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Space logistics and risks: A study on spacecraft

Uzay lojistiği ve risk: Uzay araçları üzerine bir çalışma

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Space Logistics and Risks: A Study on Spacecraft

Highlights

- *The İmportance of Space Exploration*
- *Space Exploration and Logistics*
- *Space Logistics and Risk*
- *The Risks Encountered in Space*
- *Türkiye and Space Logistics*

Graphical Abstract

Risks affecting the launch and transportation activities, which are one of the most important processes of space logistics, were categorized, and their relationships were examined. It has been determined that technical risk, quality, environmental risk, and process risk significantly affect transportation processes in space logistics.

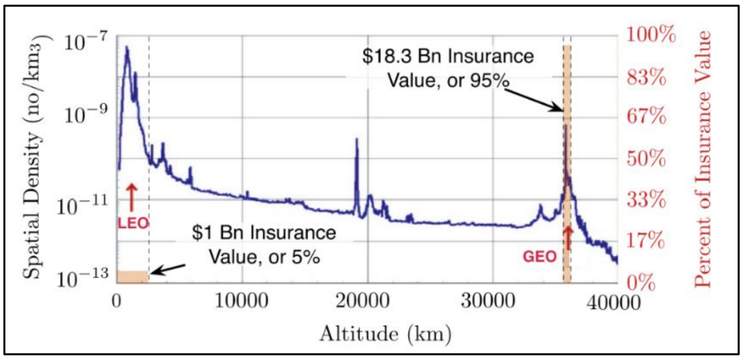

Figure. Density of Debris Population from LEO to GEO Regimes and Risk Assessment

Aim

The purpose of the research is to examine the risks faced by space vehicles, an important element of space logistics. The research was conducted specifically on the Falcon 9, which is frequently used in commercial launch activities.

Design & Methodology

The PLS-SEM method was used in the analysis of the data obtained with the participation of experts in the Aviation and Space field. Smart PLS 4 software was used in the analysis of the research.

Originality

The originality of the research lies in categorizing the risks that spacecraft, which have a significant impact on the execution of space missions, may encounter before, during, and after launch.

Findings

In the analysis of the research, a significant and positive relationship was found between the dependent variable process risks and technical risks and environmental risks, while a significant but negative relationship was found with quality.

Conclusion

Risks affecting the launch and transportation activities, which are one of the most important processes of space logistics, were categorized, and their relationships were examined. In addition to the categorized risks in the research, due to the uncertainties of space, unprecedented risks can be encountered. Space logistics is currently a dynamic and open field for development.

Declaration of Ethical Standards

The author of this article obtained ethical approval from the Nişantaşı University Ethics Committee on 04.04.2023 with protocol code 2023/16 for the materials and methods used in their study.

Space Logistics and Risks: A Study on Spacecraft

Araştırma Makalesi / Research Article

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ABSTRACT

The mysteries of space have aroused curiosity throughout history. To understand the secrets of space, it is possible to observe, reach, research, and return through the elements of space logistics. However, in space, where there are no boundaries, there are uncertainties and various risks. The purpose of the research is to examine the risks faced by space vehicles, an important element of space logistics. The research was conducted specifically on the Falcon 9, which is frequently used in commercial launch activities. The PLS-SEM method was used in the analysis of the data obtained with the participation of experts in the Aviation and Space field. Smart PLS 4 software was used in the analysis of the research. In the analysis of the research, a significant and positive relationship was found between the dependent variable process risks technical risks, and environmental risks, while a significant but negative relationship was found with quality. Risks affecting the launch and transportation activities, which are one of the most important processes of space logistics, were categorized, and their relationships were examined. In addition to the categorized risks in the research, due to the uncertainties of space, unprecedented risks can be encountered. Space logistics is currently a dynamic and open field for development.

Keywords: Space, logistics, space logistics, risk, spacecraft

Uzay Lojistiği ve Risk: Uzay Araçları Üzerine Bir Çalışma

ÖZ

Uzayın bilinmezliği tarih boyunca merak uyandırmıştır. Uzayın sırlarının anlaşılabilmesi için gözlemlemek, ulaşmak (gitmek), araştırma yapmak ve geri dönmek uzay lojistiği unsurlarınca mümkün olmaktadır. Fakat sınırların olmadığı uzayda bilinmezlikler ve çeşitli riskler vardır. Araştırmanın amacı uzay lojistiğinin önemli bir unsuru olan uzay araçlarının karşılaştığı risklerin incelenmesidir. Araştırma ticari fırlatma faaliyetlerinde sıklıkla kullanılan Falcon 9 özelinde gerçekleştirilmiştir. Havacılık ve Uzay alanında uzmanların katılımıyla elde edilen verilerin analizinde PLS-SEM yöntemi kullanılmıştır. Araştırmanın analizinde Smart PLS 4 programı kullanılmıştır. Bağımlı değişken process risks ile technical risks and environmental risks arasında anlamlı ve pozitif quality ile ise anlamlı ama negatif bir ilişki bulunmuştur. Uzay lojistiği sürecinin en önemli süreçlerinden biri olan fırlatma ve taşıma faaliyetlerini etkileyen riskler kategorize edilip aralarındaki ilişki incelenmiştir. Araştırmada kategorize edilen risklerin yanı sıra uzayın belirsizliklerinden dolayı önce görülmemiş riskler ile karşılaşılabilir. Uzay lojistiği hali hazırda dinamik ve gelişime açık bir alandır.

