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Space Mission Risk, Sustainability and Supply Chain: Review, Multi-Objective Optimization Model and Practical Approach

Bartosz Sawik [1,2,3]

[1] Department of Business Informatics and Engineering Management, AGH University of Science and Technology, 30-059 Krakow, Poland; bartosz_sawik@berkeley.edu
[2] Institute of Smart Cities, GILT-OR Group, Department of Statistics, Computer Science and Mathematics, Public University of Navarre, 31006 Pamplona, Spain
[3] Haas School of Business, University of California at Berkeley, Berkeley, CA 94720, USA

Abstract: This paper investigates the convergence of risk, sustainability, and supply chain in space missions, including a review of fundamental concepts, the introduction of a multi-objective conceptual optimization model, and the presentation of a practical approach. Risks associated with space missions include technical, human, launch, space environment, mission design, budgetary, and political risks. Sustainability considerations must be incorporated into mission planning and execution to ensure the long-term viability of space exploration. The study emphasizes the importance of considering environmental sustainability, resource use, ethical concerns, long-term planning, international collaboration, and public outreach in space missions. It emphasizes the significance of reducing negative environmental consequences, increasing resource use efficiency, and making responsible and ethical actions. The paper offers a multi-objective optimization conceptual model that may be used to evaluate and choose sustainable space mission tactics. This approach considers a variety of elements, including environmental effects, resource utilization, mission cost, and advantages for society. It provides a systematic decision-making approach that examines trade-offs between different criteria and identifies optimal conceptual model solutions that balance risk, sustainability, and supply chain objectives. A practical approach is also offered to demonstrate the use of the multi-criteria optimization conceptual model in a space mission scenario. The practical approach demonstrates how the model can aid in the development of mission strategies that minimize risks, maximize resource consumption, and fit with sustainability goals. Overall, this paper delivers a multi-criteria optimization conceptual model and provides a space mission planning practical approach, as well as an overview of the interaction between risk, sustainability, and supply chain in space mission organization, planning, and execution.

Keywords: space mission; risk; sustainability; supply chain; multi-objective optimization; environmental impact; ethical considerations

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1. Introduction

Space mission has always been an inherently dangerous activity, fraught with various hurdles and unknowns. Humanity has embarked on ambitious space missions in quest of knowledge, scientific discovery, and the exploration of our universe. However, as our space activities develop, it becomes increasingly important to handle the dangers associated with and assure the long-term viability of our space exploration endeavors. This paper dives into the crucial topics of risk, sustainability, and supply chain in space missions, providing a description of the review, multi-criteria conceptual optimization model, and practical approach.

The history of space missions dates back to the middle of the 20th century, when the Space Age was inaugurated by the Soviet Union's launch of Sputnik 1 in 1957. This momentous occasion made history by putting the first artificial object into orbit around the Earth and opening the door for later space exploration missions. Space missions have accomplished important milestones throughout history, such as the Apollo program's successful Moon landing in 1969. This significant accomplishment showed how willing we are as a species to investigate and push the limits of what we know about the universe. Heading to the decades to come, space missions hold immense promise for scientific discovery and exploration. Present attempts are centered on expeditions to Mars, particularly the Mars Rover missions, with the eventual objective of human colonization of the Red Planet. These missions aim to unearth potential evidence of life, investigate the planet's geology, and prepare for future human trips. The upcoming scope of space missions involves the discovery of other celestial bodies, such as the moons of Jupiter and Saturn, which are believed to possess conditions favorable for extraterrestrial life to exist. Missions such as the Europa Clipper and the projected Enceladus Life Finder seek to examine these moons and determine their possibility of being habitable. In addition to scientific discovery, space missions have grown into commercial enterprises, with private corporations such as SpaceX and Blue Origin playing key roles. These businesses are building reusable rocket systems, such as SpaceX's Starship, to permit frequent and attainable space travel, bringing up prospects for space tourism and the construction of commercial space settlements. In general, the historical background of space missions demonstrates great successes in space exploration, while the future scope offers even more fascinating discoveries and breakthroughs in our understanding of the universe.

Space exploration encompasses a wide range of risks that must be carefully managed to ensure the safety of astronauts and the success of the mission. Technical risks, such as rocket malfunctions, spacecraft failures, or equipment malfunctions, can have dire consequences on the mission's outcome. Human risks arise from the physiological and psychological effects of prolonged space travel, including muscle and bone loss [1], cardiovascular issues, and psychological stress [2]. Launch and reentry risks involve critical maneuvers that can encounter complications, potentially jeopardizing the mission. The space environment itself presents risks such as microgravity, extreme temperatures, radiation, micrometeoroids, and space debris. Mission design and planning risks encompass factors such as trajectory calculations, fuel requirements, navigation accuracy, and communication protocols. Budgetary and schedule risks add additional complexity, requiring careful financial planning and management to avoid cost overruns and schedule delays. Furthermore, space missions often involve international collaborations, leading to political risks arising from geopolitical tensions, disputes over intellectual property rights, or changes in national priorities.

While managing these risks is crucial, it is equally important to integrate sustainability principles into space missions. Environmental sustainability involves minimizing the negative impact on the space environment, such as avoiding contamination of celestial bodies with Earth-based microorganisms and reducing space debris through responsible satellite disposal practices. Resource utilization plays a significant role in sustainability, with the exploration and utilization of space resources offering potential solutions for life support, propulsion, and manufacturing. Ethical considerations in space missions involve respecting the cultural and scientific value of celestial bodies, as well as ensuring equitable participation and benefit-sharing among nations and individuals. Long-term planning emphasizes the need to make decisions that consider the consequences and impacts on future missions and generations. International cooperation facilitates responsible behavior, information sharing, and standardization of practices. Competition is gaining popularity as a potentially helpful kind of inter-organizational collaboration model for improving ventures' long-term success [3]. Lastly, public outreach and education are essential for fostering understanding, support, and engagement from society in sustainable space exploration practices.

To effectively address the complex relationship between risk, sustainability, and supply chain in space missions, a multi-criteria optimization model can provide a systematic framework for decision-making. This conceptual model considers a variety of criteria, including environmental impact, resource utilization, mission cost, and societal benefits, allowing decision-makers to evaluate trade-offs and identify optimal mission strategies that balance risk and sustainability objectives, in addition to the optimal supply chain for space mission organization and execution. Using such a model, space agencies can make intelligent choices that maximize the benefits of a space mission while minimizing their environmental footprint, efficiently handling risks, and optimizing the supply chain structure required for delivering needed components and resources for completing space mission-required (planned) tasks.

A practical approach is offered in this paper to demonstrate the actual implementation of the multi-criteria optimization conceptual model. The practical approach demonstrates how the model may be used to guide the design of a space mission, while having a focus on risk factors, sustainability concerns, and an efficient supply chain structure [4]. By examining a real-world scenario, we can gain valuable insights into the challenges, opportunities, and trade-offs involved in addressing risk, sustainability and supply chains in space missions.

The risks associated with space exploration span technical, human, launch, space environment, mission design, budgetary, and political dimensions.

Sustainability principles emphasize the need to minimize environmental impact, optimize resource utilization, consider ethical considerations, engage in long-term planning, encourage international cooperation, and promote public outreach and education.

The supply chain of required resources for components for space mission tasks involves a collection of dependable and resilient vendors who can deliver on time, with the requested quality and quantity.

