in global CO_2 emissions is still relatively small compared to other modes of transport, but current policies anticipate its growth. In 2020, space transport activities accounted for only a minor portion of total global CO_2 emissions. However, by 2050, according to certain scenarios [49], emissions associated with spacecraft launches are expected to rise due to the increasing number of missions supporting expanding satellite networks and space exploration. Despite growing demand, efforts to decarbonize the space transport sector play a key role in reducing emissions and ensuring the sustainable development of space activities. This includes the adoption of sustainable propulsion technologies, improvements in launch efficiency, and the implementation of policies that encourage the use of cleaner and more environmentally friendly solutions [47].

In space systems, several distinct transport links can be identified, the first being between the logistics system's hinterland on Earth and orbit. This segment represents the most expensive and challenging part of transport, both in terms of operational costs and physical constraints [46], as well as in terms of emissions of air-polluting gases [50]. The second transport link occurs in space between two distant locations (for example, two celestial bodies). The vast distances between Earth and other celestial bodies pose a significant challenge in terms of travel time and represent one of the main obstacles that will need to be overcome in the future. The third transport link in space logistics concerns short distances between orbital space stations or between subsystems on other celestial bodies. Transportation within the space logistics system is recognized in the literature as an important subsystem, but scientific and professional works often treat it as the sole critical element of space systems. It is essential to view the transport subsystem as part of a more complex system, the space logistics system, where transport establishes connections between infrastructural and organizational elements, namely space logistics centers [3].

Logistics hubs, such as terminals, logistics centers, distribution centers, airports, and seaports on Earth, in space can include space stations, asteroids, planets and their moons, the previously mentioned orbital depots, or other celestial bodies. Logistics centers (terminals) represent the primary infrastructural element of logistics on Earth and, as such, are a central link in the execution of logistics activities. They enable spatial and organizational integration of complex logistics systems. These centers can be classified according to their function, size, area of influence, position within the logistics network, applied strategies, organization and technology, ownership, type of goods, and other criteria [2, 3, 51]. Logistics centers on Earth and in space share certain similarities, such as the need for infrastructure (warehouses, transport vehicles, certain robotic systems, and more). However, some subsystems of a logistics center can be physically relocated, so in space there may be research bases or parts of a space station that are physically separate from the main center but remain under its control. Considering the vast distances in space, this operational model can generate numerous challenges, including communication and coordination issues, systemic errors, and even psychological and social challenges faced by researchers working in locations distant from the logistics center. Proper identification and resolution of these problems is crucial for the efficient management and functioning of space logistics operations. To date, relatively few researchers have addressed the topic of logistics centers within space logistics systems. In [3] emphasized is the importance of developing different categories, structures, and roles of logistics centers in space to understand their capabilities, opportunities, limitations, weaknesses, and future development directions. A common feature of all logistics centers, including those in space, is the ability to perform various transformations of goods flows: spatial, temporal, quantitative, qualitative, structural, dynamic, informational, ownership-related, value-related, as well as transformations of determinacy and dependency [2]. Just like logistics centers on Earth, by establishing adequate transport links (connections) between space logistics centers (terminals, nodes), a space logistics network is formed [3].

5. CONCLUSION

A well-developed logistics system is crucial for the efficient flow of goods in space, perhaps even more so than for terrestrial logistics. Although space logistics is still an emerging field poised for expansion and development, it is evident that it can draw on solutions applied in Earth-based logistics. However, significant differences must be taken into account when planning and managing logistics systems and processes for space missions and operations. These differences include the unique working conditions in space, vast distances between origin and destination points, limited cargo and storage capacity, extreme temperature variations, high launch costs, and the inability to quickly replenish supplies. Consequently, it is essential to define logistics models, systems, and strategies based on terrestrial solutions but adapted to function effectively in extraterrestrial environments. Additionally, any unforeseen event in space carries far more serious consequences than on Earth, requiring careful planning and multiple verification steps in logistics processes. Due to the fundamental differences in the environment in which logistics operations take place, space logistics rightly emerges as a distinct field, demanding specialized approaches, tailored methods, and unique solutions, making the management of flows in space significantly more challenging than on Earth.

This study provides an overview of the fundamental characteristics of logistics systems both in space and on Earth, identifying the challenges, similarities, and differences between the two environments, with the aim of fostering scientific interest in the field of space logistics. It offers a detailed insight into the critical importance of effective planning and management of flows, supplies, information, risks, safety, and system reliability, particularly in the still relatively underexplored environment of space. In this way, the study achieves its goal: introducing the field of space logistics and clarifying its significance for the successful execution of all operations in space.

Considering the low degree of cooperation among stakeholders in space, future research directions could include examining the benefits of joint efforts in space projects and the significance of such cooperation from a logistics perspective. Furthermore, it is necessary to more precisely identify the specific requirements that may arise in missions to distant celestial bodies, as different celestial environments present varying conditions (depending on their distance from the Sun, types of radiation, gravitational and atmospheric characteristics, and other factors). These requirements differ significantly from those of systems located near Earth, such as the ISS. Understanding them would facilitate more accurate mission planning (including the selection of spacecraft type and size, required supplies, storage capacities, mission duration, delivery timing, and more) as well as defining logistics services across interplanetary distances. Additionally, the consequences of reverse flows within the space-Earth system should be identified and analyzed, given the expected intensification of space exploitation in the coming decades alongside global population growth, which will increase the volume of flows both in space and on Earth. The previously mentioned categories of logistics centers will undoubtedly play a crucial role in organizing and efficiently managing flows under these conditions.

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REZIME

SLIČNOSTI I RAZLIKE ZEMALJSKE I SVEMIRSKE LOGISTIKE

Počev od vremena starih civilizacija, pa sve do modernog doba u kome živimo, logistika je imala važnu ulogu. Svakodnevne aktivnosti koje su ljudi obavljali hiljadama godina unazad, poput berbe i sakupljanja plodova, njihovog odlaganja, čuvanja i prerade, transporta do mesta razmene ili prodaje, preteče su logističkih aktivnosti u modernom dobu. Logistika je danas prisutna i važna u svim oblastima ljudskog delovanja. Velika geografska otkrića i ekspedicije, industrijska revolucija, ali i različiti pohodi i ratovi zahtevali su postojanje složenog sistema logistike. Potpuno novu dimenziju dobila je sredinom dvadesetog veka, kada su napravljeni prvi koraci ka osvajanju svemira. Budući da je svemir složen i nestabilan sistem, svaka misija zahteva jaku logistiku, od početka do kraja realizacije. Obzirom da se radi o prilično novoj oblasti logistike, ovaj rad bavi se uporednom analizom, sličnostima i razlikama svemirske i logistike na Zemlji. Cilj i doprinos ovog rada je pokretanje naučne diskusije o svemirskoj logistici, sa posebnim fokusom na ulogu savremenih logističkih sistema i menadžmenta u odgovoru na izazove svemirskog okruženja.

Ključne reči: *logistika, svemirska logistika, upravljanje, razvoj, funkcija*