Anahtar Kelimeler: Uzay, lojistik, uzay lojistiği, risk, uzayaracı

1. INTRODUCTION

Space is a place of unknowns and without boundaries. The mystery of space has always aroused curiosity [1]. However, to uncover the mystery of space, it is necessary to have the capabilities of space logistics, a specialized area of logistics [2]. This has made it imperative for governments and companies to act by a common policy framework [1;3]. Generally, logistics is the planning, implementation, and control of the flow of goods and services from production to the final consumption point [4;5] and thus the concept is one of the key elements for the success of space missions [6].

However, due to the different risks that space includes, it is necessary to have capabilities in space logistics [2]. Space logistics is implemented at altitudes kilometers above the Earth's surface, where there is no gravity and various risks exist. Furthermore, it consists of supply, handling, storage, and service provision activities facilitated through specialized vehicles and techniques to enable the execution of space missions [3;7]. Space logistics refers to activities for space missions both on Earth and beyond the atmosphere [6]. Having effective capabilities in space logistics requires increasing logistics competencies to enable the discovery of space and the conduct of scientific research in space. In this context, it is necessary to conduct the necessary technical research and develop the infrastructure. Particularly important research topics include the various risks and uncertainties that space, brings [8]. To explore space carry out scientific research, and to increase logistics competencies, it is necessary to go through a long and arduous process.

The technology of rockets and spacecraft, which is essential for space exploration, has evolved from past to present. The rockets and vehicles used in this field are important and key elements of space logistics. The journey into space with the WAC Corporal sounding rocket began at the White Sands Proving Ground

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(WSPG) in New Mexico in 1946, and by 1948, the two-stage, liquid-fueled V-2 rocket was launched into space through the combination of German and American technologies [9;10]. The development of liquid-fueled rocket technology, which enables space research, was influenced by Germany's rocket and missile studies after World War II [10]. The Soviet Union's launch of Sputnik 1, the world's first artificial satellite weighing 83 kg, on October 4, 1957, brought a different perspective to space studies. The first artificial satellite, Sputnik 1, initiated the era of remote sensing by obtaining the first images of Earth and the atmosphere [11]. Subsequently, on November 3, 1957, Laika was launched aboard Sputnik 2 [12], and on March 17, 1958, the United States launched its first satellite, Vanguard 1 [13]. To not fall behind in the space race against the Soviet Union, the United States began working on the National Aeronautics and Space Act in 1958. NASA, which would oversee non-military space activities, was established on July 29, 1958, with the signature of President Dwight D. Eisenhower. NASA started its activities in the same year [14]. The journey into space with modern rockets began in 1989 with Konstantin Tsiolkovsky, who researched liquid-fueled rocket technology and is known as the father of this idea. This paved the way for modern space activities [9]. After the first manned space flight by Soviet cosmonaut Yuri Gagarin aboard the Vostok spacecraft in 1961 [15], significant developments were made in space tourism after the first commercial flight by Dennis Tito in 2001 [16]. In recent years, SpaceX can be seen as the beginning of a major transformation in space logistics. The successful launch of the liquid-fueled Falcon 1 rocket into Earth's orbit by the private venture SpaceX in 2008 marks the beginning of this transformation [17]. In 2012, SpaceX's Dragon spacecraft delivered its first contracted NASA cargo to the International Space Station (ISS). By 2015, the Falcon 9 rocket had launched 11 communication satellites into orbit and successfully landed back on Earth [17;18]. Finally, on May 30, 2020, for the first time, NASA astronauts were launched to the ISS aboard the Crew Dragon spacecraft, built and operated by a private company, SpaceX [10]. SpaceX's spacecraft can be considered new technology in space logistics. Falcon 9's technology enables reusability, reducing the cost of access to space and lowering the costs of space missions. This is an important advantage for future moon and Mars missions [17]. In addition to positive developments in space logistics processes, there are also negative ones.

From the past to the present, NASA's Space Shuttle Challenger disintegrated 73 seconds after liftoff on January 28, 1986 [19]. Following its launch from the Kennedy Space Center in Florida, NASA's spacecraft Columbia lost communication 16 minutes later on February 1, 2003. The NASA space mission ended in failure [20]. Virgin Galactic's SpaceShipTwo, a space tourism company, exploded during a test flight on October 31, 2014. After the explosion, SpaceShipTwo crashed in the Mojave Desert [21]. Falcon 9 successfully landed on a sea platform after its 19th mission on December 25, 2023. However, Falcon 9 Booster B1058 toppled over due to adverse weather conditions (high winds and waves) afterward. Following the incident, B1058 became unusable. Lastly, the Japanese company Spaceone was supposed to place a commercial satellite into orbit with the Karios rocket. However, the Karios rocket exploded 5 seconds after liftoff. Company officials stated that the rocket automatically destroyed itself after the first-stage engines were fired, determining that the rocket could not reach its target [22]. Ultimately, there are various risks due to technical errors, malfunctions during launch, or adverse weather conditions before which may lead to the failure of space missions.