As a result, the research flow is as follows: we begin by evaluating relevant articles to find possible overlaps with existing material. As a result, Section 2 comprises a survey of the literature, including the most essential references on the issue. This covers problem contextualization, approaches, and conclusions that may help to improve the position of this work paper. A summary of space mission risk is in Section 3. In Section 4 description of space mission sustainability is explained. The definition of the main aspects related to space mission planning is shown in Section 5. In Section 6 an explanation of the required materials and methods for space mission planning is provided. Section 7 discusses the main elements and optimization framework for the space mission supply chain. A multi-objective conceptual optimization model's definition and design with risk, sustainability, and supply chain for space mission is the following step, which can be shown within Section 8. A space mission practical approach with the use of a conceptual multi-objective optimization model is explained in Section 9. Finally, Sections 10–13 present the application and analysis of the proposed approach, an analysis of the key findings and outcomes, in addition to an explanation of boundaries, potential future study areas, and findings.

The presented work is needed at the time, because optimization technique in space mission planning is vital to maximize resource efficiency, enhance safety, accomplish scientific objectives, reduce mission durations, permit interplanetary exploration, and facilitate collaboration. As space missions become increasingly ambitious and diversified, optimization techniques serve a critical role in maximizing outcomes and advancing our understanding of the universe.

2. Literature

The quantity of publications about space mission risk, sustainability, and supply chain is quite minimal, but it is abundantly clear that there is a tremendous demand for exploring and presenting this topic as research publications. However, there have been no articles on multi-objective optimization models for space missions that take into account risk, sustainability, and supply chain.

A risk identification, assessment, mitigation, and continuous management method is used throughout the design of a space mission. Anything that can go wrong, as well as the likelihood and repercussions of that happening, is defined as risk. The indicators, causes, and repercussions of these hazards extend across multiple levels of people and processes involved in the design, as well as the actual design outcome itself [5].

A text mining-based strategy for improving space mission risk classification is offered. Every of the potential risk factors indicated is assigned a weight, and an overall class score for space missions is computed. The proposed method assists the designated panel of experts who are normally entrusted with assigning weights to the parameters. It enables the examination of parameters of varying relevance, as much as an amount of magnitude. The NASA Mars Perseverance expedition is used to prove the practical use of the categorization algorithm [6].

Making risk judgments is inevitably subjective, however, it ought to be founded based on objective evaluation. However, qualitative risk evaluation methodologies popular for subjective judgments are easily introduced into investigations in the aerospace industry. This method provides a quantitative risk assessment methodology that enables mission risk evaluations to be considered and compared by decision-makers [7].

The risk assessment approach described in the European Cooperation for Space Standardization (ECSS) safety risk assessment standard specifies how the standard is applied: its role in space programs, how it is made applicable, how it is to be used, and so on. The linkages to other ECSS standards, as well as the disciplines of safety and risk management, are also explained. While originally intended for space systems, safety, and risk analysts are encouraged to consider using the outlined approach for safety risk assessment in non-space applications [8].

Amounts of human-made objects in orbit are increasing, creating an imminent danger of cosmic sustainability. As a response, space agencies have developed a set of mitigation guidelines that allow space users to prevent the generation of space debris by, for example, limiting the orbital lifetime associated with their spaceship and rocket stages once their mission is over. Vast satellite constellations in low Earth orbit (LEO) may undermine the sustainability of the space environment enabled by these mitigation methods, despite addressing a shortage of basic internet service in some world locations. The response of the space item population to the creation of a large formation that adheres to a post-mission destruction protocol with different levels of accomplishment and disposal orbit options. [9].

Long-term science missions are envisaged in future space exploration visions, necessitating the necessity of supporting long-term expeditions. Resilience is an important characteristic of systems with sustainability that can be managed via autonomicity (enabling autonomic communications in a network), a growing paradigm for the independence of future computer-based systems motivated by mankind's nervous system's autonomy. Some investigations examine current research attempts to accomplish these targets of survivable systems as a whole with a focus on breakthroughs in the technology of Autonomic Policies [10].

Continuous trips to LEO, the Moon, and possibly Mars are expected in the upcoming phases of human spaceflight. The mission is vast in scope, including everything from scientific research to commercial exploitation. Such missions are aimed at profiting from in-situ resource utilization, which will reduce the amount of effort required for product delivery to mission areas, for instance, by providing water or fuel on the lunar or Martian ground. Environmentally friendly development and sustainability have grown and become increasingly relevant in many aspects of human existence and society. These phrases have even made their way into more specialized professions, such as spaceflight. For a thorough examination of the notions of sustainable development and sustainability as they have been expressed implicitly and explicitly in the context of spaceflight. Aspects that originate on Earth or in space and swap with the designated target between each of these are provided. The core concept is to provide a full assessment of mission scenarios and roadmaps in terms of their sustainability [11].

A hybrid optimization approach has been proposed involving a multiple criteria genetic algorithm with a calculus of variations-based low-thrust trajectory optimizer. For both Earth-Mars and Earth-Mercury missions, fronts of Pareto optimum trajectories are produced, and unique trajectories are identified. A Pareto genetic algorithm combined with a gradient-based algorithm yields an effective way for constructing sets of perfect interplanetary low-thrust itineraries. The approach is employed in two interplanetary missions: Earth-Mars connection and Earth-Mercury encounter. Families of ideal trajectories are generated in both circumstances, with family members linked by continuous Pareto fronts. Simple trajectories with a limited number of heliocentric revolutions get the best outcomes. Populations are distributed less equally throughout putative Pareto fronts as trajectory complexity increases [12].

There are several mobile applications available that provide information and enhance the experience related to space missions [13]. NASA App [14] is NASA's official app that provides the most up-to-date news, photos, videos, and mission information from numerous NASA missions. It also contains live NASA TV streaming, 3D spacecraft models, and satellite tracking. SpaceX GO [15] app, developed by SpaceX, gives real-time updates on SpaceX missions, such as launch schedules, mission details, and live video broadcasts. It also provides details on the Falcon 9 and Falcon Heavy rockets, the Dragon spacecraft, and the Starship program. ISS Tracker [16], with this app, it may monitor the International Space Station (ISS) in real-time. It shows the present location of the ISS, its course over your location, and impending passes. It can also get notifications for observable passes and see live video feeds from the International Space Station. SkyView [17] is an augmented reality—the internet's virtual telescope—that allows to identify stars, constellations, and satellites in the night sky. It is not specialized for space missions. It can track the International Space Station (ISS) and other satellites, view their movements, and receive notifications when they are visible. exoplanet: Exoplanet [18] is a planet discovery and exploration program that focuses on worlds beyond our solar system. It contains information about known exoplanets, their properties, and the most recent discoveries. It is also capable of seeing 3D models of exoplanetary systems. Mars Images app [19] delivers the most recent photographs and data from Mars missions such as the Curiosity rover and the Mars Reconnaissance Orbiter. It can look at high-resolution photographs, receive mission updates, and learn about the geology and characteristics of Mars. Solar System Scope [20] is a 3D interactive representation of the solar system that allows users to explore planets, moons, asteroids, and spacecraft. It displays the positions of celestial objects in real-time, as well as detailed information and simulations of numerous space missions. Many mobile applications are available that cover various aspects of space missions and exploration [21].

3. Risks in the Space Mission

Space missions involve a variety of risks due to the complex and challenging nature of space exploration. These risks can be broadly categorized into several types:

Technical Risks: Space missions require advanced technology and complex systems, which can be prone to failures. Technical risks include issues such as rocket malfunctions, spacecraft failures, communication system breakdowns, propulsion problems, or equipment malfunctions. These risks can jeopardize the success of a mission or even endanger the lives of astronauts [22].

Human Risks: Human risks are associated with the well-being and safety of astronauts. Extended exposure to microgravity, radiation, and isolation in space can have significant physiological and psychological effects on the human body [23,24] and conditions during space missions, due to gravity level are very similar to aquatic environments [25]. Space travelers may suffer from muscle and bone loss [1], cardiovascular problems, compromised immune systems, and psychological stress [2]. These risks need to be mitigated through rigorous training, monitoring, and appropriate medical support [26].

Launch and Reentry Risks: Launching a spacecraft into space and bringing it back safely involve critical maneuvers. Risks during launch include engine failures, structural integrity issues, or control system malfunctions. Reentry risks include heat shield failures, atmospheric uncertainties, and parachute problems. These stages of a mission require meticulous planning, engineering, and redundancy to minimize the risks associated with extreme conditions [27].

Space Environment Risks: Space is a hostile environment with several inherent risks. The presence of microgravity, vacuum, extreme temperatures, solar radiation, micrometeoroids, and space debris pose significant challenges. Spacecraft and astronauts must be protected from these risks through shielding, insulation, radiation-hardened electronics, and debris avoidance measures [28,29].

Mission Design and Planning Risks: Mission design and planning involve numerous decisions and factors that can introduce risks. These include trajectory calculations, fuel requirements, navigation accuracy, timing considerations, and communication protocols. Errors in these areas can result in mission failures, missed objectives, or inefficient resource utilization [30].

Network and Cybersecurity Risks: To mitigate these risks, it is essential to follow best practices in secure system design, conduct thorough risk assessments, implement robust authentication and encryption mechanisms, regularly update software and firmware with proper security protocols, and establish incident response plans to address any network or cybersecurity incidents promptly [31–34]. Additionally, promoting cybersecurity awareness among mission personnel and stakeholders can contribute to a more secure space mission environment (see Section 3.1).

Budgetary and Schedule Risks: Space missions are often large-scale endeavors with substantial financial investments and strict schedules. Budgetary risks involve cost overruns, funding shortfalls, or unexpected expenses. Schedule risks include delays in manufacturing, launch vehicle availability, technical setbacks, or adverse weather conditions. These risks can impact the overall feasibility and success of a mission [35].

International and Political Risks: Space missions often involve international collaborations and partnerships. Political risks can arise due to geopolitical tensions, changes in national priorities, or disputes over intellectual property rights. Coordinating different countries' interests and managing diplomatic relationships is crucial to ensuring smooth collaborations [36–39].

In Table 1, considered risks in the space mission are presented.

Table 1. Risks in the space mission.

Risk	Factor
Technical Risks	Reliability of spacecraft systems and components.
Human Risks	Physical and psychological health of astronauts.
Launch and Reentry Risks	Reliability and performance of launch vehicle or spacecraft.
Space Environment Risks	Exposure to radiation, micrometeoroids, and extreme temperatures.
Mission Design and Planning Risks	Adequacy of mission requirements, systems architecture, and operational procedures.
Network and Cybersecurity Risks	Vulnerability of space mission systems to cyber threats.
Budgetary and Schedule Risks	Effective management of project resources and adherence to established timelines.
International and Political Risks	Geopolitical tensions, policy changes, and international conflicts.

To address these risks, space agencies employ robust engineering practices, stringent safety protocols, extensive testing, comprehensive training programs, and continuous monitoring and risk assessment throughout the mission lifecycle. Risk mitigation strategies include redundancy in critical systems, contingency plans, thorough pre-launch testing, astronaut health monitoring, and regular updates to mission protocols based on lessons learned from previous missions.

3.1. Network and Cybersecurity Risks in Space Missions

Network and cybersecurity risks in space missions are crucial to address, as they can have significant consequences on the operation and safety of the mission. Several main factors contribute to these risks [31–34]:

- Satellite Vulnerabilities: Satellites are exposed to various vulnerabilities due to their complex systems, which include software, firmware, and hardware components. Weaknesses in any of these areas can be exploited by hackers or malicious actors to gain unauthorized access, disrupt communications, or take control of the satellite.
- Communication Security: Space missions rely on communication links between ground stations, satellites, and spacecraft. These communication channels are susceptible to interception, eavesdropping, or jamming, which can compromise the confidentiality, integrity, and availability of the transmitted data. Ensuring secure and encrypted communication is crucial to mitigate these risks.
- Spacecraft Operations: Spacecraft are vulnerable to cyber threats throughout their operational lifecycle. This includes the pre-launch phase, where attackers may target ground-based systems, such as mission control centers or satellite assembly facilities, to compromise the spacecraft's security. During the mission, potential risks include unauthorized access to onboard systems, alteration of commands, or interference with critical functions.
- Supply Chain Security: Space missions involve a complex supply chain with a wide range of suppliers. Each entity within the supply chain introduces potential vulnerabilities, making it essential to ensure the security of the components, software, and services used in space systems. Any compromise in the supply chain can lead to backdoors, malware, or other vulnerabilities being introduced into the mission-critical systems.
- Space Traffic Management: The increasing number of satellites and space objects in orbit raises concerns about space traffic management and collision avoidance. Cybersecurity risks come into play when it comes to coordinating and managing the communication and data exchange between different satellites, ground-based control systems, and space traffic control centers. Unauthorized access to these systems or tampering with the data could lead to collisions or other hazardous situations.
- Mission Data Protection: Space missions generate vast amounts of sensitive data, including scientific data, proprietary information, and operational details. Safeguarding this data from unauthorized access, theft, or tampering is crucial. Encryption, access controls, secure data storage, and robust authentication mechanisms are essential to protect mission data from cyber threats.
- Ground Systems Security: Ground-based systems, including mission control centers, ground stations, and data processing facilities, are critical components of space missions. These systems are vulnerable to various cyber threats, such as malware infections, insider attacks, or social engineering attacks targeting the personnel responsible for operating the systems. Implementing robust security measures, conducting regular audits, and training personnel on cybersecurity best practices are necessary to protect ground systems.

Addressing these main factors requires a comprehensive and layered approach to network and cybersecurity in space missions. It involves incorporating secure design principles, employing encryption and authentication mechanisms, conducting regular risk assessments, implementing intrusion detection and prevention systems, and establishing robust incident response plans to mitigate the impact of potential cyber-attacks.

Network and cybersecurity risks during the planning and conducting of space missions encompass a range of challenges that need to be addressed to ensure the success and security of the mission. Here are some key risks specific to this phase:

- Mission Planning Stage Risks: During the mission planning stage, various network and cybersecurity risks can arise, including [31–34]:
    - Data Leakage: Sensitive mission details, including launch schedules, spacecraft capabilities, or orbital parameters, can be targeted by adversaries seeking to gain a competitive advantage or disrupt the mission.
    - Insider Threats: Personnel involved in the mission planning process may pose a risk if they intentionally or inadvertently disclose confidential information or introduce vulnerabilities in the mission's design or infrastructure.
    - Interference with Communication: Adversaries may attempt to interfere with the communication channels used for mission planning, such as disrupting or jamming radio signals or compromising data transmission.
- Launch and Initialization Risks: Network and cybersecurity risks continue during the launch and initialization phase of a space mission. Some specific risks include:
    - Physical Security: During the launch and initialization process, physical access to mission-critical systems and infrastructure must be tightly controlled to prevent unauthorized tampering or sabotage.
    - Supply Chain Attacks: Malicious actors may attempt to compromise the mission by introducing compromised or counterfeit components during the manufacturing, integration, or transportation process.
    - Firmware and Software Vulnerabilities: The firmware and software used in launch vehicles, spacecraft, and ground-based systems may contain vulnerabilities that can be exploited to compromise the mission's integrity or disrupt its operations.
- Ground Station and Communication Risks: Ground stations play a vital role in space missions by establishing communication links with spacecraft and transmitting mission data. Risks associated with ground stations and communication include:
    - Unauthorized Access: Attackers may attempt to gain unauthorized access to ground station facilities or equipment, compromising the security and integrity of mission-critical data.
    - Interception and Eavesdropping: Sensitive mission data transmitted between ground stations and spacecraft may be intercepted or eavesdropped upon, leading to the exposure of confidential information.
    - Data Integrity: Adversaries could manipulate or tamper with mission data during transmission, potentially leading to incorrect decisions or compromised mission objectives.
- Satellite Operations and Control Risks: Once the space mission is underway, risks related to satellite operations and control come into play. These risks include:
    - Command and Control Attacks: Adversaries may attempt to gain unauthorized access to satellite control systems, enabling them to manipulate the spacecraft's operations, alter its trajectory, or disable critical functions.
    - Software and Firmware Updates: Deploying software patches or firmware updates to satellite systems during the mission carries a risk of introducing vulnerabilities or disruptions if not performed securely and rigorously.
    - Spacecraft Anomalies: Network and cybersecurity risks can also manifest in the form of anomalies or malfunctions in spacecraft systems, which may be caused by cyber-attacks or inadvertent errors in software or firmware updates.