Above discussion shows that both spacecraft and rockets that enable the realization of basic logistics processes in space missions and supply chain management processes have various risks. Risk management is crucial and necessary for the successful completion of missions [23;24]. However, when the literature is examined, it can be seen that space logistics and risks in the field of social sciences are rather neglected fields. Therefore, in the current study, the impact of categorized environmental risks and technical risks on quality and process risks was examined. The study has two research questions; RQ1: "How do experts in the aviation and space sector in Türkiye define risks in the space logistics process?", and RQ2: "How do environmental risks, technical risks, and quality of Falcon 9, used in the transportation process in space logistics by experts in the aviation and space sector in Türkiye, can be affected, affect space logistics process risks?". In order to answer these research questions, firstly, risks were categorized into three main headings: Environmental, Technical, and Process Risks. Then, the relationship and explanatory percentage between process risks in space logistics and other variables such as environmental risks, technical risks, and quality were examined.

2. SPACE LOGISTICS and RISKS

Space logistics is a new field of study [1]. Space logistics is defined as managing the necessary design, material, service, and information flow for the successful completion of space missions [6]. Space logistics can also be defined as the transportation, storage, and tracking of crew and equipment necessary for performing space missions [25]. This means, space logistics involves providing material flow for activities beyond the atmosphere, planning and implementing manned space missions, both forward from Earth to space and the return of the crew from space to Earth [2;7]. Although, sometimes the definition of space logistics does not include other activities carried out on Earth, such as the design, production, assembly of the spacecraft and equipment, handling of loads, and storage, that ensure the completion of the mission [26], the preparation activities carried out on Earth are also crucial for the success of space missions [27]. As space logistics involves planning, implementing, and controlling missions from low Earth orbit (LEO) to deep space or beyond the atmosphere [28], the process involves the production of materials to be used in space missions, equipment providing mobility in space, essential life support materials, spare parts, and ensuring the successful return of the crew to the starting point. Space logistics is the sum of activities such as supply, transportation, handling, storage, and service provision to ensure the sustainability of activities in space [29;7]. The increasing interest in space exploration is expected to lead to the development of satellites, space stations, space transportation, and space exploration vehicles, as well as the commercialization of space [30]. Additionally, planning for activities such as space tourism, energy, production, and mining in space supports this situation [21;31]. The most recent example is the announcement by Yuri Borisov, the head of Russia's space agency Roscosmos, that Russia and China will build a nuclear power plant on the Moon between 2033 and 2035 [32]. Furthermore, in the concept of Industry 4.0 or smart production, efficient and effective production will be ensured using technologies such as artificial intelligence, big data, Internet of Things (IoT), machine learning, cloud computing, etc. [33;31]. The use of these technologies involves the use of satellites, one of the elements of space logistics. Data transfer will be facilitated more easily and effectively through satellites. These technologies are important for supporting the space economy or industry [33]. The use of these technologies can provide advantages in terms of speed, time, and efficiency through satellite-based internet services. Statistical data shows that investments in the space industry have increased since the 2000s. Especially between 2017 and 2022, the space economy has reached significant size [31]. Space offers commercial opportunities. However, to ensure the sustainability of logistic activities in space, space policy and infrastructure need to be developed [1]. The increasing interest in space activities will lead to rapid commercialization of space in the future which will make space logistics, and therefore carrier rockets and vehicles, more important.

For instance, SpaceX, founded in 2002, is a commercial enterprise, that supports future space exploration with its developed rockets, spacecraft, satellites, and technical equipment. Since its establishment, SpaceX has developed spacecraft and rockets for various missions, and Falcon 9, Falcon Heavy, and Dragon are now in use. Starship, on the other hand, is undergoing various tests in order to be used in Mars and deep space missions in the future. SpaceX's spacecraft can be considered a disruptive technology in space logistics because, for example, Falcon 9 enables reusability with its technology. Additionally, SpaceX has developed the Starlink project with its subsidiary company Starlink, which involves a constellation of satellites in low Earth orbit (LEO). This has enabled Falcon 9's reusable launch operations to be carried out at lower costs [34].

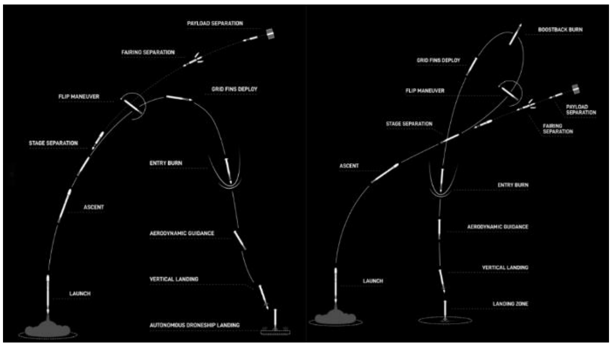

Figure 1. Falcon 9 Launch and Landing Process
Source: [17].

Figure 1 shows Falcon 9's reusability proces. At the end of the mission, Boosters land at the landing zone or on an autonomous droneship [35]. Reusability reduces the costs of space missions which provides a significant advantage for future missions to the Moon and Mars [36]. Falcon 9 is a two-stage launch vehicle consisting of the first stage, second stage, and fairing sections. Falcon 9 has 9 engines in the first stage and one engine in the second stage. Falcon 9 has achieved a total of 313 launches, 271 landings, and 244 reflights. Falcon 9 can perform flights with either a fairing or the Dragon spacecraft. Its reusability sets Falcon 9 apart from other rockets. Falcon 9 is actively used for satellite launch missions and cargo and crew transportation to the ISS. Falcon Heavy, on the other hand, is used for launching heavier payloads. Falcon Heavy is reinforced with 2 additional boosters compared to Falcon 9. Falcon Heavy has achieved a total of 9 launches, 17 landings, and 14 reflights. Falcon Heavy can carry more payload to LEO and GTO. Falcon 9, Falcon Heavy, and Starship spacecraft are designed to reach more payload and longer distances, respectively [17;36].