To mitigate these risks, it is essential to follow best practices in secure system design, conduct thorough risk assessments, implement robust authentication and encryption mechanisms, regularly update software and firmware with proper security protocols, and establish incident response plans to address any network or cybersecurity incidents promptly. Additionally, promoting cybersecurity awareness among mission personnel and stakeholders can contribute to a more secure space mission environment [31–34].

4. Sustainability Aspects of the Space Mission

Sustainability in space missions refers to the practice of conducting space exploration and activities in a manner that preserves and protects the long-term viability [40,41] of space resources, the space environment, and future space missions [42]. It involves considering the environmental, social, and economic impacts of space exploration and striving for responsible and ethical practices.

Environmental Sustainability: Environmental sustainability in space missions focuses on minimizing the negative impact on the space environment. This includes avoiding contamination of celestial bodies with Earth-based microorganisms to protect potential life and future scientific exploration. It also involves reducing space debris through responsible satellite disposal practices and designing spacecraft and satellites for longevity and recyclability [43,44].

Resource Utilization: Sustainable space missions aim to maximize resource utilization efficiency. This includes exploring and utilizing space resources, such as water ice on the Moon or asteroids, for life support, propulsion, or manufacturing purposes. By utilizing local resources, space missions can reduce the need for Earth-based supplies and minimize the environmental impact of resource extraction [45].

Ethical Considerations: Sustainability in space missions encompasses ethical considerations and responsible decision-making. This involves respecting the cultural, historical, and scientific value of celestial bodies and avoiding actions that could harm or compromise their integrity. It also includes considerations of equity and inclusivity in space exploration, ensuring that different nations, organizations, and individuals have fair opportunities to participate and benefit from space activities [46].

Long-Term Planning: Sustainable space missions require long-term planning and strategic thinking. This involves considering the potential consequences and impacts of current space activities on future missions and generations. It includes designing missions with the ability to adapt and evolve over time, allowing for long-duration space exploration, and developing technologies that can be upgraded or repurposed to reduce waste and increase efficiency [47].

International Cooperation: multinational partnership and collaboration enhance space mission sustainability. Important preconditions for sustainability-driven cooperation in space mission supply chains: the presence of economic benefits from sustainability initiatives. The potential synergy of competitors' space mission supply chain operations. The beneficial facilitative role of third-party organizations. Overcoming the cultural and psychological difficulties that come with working with competitors. Being able to work efficiently within the confines of anti-trust rules. Creating performance management scales and constantly evaluating the relationship. Being able to balance short-term and long-term gains and transform collaboration into a strategic competency [3]. By promoting information sharing, standardization of practices, and responsible behavior, nations and space agencies can work together to create guidelines and protocols that ensure permanent space exploration sustainability. This includes cooperation in the handling of aerospace transit, and debris mitigation, in addition to the development of best practices for sustainable exploration [3,48–50].

Education and Public Outreach: Sustainability in space missions also involves education and public outreach efforts to raise awareness and foster a sense of responsibility among the public. By promoting scientific literacy and engagement, as well as communicating the benefits and challenges of space exploration, society can participate in shaping sustainable practices and support missions that align with ethical and responsible principles [51,52].

In Table 2, considered sustainability in the space mission is presented.

Table 2. Sustainability in the space mission.

Sustainability	Factor
Environmental Sustainability	Conservation of natural resources, minimization of waste generation, and reduction of environmental impact.
Resource Utilization	Efficient and responsible use of resources, including water, energy, and materials, to maximize mission effectiveness and minimize waste.
Ethical Considerations	Ensuring adherence to ethical standards in space missions, including considerations for human rights, equity, and social responsibility.
Long-Term Planning	Incorporating long-term perspectives in mission planning, including sustainability of infrastructure, operations, and exploration efforts over extended periods.
International Cooperation	Important preconditions for sustainability-driven international cooperation in space mission supply chains: the presence of economic benefits from sustainability initiatives. The potential synergy of competitors' space mission supply chain operations. The beneficial facilitative role of third-party organizations. Overcoming the cultural and psychological difficulties that come with working with competitors. Being able to work efficiently within the confines of anti-trust rules. Creating performance management scales and constantly evaluating the relationship. Being able to balance short-term and long-term gains and transform collaboration into a strategic competency. Promoting collaboration and cooperation among nations and space agencies to share resources, knowledge, and expertise for mutual benefit and advancement of space exploration.
Education and Public Outreach	Engaging the public and promoting awareness and understanding of space missions, their goals, and their impacts to foster support, enthusiasm, and participation in sustainable space exploration.

By integrating sustainability principles into space missions, we can ensure that space exploration continues to advance our understanding of the universe while minimizing environmental impact, promoting long-term resource utilization, and fostering international cooperation and ethical practices.

5. Definition of Main Aspects Related to Space Mission Planning

Risk management in space mission: Risk management in space mission refers to the process of identifying, analyzing, and mitigating potential risks and uncertainties associated with space exploration. It involves assessing and understanding the various risks involved in a mission, such as technical failures, human errors, environmental hazards, and financial constraints. The goal of risk management is to minimize the likelihood and impact of risks, ensuring the safety of crew members, spacecraft, and mission objectives [53–55].

Sustainable space exploration: Sustainable space exploration refers to the practice of conducting space missions in a manner that balances social, economic, and environmental considerations over the long term. It entails reducing the harmful effects of space activities on Earth and in space, as well as improving resource usage, energy efficiency, and waste management. Sustainable space exploration aims to ensure that our exploration and utilization of space resources are conducted responsibly and do not compromise future space missions or harm the environment [56,57].

Space mission sustainability: Space mission sustainability refers to the ability of a space mission to continue and achieve its objectives over an extended period while considering environmental, economic, and technological constraints. It involves designing and operating space missions in a way that maximizes their longevity, efficiency, and effectiveness. This includes managing resources, reducing waste, adopting sustainable technologies, and implementing strategies for long-term mission success [58].

Environmental impact of space mission: The environmental impact of space mission refers to the effects and consequences of space activities on the Earth's environment and outer space. Space missions can have various environmental impacts, including the release of pollutants and emissions during launches, the creation of space debris, and the potential contamination of celestial bodies with biological or chemical substances. Understanding and mitigating these impacts is crucial for ensuring sustainable space exploration and minimizing harm to both Earth and space environments [59].