As mentioned above, there have been unsuccessful launch operations such as Challenger, Columbia, SpaceShipTwo, Karios, and Falcon 9 rocket for various reasons. Due to the nature of space activities, spacecrafts and rockets, there is a lot of uncertainty, which brings various risks [23;37]. These risks could be grouped into environmental, process, and technical risks which occur before launch, at the time of launch, and after the launch [38;39]. These risks, unfortunetaly, can lead to the failure of space missions. Therefore, risk management is crucial and necessary for the successful completion of space missions. To successfully carry out space activities, risks must be identified, and uncertainty must be reduced [40]. Reducing risks in the process will reduce the payback period for businesses' investments [41;37]. This may, in turn, attract the interest of companies providing goods and services in space, increase competition, and reduce costs [1].

2.1. Risk of Space Logistics

In space missions, various factors adversely affect the rockets and spacecraft used. The risks affecting space logistics have been identified based on the information obtained by experts in the field of aerospace engineering. Firstly, various risks in space logistics were identified using insights from the literature. The semi-structured in-depth interviewing method was employed to analyze the obtained data. At least four experts with a doctoral level from the department of aeronautics and space engineering participated in the study. Information about the participants is provided in Appendix 1, Table 7. In qualitative studies, researchers may decide that they have reached a sufficient data source when the concepts emerging from the data begin to repeat themselves [42]. The risks that may be encountered in space were obtained verbally from the experts who participated in the study. In the data analysis related to qualitative research methods, the content of the discourses is examined to determine which concepts, events, or thoughts are emphasized the most or the least. Two methods can be recommended for the analysis of data obtained in qualitative research: descriptive analysis and content analysis. The descriptive analysis method, which is used for processing data that does not require in-depth analysis, was utilized in the conducted interviews [43]. In this context, not only the risks specified in Table 6 but also Supply Risk, Cost (Financial) Risk, Permission, Licensing and Certification Risk, Transportation (to Launch Area) Risk, Human (Individual) Risk, and various unforeseen risks were also identified by the experts. However, since the current study focuses on the launch, i.e., transportation process, with the Falcon 9 Rocket, only the Environmental, Technical, and Process risks that could affect the transportation process were included in the research. The Environmental Risks included in the study are supported by the works of [44;45;46;47]. The Technical Risk is supported by the studies of [48;49;50]. Additionally, the Process Risks are supported by the study of [51]. In a research study, the information collected is likely to yield similar information even if the validity is not the same in a similar type of study [42]. It is crucial to support the study with similar works from the literature due to the absence of identical studies. Reliability pertains to the ability to obtain the same results if the study is replicated [52]. It can be observed that the examined risks have been studied in various research without needing to conduct the same study [53]. However, in this study, the risks were posed to experts from the Department of Aeronautics and Space in a survey format and were not examined within the framework of a quantitative study. This research aims to fill the gap in this area. Space risks are detailed in Appendix 1. In the current study, the risks encountered in the transportation process have been categorized into 3 categories including environmental, technical and process risks, and examined. The research model is shown in Figure 2.

Environmental Risks: Environmental risks refer to the impact of the natural environment on the spacecraft before, during, and after the transportation process on Earth and in space [54;46]. In this study, environmental risks can be categorized as adverse weather conditions on Earth, space weather (cosmic radiation and solar radiation), ionization, asteroids, and space debris [44;45;46]. Space weather refers to events that occur as a result of the Sun's activities affecting Earth and having adverse effects. Environmental risks can lead to the disruption of communication with the spacecraft and the malfunctioning of avionic systems due to cosmic and solar radiation, satellite losses due to ionization, the safe transportation of cargo and crew to the ISS, and problems in the return process [46].

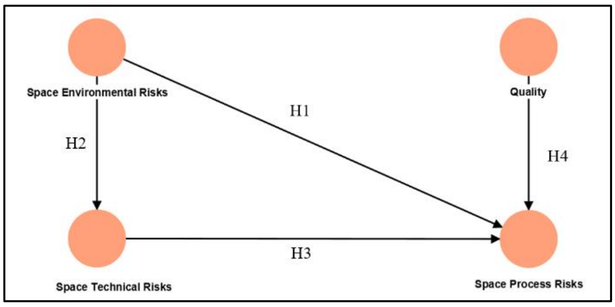

Figure 2. Research Model

Environmental risks are important not only for spacecraft and space missions but also for the radiation exposure of the crew in space missions [55;47;46]. Adverse weather conditions can lead to delays in operations, failure to complete the process on time, and failure of missions. Since the beginning of space activities, human-made space debris has become a major problem.

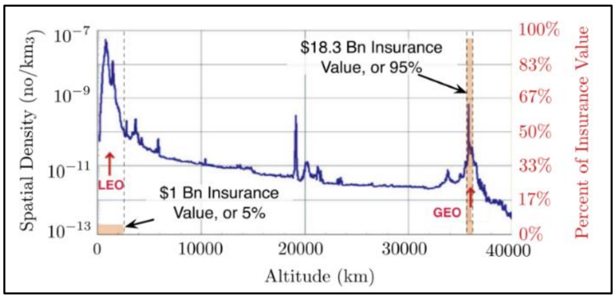

Figure 3. Density of Debris Population from LEO to GEO Regimes

Source: [47].