Space mission planning and risk assessment: Space mission planning and risk assessment involve the systematic process of developing mission objectives, defining mission requirements, and evaluating potential risks and uncertainties. It includes identifying and analyzing risks related to mission design, technology development, operations, and safety. By conducting comprehensive risk assessments, mission planners can make informed decisions, develop contingency plans, and allocate resources effectively to ensure mission success and minimize potential hazards [60,61].

Space mission safety and risk analysis: Space mission safety and risk analysis involve evaluating and managing the safety aspects and risks associated with space missions. It includes assessing potential hazards, such as launch failures, onboard emergencies, radiation exposure, and crew health risks. Risk analysis involves quantifying and prioritizing risks, identifying potential mitigation measures, and developing safety protocols and procedures. The objective is to protect the well-being of astronauts, ensure mission success, and prevent accidents or critical failures during space missions [62].

6. Required Materials and Methods for Space Mission Planning

In this section, we present the explanation of required materials and methods for space mission planning. Space mission planning requires careful consideration of various materials and methods to ensure successful execution. The following is a description of some of the key components involved in the planning process:

Mission Objectives and Requirements: Defining clear mission objectives and requirements is the foundation of space mission planning. This includes identifying scientific goals, exploration targets, payload requirements, and mission duration. These objectives serve as a guide for all subsequent planning activities [63].

Systems Engineering: Systems engineering is a crucial methodology used in space mission planning. It involves the systematic identification, analysis, and integration of various subsystems and components to ensure the mission's overall success. Systems engineering techniques help in defining system architectures, interfaces, and functional requirements [64].

Payload and Instrumentation: Space missions often carry scientific instruments or payloads designed to collect data or perform experiments. The selection and integration of these payloads into the spacecraft require careful planning. This includes defining payload requirements, ensuring compatibility with the spacecraft's resources and interfaces, and considering power, data, and communication requirements [65].

Launch Vehicle Selection: Choosing the appropriate launch vehicle is essential for space mission planning. Factors such as payload mass, volume, trajectory requirements, and launch availability need to be considered. Launch vehicle selection impacts the mission's cost, schedule, and overall feasibility [66].

Mission Design and Trajectory: Mission design involves determining the spacecraft's trajectory, including the launch phase, cruise phase, and arrival at the destination. This includes trajectory optimization to minimize fuel consumption, achieve desired orbital parameters, and enable necessary maneuvers during the mission [67].

Spacecraft Design and Manufacturing: The design and manufacturing of the spacecraft involve various disciplines, including mechanical, electrical, and thermal engineering. Materials selection, structural analysis, thermal control systems, and power management are crucial considerations. Manufacturing processes must adhere to strict quality control standards to ensure the spacecraft's reliability and robustness [68].

Ground Systems and Operations: Ground systems and operations encompass the infrastructure, facilities, and procedures necessary to support the space mission. This includes mission control centers, communication networks, tracking stations, and data processing systems. Ground systems also involve planning and executing mission operations, monitoring spacecraft health, and coordinating data collection [69].

Risk Management: Risk management is an integral part of space mission planning. It involves identifying potential risks, assessing their impact and likelihood, and developing strategies to mitigate or manage them. Risk analysis techniques [70], contingency planning, and reliability assessments are employed to minimize the likelihood of mission failure [71].

Budgeting and Resource Allocation: Effective budgeting and resource allocation are essential for space mission planning. This includes estimating the cost of spacecraft development, launch services, ground operations, and data analysis. Financial planning and resource management ensure the mission remains within budgetary constraints and maximizes the utilization of available resources [72,73].

Regulatory and Legal Considerations: Space mission planning requires compliance with national and international regulations, treaties, and guidelines. This includes obtaining necessary licenses, permits, and approvals. Legal considerations also encompass intellectual property rights, liability issues, and adherence to space debris mitigation guidelines [74].

Collaboration and International Cooperation: Many space missions involve collaboration and international cooperation. Potential opportunistic behavior during international space mission partnership. The existence of these kinds of actions must be neutralized by incorporating game theory [75], which may bring light on the root causes and characteristics of potential opportunism in space mission international cooperation, thereby assisting in understanding the best strategic decisions to maximize gains by creating win-win circumstances [3]. Establishing partnerships with other space agencies, institutions, or industry stakeholders can enhance mission capabilities, share resources, and distribute costs. Cooperation also fosters knowledge exchange and scientific advancements [76].

In summary, space mission planning requires the integration of various materials and methods. From defining mission objectives to considering launch vehicles, payload selection, trajectory optimization, spacecraft design, ground systems, risk management, budgeting, and legal considerations, each component plays a critical role in ensuring a successful and well-executed space mission.

7. Optimization of the Space Mission Supply Chain

The optimization of the space mission supply chain is critical to ensure the efficient and continuous flow of resources and equipment needed for space exploration. Space agencies can reduce costs and optimize resource utilization by utilizing advanced logistics and supply chain management strategies such as demand forecasting, inventory optimization, and efficient transportation [77–79].

The optimization process begins with precise demand forecasting, which entails assessing historical data based on simulation and taking into account elements such as mission objectives, payload requirements, and personnel requirements [80,81]. This aids in the determination of the quantity and types of items to be conveyed. Inventory optimization is critical in managing basic products such as spamission-requiredred resources, among them food, water, fuel, replacement parts, and scientific equipment. The risk of shortages or excesses can be reduced by maintaining adequate inventory levels, resulting in cost savings and increased mission efficiency [82,83].

Efficient transportation routes [84,85] are essential for the timely and dependable delivery of materials to the launch site and, ultimately, space.

Collaboration and coordination among many stakeholders, including space agencies, suppliers, contractors, and mission control centers, are critical for optimizing the space mission supply chain. Previous research has not established a clear substantive theory or empirical evidence for the process of sustainability-driven space mission international collaboration. It is critical to investigate how competing space agencies and supply chain corporations might collaborate in their space mission supply chains to attain a higher degree of sustainable performance by identifying coopetition drivers, facilitators, and barriers [3]. Effective communication and information sharing ensure that everyone is on the same page and working toward the same objective. The continuous monitoring, evaluation, and improvement of the space mission supply chain are critical components of improving it [86,87]. Space agencies can improve the overall efficiency and efficacy of future missions by monitoring performance metrics, finding bottlenecks, and implementing remedial actions [88,89].

8. Multi-Objective Conceptual Model for Optimizing Risk, Sustainability and Supply Chain of Space Mission

The mathematical programming conceptual model [90,91] is designed to support the planning, organization and optimization of space missions, as well as taking into consideration risks and sustainability factors, and moreover supply chain efficiency. Possible optimization criteria can consider the following aspects of a space mission:

- Minimization of stress levels related with space mission preparation.
- Minimization of risk factors related with space missions.
- Minimization of costs of space missions.
- Minimization of time required for space mission preparation.
- Minimization of time required for space mission tasks.
- Maximization of efficiency of resource allocations.
- Maximization of resource utilization.
- Maximization of sustainability of space missions.
- Maximization of the safety level of space mission accomplishment.
- Maximization of supply chain efficiency.
- Maximization of a set of resilient suppliers.
- Minimization of disruptions in the supply chain.
- Minimization of space mission components vs. Maximization of space mission tasks.

Multi-Objective Optimization Model with Risk, Sustainability, and Supply Chain for Space Mission (SMORS)

Selected the following three conceptual optimization criteria (f_i, for $i = 1 \ldots n$, there $n = 2$) in the multi(triple)-criteria weighted-sum approach optimization model: the maximization of sustainability factors in the space mission, the minimization of the level of risk of factors considered with space mission, and the maximization of supply chain efficiency.