Possible collisions pose a risk for satellites and spacecraft. Therefore, space debris is one of the important issues in space logistics [56;57]. Space debris poses a risk for satellite operations. According to future projections, if necessary precautions are not taken while space activities continue, the density of space debris in orbits, especially in Low Earth Orbit (LEO), Geostationary Orbit (GEO), and High Earth Orbit (HEO), will increase [47].

In Figure 3, it can be seen that the intensity of activities in LEO and GEO has particularly led to an increase in space debris in these orbits. Space debris poses an environmental risk. This has led to an increase in the resistance of spacecraft to collisions [57;47]. Additionally, the presence of collision risks has increased the insurance costs of satellites. Risks also increase costs. Insurance costs are shown in Figure 3. Despite the high intensity of satellite activities in LEO, the total insurance value being only 5% can be explained by the presence of high-value satellites in GEO [47]. Accordingly, H1 and H2 hypotheses have been formulated.

H1. *Space environmental risk affects the space process risk.*

H2. *Space environmental risk affects the space technical risk*

Technical Risks: Technical risks refer to the failure of the equipment, technical software, and hardware used in logistical processes to function as planned [51]. The technical risks are examined as problems of payload test, problems of engines, disconnection of Falcon 9 from ground control, problems of avionics systems, and problems of payload (fairing) not separating from Falcon 9. For example, the O-rings in the solid rocket boosters of the Space Shuttle Challenger had eroded in previous which resulted in hydrogen leaking into the external tank. Additionally, it is noted that cold weather conditions could have played a role [48;58]. These demosntrate that the Challenger's mission failed due to a technical error that led to its explosion [48]. Risks are always present in logistical activities. Allocating significant resources in terms of time, money, and material design is necessary to minimize risks which hardnes to carry out space missions [49]. Identifying possible risks and taking preventive measures will ensure the success of space missions [50]. According to the discussion above, the H3 hypothesis has been formulated.

H3. *Space Technical risk affects the space process risk.*

Process Risks: Process risks refer to the problems that can be encountered throughout the mission in logistical processes. Managing logistical processes effectively and efficiently is crucial in terms of time, cost, and success [51]. For example, CubeSat production can lead to delays in the process and increased costs. Other process risks include separation from spacecraft engines, and damage from spacecraft such as overheating, overload, and vibration.

Quality: Quality refers to the fulfillment of expectations in logistical processes. Completing the relevant operation will increase the perceived quality in the logistical process [59]. Experts' perception of quality regarding the tools used in logistical processes will affect the use of quality and risk perception [60]. Increasing the perception of quality will reduce the perception of risk for the tools used in logistical processes [61]. Accordingly, hypothesis H4 was formulated.

H4. *Quality affects the space process risk.*

3. RESEARCH METHODOLOGY

The research utilized Partial Least Squares-Structural Equation Modeling (PLS-SEM). Since the research was conducted in the field of space logistics, it was necessary to identify and analyze space-specific risks rather than those commonly addressed in studies on existing supply chain and logistics risks. The experts in space engineering who participated in the study were asked questions about space logistics and risks. The semi-structured in-depth interviewing method was employed to analyze the obtained data. Additionally, the risks in space logistics were supported by scientific data obtained from the literature. As a result of the interviews with the experts, the risks that could potentially affect space logistics were categorized. The categorized risks are detailed in Appendix 1. The related questions were added to the scale. Subsequently, a pilot analysis of the data collected with the participation of aerospace engineers was performed. Reliability and validity analyses were conducted during the pilot test. Necessary adjustments were made to the scale based on feedback from experts. PLS-SEM is commonly used in studies that examine the relationship between multiple variables. PLS-SEM can also perform path analysis along with reliability and validity analyses. Finally, since there are not many experts in aviation and space in Türkiye, PLS-SEM was used in the current research. PLS-SEM allows reaching accurate results with relatively lower samples[62].

3.1. Sampling and Data Collection

The current study aimed to gather the opinions of experts in the field of aviation and space. Before the scale survey began, a pilot test was conducted with 20 participants. After receiving feedback and completing the necessary revisions, the survey was launched. By attending the "Near Orbit and Cube Satellite Workshop" held in late 2023 in the field of space, experts in the field were personally consulted. The link to the online survey, prepared in the form of a QR code, was distributed to experts in the space field. Experts were asked to answer the survey questions. Additionally, the survey link was sent to the email addresses of experts teaching in the departments of aviation and space engineering in Türkiye. The survey of the current study was sent to 206 people. The number of participants in the survey was 176. After data cleansing and editing, it was understood that data from 155 individuals were suitable for analysis. Subsequently, the data of the study were analyzed. It is important to achieve successful results with a low sample size using PLS-SEM and considering the studies in the literature on this subject. When looking at the number of aerospace engineers in the country in the study conducted specifically in Türkiye, it is understood to be sufficient [62;63;64]. The demographic information of the experts who participated in the research is mentioned in the first paragraph of the results section.