The non-dominated solution set of the multi-objective mathematical programming model [92] can only be gained in part by the parametrization on λ of the weighted-sum program [93]:

Model M_λ
Maximization or minimization of $\sum_{k=1}^{m} \sum_{i=1}^{n} \lambda_k f_i$

where it is subject to some specific model constraints, where $0 \leq \lambda_k \leq 1$, $\forall\, k = 1 \ldots m$; $\lambda_1 > \lambda_2 > \mathrm{I} > \lambda_\mathrm{m}$; $\lambda_1 + \lambda_2 + \mathrm{I} + \lambda_\mathrm{m} = 1$; where f_i is defined as criterion (objective) f in a multi-objective function for a number of criteria from $i = 1$ to $i = n$, and where in the SMORS model n = 3.

It is generally known, however, that even if the entire parametrization on λ is tried, the non-dominated solution set of a multi-objective mathematical problem such as this cannot be fully ascertained (e.g., [94]). To find unsupported non-dominated solutions, some upper bounds on the objective functions should be added (e.g., [95]).

This integer (binary) programming optimization conceptual model can be defined over the same set of nodes $i \in I$, $j \in J$, and $l \in L$ representing, respectively, the risk, sustainability, and supply chain factors of space mission organization. Thus, the optimization model searches for the optimal assignment of considered resources allocation, with the objective of maximizing the total sustainability of mission versus the minimization of risks estimated for space mission success rate, and versus maximization of supply chain efficiency. The model decision variable, model parameters, and model criteria are described in detail in Tables 3–5, respectively.

Table 3. Model decision variables.

Decision Variable	Description
xij	1 if space mission component $j \in J$ is assigned to space mission task $i \in I$, 0 otherwise
yi	1 if space mission task is considered $i \in I$, 0 otherwise
zj	1 if space mission component is considered $j \in J$, 0 otherwise

Table 4. Model parameters.

Parameter	Description
λ_k	Weight for criterion $k \in K$ in the multi-objective function
a_{ij}	Level of sustainability of component $j \in J$ utilization, while fulfilling space mission task $i \in I$
b_{ij}	Level of risk of malfunction of component $j \in J$, while fulfilling space mission task $i \in I$
c_{il}	Level of fulfillment of resource $l \in L$ from supply chain, required to fulfill space mission task $i \in I$
Y	Number of required space mission tasks
Z	Number of required space mission components

Table 5. Sustainability, risk, and supply chain criteria included in the multi-objective function.

Criterion	Description
$\sum_{i \in I} \sum_{j \in J} a_{ij} x_{ij}$	Risk Factors of Space Mission Resources Assignment
$\sum_{i \in I} \sum_{j \in J} b_{ij} x_{ij}$	Sustainability Factors of Space Mission Resources Assignment
$\sum_{i \in I} \sum_{l \in L} c_{il} x_{ij}$	Supply Chain Efficiency of Space Mission Resources Assignment

Presented in Table 5, set of criteria, to be considered in multi-objective conceptual optimization model have been chosen based on best representation of space mission planning and for optimizing risk, sustainability and supply chain of space mission, however at the beginning of Section 8, there is a list of potential objectives, which might be considered in a multi-criteria optimization model for space mission, planning, organization, support and optimization. All those criteria are related to risk, sustainability and supply chain of space missions. The decision maker has to decide which criteria, should be included in multi-objective function of the optimization model, based on decision maker preferences and space mission type.

Afterward, the mathematical programming model (SMORS) is defined as the following, with the multi-objective function (Equation (1)), which has the following mathematical formulation:

Minimize

$$\lambda_1 \sum_{i\in I} \sum_{j\in J} a_{ij}x_{ij} - \lambda_2 \sum_{i\in I} \sum_{j\in J} b_{ij}x_{ij} - \lambda_3 \sum_{i\in I} \sum_{l\in L} c_{il}y_i \tag{1}$$

subject to

$$\sum_{i\in I} x_{ij} = z_j,\ \forall j \in J \tag{2}$$

$$\sum_{j\in J} x_{ij} = y_i,\ \forall i \in I \tag{3}$$

$$\sum_{i\in I} y_i = Y \tag{4}$$

$$\sum_{j\in J} z_j = Z \tag{5}$$

$$x_{ij} \in \{0,1\}, \forall i \in I,\ \forall j \in J \tag{6}$$

$$y_i \in \{0,1\}, \forall i \in I \tag{7}$$

$$z_j \in \{0,1\}, \forall j \in J \tag{8}$$

The multi-objective model (SMORS) is expressed in Equation (1), compounded by the criteria described in Table 3, making Equation (2) to Equation (8) define the constraints:

1. Equation (1) describes multi-criteria (triple-objective) function, where efficiency of component/tasks assignment, risks factors of space mission are minimized while, sustainability factors of space mission are maximized, and supply chain efficiency (fulfillment of resources required for space mission tasks) are maximized.
2. Equations (2) and (3) describe the condition of the assignment considered for space mission required components and tasks.
3. Equation (4) describes the fulfillment of required number of space mission tasks.
4. Equation (5) describes the fulfillment of required number of space mission components.
5. Equations (6)–(8) describe the variable ranges.

Computational experiments with the use of only experimental data were performed using the AMPL programming language and the Gurobi 9.0.2 solver on a MacBookAir laptop with Dual-Core Intel Core i7 processor running at 1.7 GHz and with 8 GB RAM. The size of the integer (binary) program for the example problem was relatively small. The set of non-dominated optimal solutions was obtained within seconds. Due to the lack of access to real data for computations, the above mathematical programming multi-objective optimization model (SMORS) was verified with the use of experimental data. The size of the experimental data set was the following: it takes into account 10,000 sustainability and risk factors with 10,000 space mission components to 10,000 space mission tasks and 1000 suppliers in the space mission supply chain. The author names this model conceptual. For this reason of experimental data use only, even the proposed set of mathematical equations gives promising solutions. This part of the research is going to be continued in the future as the next stage of this project.

Based on the best knowledge of the author and after a careful check of published research papers [96], this proposed multi-objective optimization model SMORS is one of only a few proposed multi-objective optimization models [97] in the area of space mission risk, sustainability and supply chain.

9. Practical Approach

In this section a practical approach for the application of the multi-objective optimization conceptual model in a real-world space mission scenario is presented. In this practical approach, we explore the practical application of the multi-criteria optimization model in a real-world space mission scenario. The purpose is to demonstrate how this model can assist in designing mission strategies that minimize risks, optimize resource utilization and optimize supply chain efficiency, and align with sustainability goals. By examining the decision-making process [98] and trade-offs involved, we can gain insights into how the model can guide the design of space missions that balance various criteria effectively.

A real-life practical approach from NASA [99] and other space agencies [100] can be better organized and improved with the use of the approach and methodology proposed in this paper. Here are some examples of cases and relations between organization of space missions with relation to presented research.

One example of real space mission planning is VERITAS, NASA's Venus exploration mission [99,101]. This mission is going to be delayed; one of the reasons is inefficient space mission supply chain, not considering the risk and sustainability factors that appeared recently, and have not been taken into account at the beginning of mission planning.

Another example is the planning of space farming during a space mission. If future astronauts are to survive voyages far from Earth, they will need to develop their own plants in artificial environments [99,101]. This is an excellent illustration of the critical importance of considering and optimizing risk, sustainability, and the supply chain in order to provide the necessary resources for astronauts at the start and throughout the space mission in order to enable the development of a space farm.

The third example is related to the tools and machinery required to successfully conduct space missions. A Rolls-Royce engine is required on the Moon. Humanity may be able to return to the moon by the 2030s, thanks to a British vehicle business aiming for the surface [98,101]. Coordination of the space mission supply chain, taking into account risk and sustainability concerns, is critical to overcoming all hurdles and organizing a successful mission. Tools and machinery are required for space travel and for constructing the space village, which would be made up of inflated pods covered by hard outer shells and housing living rooms, workstations, and life-support systems. To make the town self-sufficient, water and oxygen would be taken from permanently shaded craters, and lunar regolith would be used as a fundamental building material as well as for crop cultivation [98,101].