3.2. Data Analysis

The Smart PLS4 software, which is commonly used for analyzing data in the literature according to PLS-SEM, was preferred in the study. The Smart PLS4 package program's lack of attention to the normality assumption allows for analysis with smaller samples. However, as can be seen in the 4th Result section, the Skewness and Kurtosis values were between -1.5 and +1.5. From these values, it can be understood that the data is normally distributed. After the normality assumption in the data analysis, reliability and validity analyses were performed. The obtained data is shown in Table 1. Then, VIF, correlation, path analysis, and R^2 analyses were performed sequentially [65;63].

4. FINDINGS

When the average age of the experts included in the research is examined, 86% of them are between the ages of 20 and 50. Additionally, when the gender distribution in the aviation and space sector is examined, the majority, 80%, consists of male experts. In terms of sectoral experience, the distribution of experts is as follows: less than 1 year, 10%; between 1 and 3 years, 32%; between 3 and 5 years, 10%; between 5 and 7 years, 4%; and 7 years and above, 44%.

The normality test was conducted for the data used in the research. According to the PLS-SEM method used in the research, Skewness and Kurtosis values were examined for the normality test. Skewness and Kurtosis values were between -1.5 and +1.5. It is confirmed that the data meets the normality assumption, as it falls within the range of Skewness and Kurtosis values [65].

Table 1. Convergent Validity, Construct and Indicator Reliabilities

Items	Source adapted	Factor Loading	Cronbach's Alpha	Composite Reliability	Average Variance Extracted (AVE)
Q1 Overall, Falcon 9 works very well technically.	[66]	0.948	0.833	0.885	0.721
Q2 The overall quality of Falcon 9 appears to me as being good.		0.783			
Q3 The quality of Falcon 9 is very good.		0.808			
SER1 I think using Falcon in space mission has potential environmental risks. (adverse weather conditions).	Author	0.858	0.833	0.899	0.749
SER2 I think using Falcon 9 orbit has potential environmental risks. (adverse space weather conditions for example, Solar radiation, Cosmic radiation, Space debris and Asteroids).	Author	0.879			
SER3 I think using Falcon 9 has potential environmental risks. (ionization for example CubeSat may not function due to ionization).	Author	0.859			
SPR1 I think Falcon 9 has potential process risks during in mission. (For example, CubeSat production can lead to delays in the Process).	Author	0.207	0.893	0.934	0.825
SPR2 I think Falcon 9 has potential process risks during in mission. (stage separation and fairing separation or dragon separation).	Author	0.924			
SPR3 I think Falcon 9 has potential process risks during in mission. (pass through the atmosphere)	Author	0.937			
SPR4 I think Falcon 9 potential process risks during in mission. (damage from spacecraft for example overheating, overload and vibration).	Author	0.862			
STR1 I think Falcon 9 has potential technical risks during in mission. (problems of payload test).	Author	0.832	0.869	0.910	0.717
STR2 I think Falcon 9 has potential technical risks during in mission. (problems of engines).	Author	0.929			
STR3 I think Falcon 9 in mission has potential technical risks. (disconnection of Falcon 9 from ground control).	Author	0.852			
STR4 I think Falcon 9 in mission has potential technical risks during in orbiting. (problems of avionics systems).	Author	0.738			
STR5 I think Falcon 9 in mission has potential technical risks during in orbiting. (problems of payload (fairing) not separating from Falcon 9).	Author	0.766			

Table 1 presents the results of the reliability and validity analysis of the research. Factor loading, Cronbach's alpha, composite reliability, and AVE values are shown in Table 1. Factor loadings are expected to be higher than 0.70 [62]. Since the factor loading of SPR1 was found to be 0.207, it was excluded from the analysis. The lowest factor loading is 0.738 for STR4, and the highest is 0.948 for the Q1 variable. Cronbach's alpha and composite reliability values are expected to be above 0.70 [62;63]. The smallest Cronbach's alpha was found to be 0.833, and the composite reliability was 0.885. Finally, AVE values are expected to be above 0.50 [64;63]. The lowest AVE value in the research was found to be 0.717. When the reliability and validity analysis results of the research were examined, the results were within the statistically expected range of values. Therefore, the analysis proceeded to the next stages.

Table 2. Variance Inflation Factor (VIF)

Items	VIF	Items	VIF
Q1	1.870	**SPR3**	3.888
Q2	1.888	**SPR4**	2.055
Q3	2.027	**STR1**	2.544
SER1	1.798	**STR2**	3.965
SER2	2.004	**STR3**	2.815
SER3	2.003	**STR4**	5.266
SPR2	3.534	**STR5**	2.023

VIF is a method used to detect multicollinearity. In this method, it is expected that the VIF values of variables are less than 10, 5, and 3 respectively [62].

However, even when VIF values are below 3, this problem can still be observed [67]. In the study, STR4 was excluded from the research because its VIF value was above 5. The VIF values of the other variables are below 4 and at an acceptable level [62].

Table 3. Discriminant Validity Analysis based on Fornell-Larcker Criterion

Items	Q	SER	SPR	STR
Q	0.849			
SER	-0.040	0.865		
SPR	-0.287	0.765	0.908	
STR	-0.023	0.858	0.764	0.847

Table 3 presents the correlation analysis prepared according to the Fornell-Larcker Criterion. This table consists of the square roots of the AVE values. The Fornell-Larcker Criterion table indicates the strength and direction of the relationship between variables. The first value in each column represents the correlation with the variable itself. Additionally, it is expected to have a higher value compared to others. Upon examining Table 3, it is observed that Risks have a positive correlation among themselves while being negatively related to Quality. It is normal for quality and risks to have an inverse correlation. As the quality of Falcon 9 increases, a decrease in the expected risks is anticipated [63;64].

Table 4. Outputs of Structural Model

Hypothesis	Relation	Path Coefficient	t value	p value	<0.05 Hypothesis supported?
H1	SER→SPR*	0.396	2.519	0.012	Supported
H2	SER→STR***	0.858	19.424	0.000	Supported
H3	STR→SPR*	0.418	2.390	0.017	Supported
H4	Q→SPR*	-0.262	2.350	0.019	Supported

Note: *p < .05; **p < .01; *** p < .001

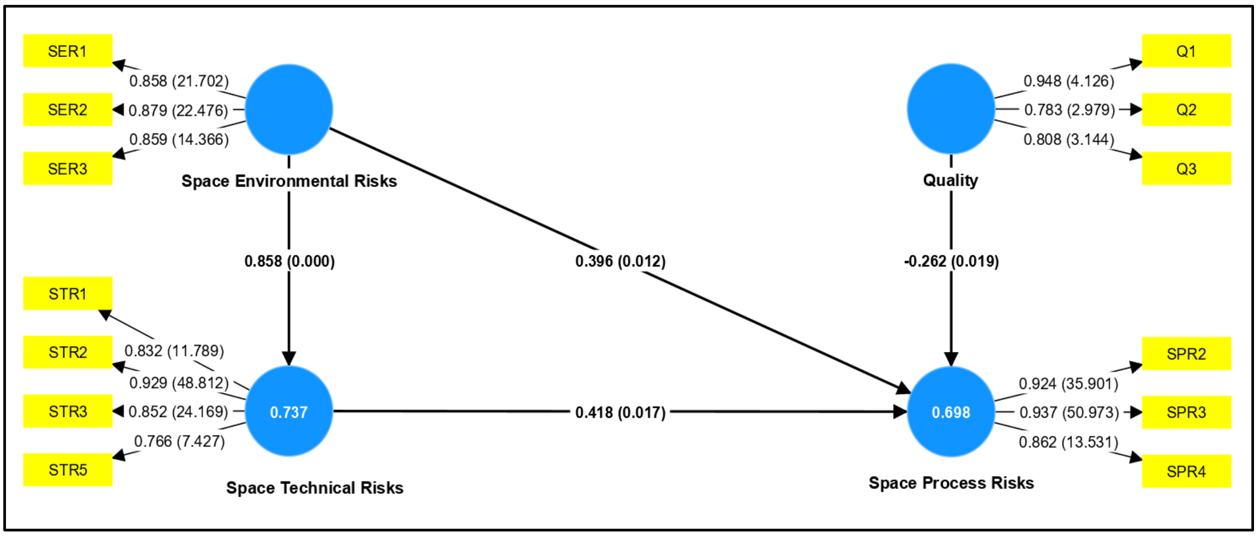

Figure 4. Smart PLS 4 analysis results.

The results of the study are presented in Table 4. The hypotheses were estimated based on bootstrapping in Smart PLS 4. All hypotheses in the model have been supported. SER had a positive effect on SPR (β = 0.396, $p < 0.05$). SER had a positive effect on STR (β = 0.858, $p < 0.05$). STR had a positive effect on SPR (β = 0.418, $p < 0.05$). Q had a negative effect on SPR (β = -0.262, $p < 0.05$).

In Figure 4, the output of the Smart PLS 4 package program for the research model is shown. In Figure 1, the R^2 values of the variables, factor loadings, T statistics, path coefficient, and p-values of the hypotheses are provided.

Table 5. R^2 Values of Variables

Items	R²	Radj²
Space Process Risks	0.698	0.679
Space Technical Risks	0.737	0.731

It is desired for the dependent variable to have a strong explanation. Additionally, an R^2 above 0.70 indicates a strong explanation. As shown in Table 5, the R^2 of Space Process Risk is close to 0.7. This situation indicates that the variables included in the research model are sufficient to explain the dependent variable [64;63;68].