In terms of space mission planning and organization, a new factor to consider is blockchain technology for future space missions. Although blockchain technology was first focused on cryptocurrencies and financial assets, there is great potential for its application across a wide range of industries, including space mission supply chain management, intellectual property rights, healthcare, and voting systems [102].

Following the presentation of some practical examples and a practical approach for the implementation of the multi-objective optimization conceptual model in a real-world space mission situation, we are going to provide more formal steps to conducting the proposed approach.

Practical approach Scenario: Let us consider a hypothetical space mission [103] aimed at establishing a research facility on another celestial body such as the Moon, Mars, or Mercury. The objective of this mission is to conduct scientific experiments, gather data, and pave the way for future human exploration. However, the mission faces various challenges and risks that need to be addressed, including technical, human, environmental, and budgetary factors.

Step 1: Determine the Criteria and Stakeholders: To apply the multi-criteria optimization model [104], we first identify the key criteria to be considered. These criteria are based on the goals of the mission, sustainability principles, and stakeholder requirements. In this case, the identified criteria include environmental impact, resource utilization, astronaut safety, scientific objectives, mission cost, international collaboration, and supply chain structure.

Step 2: Establishing Weights and Limits: Once the criteria are identified, we assign weights to them based on their relative importance. For example, environmental impact and astronaut safety might have higher weights due to their criticality in ensuring long-term sustainability and protecting human life [105–107]. Constraints are also established to reflect specific limitations or guidelines, such as regulatory requirements or technological feasibility.

Step 3: Develop Mission Scenarios: The multi-criteria optimization model allows for the generation of multiple mission scenarios by varying parameters, approaches, and trade-offs. These scenarios represent different combinations of mission design elements, such as propulsion systems, power generation methods, habitat structures, resource utilization strategies, and mission durations. Each scenario is evaluated based on the defined criteria, considering the weights and constraints assigned in Step 2.

Step 4: Consider Scenarios and Trade-Offs: Using the multi-criteria optimization model, the generated mission scenarios are evaluated against the defined criteria. This evaluation involves assessing the performance of each scenario in terms of the identified criteria, taking into account the assigned weights and constraints. Trade-offs between criteria are analyzed, as optimizing one criterion may lead to compromises in others.

Step 5: Identifying and Implementing Suboptimal Solutions in Practice: By analyzing the results of the evaluations, sub-optimal solutions that best align with the defined criteria and stakeholder requirements can be identified. These solutions represent mission strategies that strike a balance between minimizing risks, optimizing resource utilization, meeting sustainability goals, and optimizing supply chain efficiency. The sub-optimal solutions offer insights into the design choices and trade-offs necessary to achieve mission success while considering various factors.

Step 6: Analysis and Refinement of Sensitivity: After identifying the optimal solutions, sensitivity analysis can be conducted to assess the robustness of the results. Sensitivity analysis helps understand the impact of changes in criteria weights, constraints, or underlying assumptions on the optimal solutions. This analysis allows for the refinement of the model and the mission strategies, ensuring a comprehensive understanding of the implications of different scenarios.

In Table 6, the main steps of a space mission are defined.

Table 6. Space mission steps.

Step 1: Determine the Criteria and Stakeholders
Step 2: Establishing Weights and Limits
Step 3: Develop Mission Scenarios
Step 4: Consider Scenarios and Trade-Offs
Step 5: Identifying and Implementing Suboptimal Solutions in Practice
Step 6: Analysis and Refinement of Sensitivity

The application of the multi-objective optimization conceptual model in this practical approach yields valuable insights and design strategies for the space mission. The evaluation of the mission scenarios against the defined criteria provides a comprehensive understanding of the trade-offs involved. The model identifies mission strategies that balance risks, resource utilization, sustainability goals effectively, and supply chain efficient structure.

For example, the evaluation may reveal that utilizing local resources, such as water ice on the Moon, for life support and propellant production significantly reduces the mission's reliance on Earth-based supplies. This approach minimizes environmental impact, optimizes resource utilization, and reduces mission costs. Additionally, the model may suggest the use of advanced propulsion technologies to minimize the mission's carbon footprint and mitigate the potential for space debris creation during the mission. The model can also assist in evaluating and addressing astronaut safety concerns. It may recommend advanced radiation shielding techniques or mission durations that minimize exposure to radiation and reduce health risks. By considering astronaut safety as a critical criterion, the model guides the mission design toward mitigating potential hazards and ensuring the well-being of the crew. Furthermore, the model's analysis highlights the importance of international collaboration in achieving mission goals and sustainability objectives. It may reveal opportunities for joint missions, shared infrastructure, or data-sharing agreements, which not only enhance scientific outcomes but also foster cooperation and resource optimization among space agencies. Through sensitivity analysis, the robustness of the optimal solutions can be assessed. This analysis helps identify potential risks and uncertainties associated with the mission strategies, allowing for adjustments and refinements as necessary. It ensures that the model and the resulting mission design are adaptable to changing circumstances and emerging technologies. The presented practical approach demonstrates the practical application of the multi-criteria optimization conceptual model in a real-world space mission scenario. By integrating various criteria, stakeholder requirements, and trade-offs, the model assists in designing mission strategies that minimize risks, optimize resource utilization, and align with sustainability goals, and optimize the supply chain required for space missions.

The evaluation of mission scenarios and the identification of optimal solutions provide valuable insights into the decision-making process, helping space agencies make informed choices for the long-term achievement and sustainability of missions into space. As space exploration advances, the application of such models becomes increasingly important in addressing complex challenges and achieving sustainable and responsible space exploration.

10. Application and Analysis of Proposed Approach

In this section the application and analysis of the proposed approach are presented together with a flowchart [108] of the proposed method with related stages. Table 7 presents the flowchart of the proposed method with related stages. The main difference between the single-objective and multi-objective approaches is presented. A proposed practical approach is divided into eight stages. What the decision-maker has to do in each stage is explained.

Table 7. Flowchart of the proposed methodology for a space mission.

<table>
<tr><th colspan="5">Space Mission Planning</th></tr>
<tr><td colspan="5">Stage 1: Input data for the optimization model</td></tr>
<tr><td>Stage 2: Building optimization model for space mission</td><td>A single objective optimization approach</td><td colspan="3">Multi-Objective optimization approach</td></tr>
<tr><td rowspan="3">Stage 3: Criteria definition</td><td>Risk</td><td rowspan="3">Minimization of space mission risk(s)</td><td rowspan="3">Maximization of space mission sustainability</td><td rowspan="3">Maximization of space mission supply chain efficiency</td></tr>
<tr><td>Sustainability</td></tr>
<tr><td>Supply Chain</td></tr>
<tr><td>Stage 4. Analysis of results</td><td>Three independently computed single objective models.</td><td colspan="3">One multi-objective computed model with a non-dominated set of pareto solutions connected to each other.
Each criterion has an impact to another criterion.</td></tr>
<tr><td>Stage 5. Decision-maker choice based on obtained results.</td><td>No relation between the criteria. Choice is limited, due to the not calculated impact between risk, sustainability, and supply chain structure.</td><td colspan="3">Decision maker is capable to choose the best decision alternative from the inter-connected solution from a non-dominated set of pareto solutions, showing the relations between risk, sustainability, and supply chain efficiency (structure/portfolio of the optimal set of suppliers).
All relations are included in the model and reflected in the results.</td></tr>
<tr><td>Stage 6. Evaluation of chosen solution by the decision maker</td><td colspan="4">In terms of: costs, time, efficiency, quality, security, reliability, resiliency, and robustness.
In terms of: sensitivity control of the formulated mathematical model and results.</td></tr>
<tr><td>Stage 7. Implementation</td><td colspan="4">The optimal set of tasks, components, and suppliers required for a successful space mission.</td></tr>
<tr><td>Stage 8. Reevaluation during space mission preparation due to randomness factors, which could appear in time.</td><td colspan="4">The decision maker includes randomness factors and repeat steps from Stage 1. to Stage 7. if needed.</td></tr>
</table>