5. DISCUSSION

The uncertainty surrounding space continues to pique curiosity, ensuring that research related to space will continue in the future. Space logistics activities (supply, production, storage, transportation, repair, and return processes) are crucial for the sustainability of space research. Activities in space differ significantly from those on Earth, requiring rockets, vehicles, equipment, and tools used by crews to have special characteristics. However, due to the multitude of uncertainties in space, space logistics activities need to be completed taking various risks into account. In the study, space logistics processes were categorized into three main categories. An important outcome of the research is the categorization of some risks encountered in space logistics as environmental, technical, and process risks. The study was conducted focusing on risks. In the study, the relationship between process risk and environmental, technical risk, and quality variables was examined. The hypothesis results are detailed in Table 4. First, the relationship between environmental risks and process risks was examined. It was found that environmental risks have a significant and positive impact on process risk. Environmental risks can result in the failure of logistic operations. This scenario will create a risk in the space logistics process, decreasing the success rate. Extreme temperatures, radiation encountered in space, space debris, and asteroids are factors that need to be considered in space logistics operations.Environmental risks are potential issues both on Earth and in space. The probabilities of these issues can lead to increased risks and disruption or even failure of the space logistics process. Additionally, it was found that environmental risks have a significant and positive impact on technical risks. Environmental risks can trigger technical malfunctions. Technical failure can lead to disruptions or incomplete operations in the operation process. In this case, the mission may end in failure. Therefore, it is necessary to evaluate the potential natural events and the potential risks they may bring during the production phase of both Falcon 9 and the payload. The positive and significant relationship found between environmental risk and technical risk in the study is parallel to past space experiences [46]. Furthermore, it was found that technical risks have a significant and positive impact on process risks. Process risks, for example, CubeSat production, can lead to delays in the process, separation from spacecraft engines (liftoff), pass through the atmosphere, overheating, overload, and vibration. Process risks can cause various problems before launch, during launch, after launch, or after the completion of the return, resulting in delays in the next launch. Research indicates that among the significant risks affecting process risks are risks associated with suppliers and partners, as well as transport risks. The study also examines potential risks that may arise in operational processes parallel to this situation. Therefore, for the process to be successfully completed in space logistics, for example, the satellite manufacturer must not only deliver the product in good condition, on time, and complete but also consider technical risks and conduct tests [69].Taking preventive measures against technical risks is crucial for the success of operations in space logistics. Lastly, quality is related to the quality perception of the spacecraft and technical equipment. It was found that quality has a significant and negative impact on process risks. The significant and negative relationship between quality and process risks in space logistics is also among the important outcomes of the research. Research has emphasized that quality is a significant factor in logistics operations. Additionally, there is a positive relationship between quality and usage. The study found a negative relationship with process risks, which aligns with the literature [59;70].

6. LIMITATIONS and SUGGESTIONS

One of the most significant limitations of the research is that it focuses only on SpaceX's Falcon 9 rocket, which is one of the essential elements in space logistics. However, SpaceX, as a commercial enterprise, provides services to private or government entities wishing to operate in space with its technical inventory. The company SpaceX is in a significant position in space logistics with its reusable spacecraft Falcon 9, Falcon Heavy, Dragon, and StarShip. Another limitation is that the study was conducted with experts in Türkiye. Türkiye is a country that has made advancements in the aviation sector in recent years and can produce its aircraft. In the future, both state-supported institutions such as TÜBİTAK, the Turkish Space Agency (TUA), etc., and private companies based in Türkiye such as Turkish Aerospace, GUMUSH Aerospace, Hello Space Plan-S, etc., will carry out satellite, Moon, Mars, and space projects. Türkiye is aiming to achieve significant projects related to space such as MUFS, HALE, LAGARİ, etc. In this context, the current research will support future studies that are likely to be conducted. In the future, it is predicted that space logistics activities will spread over a wide area. Therefore, other logistics elements, especially space vehicles, should be researched in addition to space logistics. The current study was conducted specifically on risks. More studies using different variables specific to Falcon 9 can be conducted in the future. Identifying risks and modernizing spacecraft and rockets are important for future space studies [23]. Since the number of specialists in this field is limited in Türkiye, efforts were made to reach most of the experts. Additionally, research involving experts from various regions of the world, not just in Türkiye, could be conducted.

7. CONCLUSIONS

This study has demonstrated that environmental risks and technical risks in space logistics positively affect quality, while quality negatively affects process risks. The categorized risks can be used in future studies. Additionally, the outputs of the current study should be considered and utilized by both the private sector and academia. The strong variance (R^2) of process risks in the study is important from a research perspective. However, in the future, risks that have not yet been encountered may arise. Various uncertainties and risks that have not been included in the research should be taken into account, and tools, equipment, and different components to be used in space logistics need to be developed. The study was conducted to emphasize the uncertainties and risks of space. The outputs of the research are crucial for future activities in Türkiye's aviation and space sectors, as activities in these areas will increase. Additionally, the limited number of studies in space logistics, especially in the social sciences, is a significant source of motivation for the current research.

DECLARATION OF ETHICAL STANDARDS

The author of this article obtained ethical approval from the Nişantaşı University Ethics Committee on 04.04.2023 with protocol code 2023/16 for the materials and methods used in their study.

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Appendix 1

Table 6. Category Risks in Space

No.	Environmental Risks	Technical Risks	Process Risks
1	Adverse weather conditions	Problems of avionics systems	For example, CubeSat production can lead to delays in the process
2	Space Weather • Solar radiation • Cosmic radiation,	Problems of payload test	Separation from spacecraft engines (liftoff)
3	Ionization	Problems of engines	Pass through the atmosphere
4	Space debris	Disconnection of Falcon 9 from ground control	Damage from spacecraft for example overheating, overload and vibration
5	Asteroids	Problems of payload (fairing) not separating from Falcon 9	

Table 7. Information About the Interviews

	Age	Gender	Education	Sector	Position	Interview date	Interview time
E1	29	Male	PhD.	Department of Aeronautics and Space Engineering at University	Research Assistant	24.08.2023-25.08.2023	180-200 min.
E2	36	Male	PhD.	Department of Aeronautics and Space Engineering at University	Asst. Prof. Dr.	24.08.2023-25.08.2023	
E3	42	Male	PhD.	Department of Aeronautics and Space Engineering at University	Asst. Prof. Dr.	24.08.2023-25.08.2023	
E4	45	Male	PhD.	Department of Aeronautics and Space Engineering at University	Asst. Prof. Dr.	24.08.2023-25.08.2023	