It has been clearly presented, that the multi-objective model for optimizing risk, sustainability, and supply chain of a space mission, outperforms the single objective approach, since relations, connections, and impact between space mission risk, sustainability, and supply chain can be taken into account by the decision-maker only in case of non-dominated sub-optimal pareto solutions. A single objective approach is focused on risk, or on sustainability, or only on supply chain structure and efficiency. In space mission planning, organization, run, nowadays it is not efficient to consider each factor without relation to other factors.

Finally, controlling the subjectivity of decision-makers in the context of space missions or any complicated decision-making process can be tough but achievable. Strategies to help mitigate subjectivity and promote more objective decision-making are: explicit decision criteria, quantifying and standardizing factors, use of decision support tools, seeking diverse perspectives, employing deliberative processes, providing support, training, and guidance, using independent reviews and audits, and maintain a transparent record of the decision-making process, including the rationale behind decisions, the data considered, and the criteria applied. Documenting the process enhances responsibility, allows for retrospective analysis, and permits future improvements.

It is crucial to highlight that total eradication of subjectivity may not always be achievable or desirable. Some decisions may necessarily entail subjective factors. However, by employing these tactics, decision-makers can limit subjectivity and strive for more objective and informed decision outcomes.

11. Limitations

Human health hazards, including radiation exposure and physiological impacts such as bone and muscle loss, cardiovascular issues, and psychological challenges, limit space missions. There are technological constraints in developing reliable life support, propulsion, and navigation systems. Cost and financial limits make ambitious missions difficult. Resource management, optimizing energy use, and limiting the impact on the environment such as space debris are all examples of sustainability restrictions.

Environmental monitoring and sustainability research are critical. Developing tools for precise tracking and mitigation of space debris, assessing the environmental impact of space activities, and applying sustainable practices for resource management and energy consumption are vital to the mission's sustainability over time. Planetary science and astrobiology research is critical for mission planning. Further research into the origins of life, conditions that can be inhabited in our solar system, and the search for extraterrestrial life will inform future mission targets and techniques, while limiting the risk of contamination. International collaboration is required to pool resources, knowledge, and financing for space missions and to make the supply chain for space missions more effective.

12. Future Research

There are numerous areas of future research in space mission optimization that should be considered in terms of risk, sustainability, and supply chain [109]. Long-duration space travel requires research to create effective countermeasures, such as better radiation shielding and physiological conditioning techniques to reduce health hazards for astronauts. Propulsion system advancements, including research into alternative technologies such as ion propulsion, nuclear propulsion, and solar sails, will enable faster and more efficient interplanetary travel, lowering mission risks and boosting sustainability. In-situ resource use research is critical for long-term space exploration. Exploring extraction and use methods for celestial body resources including water, ice, and minerals can lessen reliance on Earth and enable self-sufficiency during missions. Increasing robotic exploration capabilities through autonomous system research and development, increased mobility, and dexterous manipulation would improve mission efficiency, reduce human risk, and permit remote operations in hazardous settings [110].

Future studies should concentrate on encouraging international cooperation, developing frameworks for resource sharing, and harmonizing safety and sustainability requirements. To reduce mission hazards and boost efficiency, sophisticated materials science research is critical for producing lightweight and durable spacecraft components, radiation shielding materials, and sustainable energy solutions. Continued study into space medicine and psychology is critical for better understanding and mitigating the physiological and psychological impacts of space exploration, which will lead to enhanced astronaut well-being and mission success.

13. Conclusions

In conclusion, the exploration of risk, sustainability, and supply chain in space missions is of paramount importance as we continue to venture into the vast unknown. This topic necessitates a comprehensive understanding of the potential risks involved in space exploration, while concurrently integrating sustainable practices to ensure the long-term viability of our endeavors.

The review, multi-objective conceptual optimization model, and practical approach discussed in this paper shed light on the significance of addressing risk, sustainability, and supply chain for space missions and provide valuable insights into how we can approach these challenges.

The review presented a thorough examination of the various types of risks encountered in space missions. Technical risks, human risks, launch and reentry risks, space environment risks, mission design, and planning risks, budgetary and schedule risks, as well as political and international risks, were all identified and discussed.

This comprehensive overview serves as a reminder that space exploration is a complex and high-stakes endeavor, requiring meticulous planning, robust engineering practices, and continuous risk assessment. Moreover, the review highlighted the need to incorporate sustainability principles into space missions. This includes mitigating negative environmental impacts, optimizing resource utilization, considering ethical considerations, engaging in long-term planning, fostering international cooperation, and promoting public outreach and education. By aligning space exploration with sustainable practices [111], we can maximize the benefits while minimizing the detrimental effects on the space environment and future missions.

The introduction of a multi-criteria optimization model further strengthens the approach to risk, sustainability, and supply chain in space missions. This model provides a systematic framework for evaluating and selecting mission strategies that balance multi-objective, such as environmental impact, resource utilization, mission cost, and societal benefits. By considering the trade-offs between different criteria, the model enables decision-makers to identify sub-optimal solutions that align with sustainability objectives while effectively managing risks, and optimizing supply chain efficiency.

The practical approach presented in this paper exemplified the practical application of the multi-criteria optimization conceptual model. Through the practical approach, we witnessed how the model could guide the design of a space mission, taking into account various risk factors, sustainability considerations, and supply chain planning. The practical approach underscored the importance of optimizing resource utilization, reducing environmental impact, and incorporating ethical practices in the decision-making process.

The main limitations of space mission risk, sustainability, and supply chain multi-objective optimization models are: data availability, complexity and uncertainty, trade-offs and conflicting objectives, dynamic nature of space missions.

Recommendations for further studies on space mission risk, sustainability, and supply chain multi-objective optimization models would include: increased data collecting, advanced modeling methodologies, multi-objective decision-making frameworks, integration of sustainability and risk, implementation of advanced supply chain optimization models.

Overall, the conclusions drawn from this exploration emphasize the crucial role of addressing risk, sustainability, and supply chain [112] in space missions. By understanding and mitigating the diverse risks associated with space exploration, we can ensure the safety of astronauts and the success of the mission. Simultaneously, integrating sustainability principles into space missions allows us to preserve the integrity of the space environment, make efficient use of resources, foster international cooperation, and inspire future generations.

Supply chain optimization enables efficient resource flow, needed for space mission success. As we continue to push the boundaries of human space exploration, it is imperative that we maintain a proactive and responsible approach. This entails ongoing research, technological advancements [113], and collaboration among space agencies, governments, and the scientific community. By prioritizing risk assessment, sustainable practices, and ethical decision-making, we can forge a path toward a future of space exploration that is both fruitful and sustainable. Health risks, propulsion systems, resource usage, robotics, environmental monitoring, planetary science, international collaboration, sophisticated materials, and space medicine should all be addressed in further investigation into space mission risk, sustainability, and supply chain. These areas of research have the potential to overcome restrictions in the future and provide safer, efficient, and more sustainable space flights.

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