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Towards a greener cosmos: Tool for integrating life cycle costs and sustainability for future space systems development

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Abstract. As humanity ventures further into space exploration, the imperative for sustainability and cost-effectiveness intensifies. Accurate cost estimation is pivotal for project viability, funding, and stakeholder management. However, existing tools often fall short in integrating comprehensive data and sustainability considerations. This paper proposes the Sustainable Exploration Resource Toolkit (SERT), which integrates life cycle costs (LCC) analysis, sustainability principles, and technology evaluation to address these challenges. SERT aims to provide decision-makers with holistic insights into the financial implications of space missions, identifying cost-effective solutions for sustainable bioregenerative systems. By fostering cross-industry collaboration and complexity reduction strategies, SERT strives to revolutionize cost estimation for future space exploration endeavors, ensuring economic viability and environmental responsibility.

Introduction

In the vast expanse of space exploration, the quest for sustainability and cost-effectiveness has become increasingly paramount. As humanity sets its sights on long-duration space missions and interplanetary colonization, the need for innovative solutions that balance affordability with environmental responsibility has never been more critical. Accurate cost estimation is essential for ensuring project feasibility, securing funding, and managing stakeholder expectations. By understanding the full scope of financial requirements, space agencies and organizations can make informed decisions regarding mission planning, resource allocation, and risk management. Moreover, transparent and comprehensive cost estimation enables policymakers, taxpayers, and the public to assess the value and benefits of space exploration initiatives. In an era of budget constraints and competing priorities, having a realistic understanding of project costs is critical for maintaining public trust and support for space exploration endeavors. Additionally, accurate cost estimation helps mitigate the risk of budget overruns and delays, enabling projects to stay on schedule and within budget constraints. In response to these challenges, a paradigm shift that emphasizes the integration of life cycle costs (LCC) analysis [1] and sustainability considerations to pave the way towards a greener cosmos becomes predominant. Central to this approach is the development of methodologies and tools that support space systems developers and operators in selecting the most affordable and sustainable solutions for providing vital resources in space exploration missions.

At the core of this proposal lies the incorporation of life cycle costs (LCC) analysis, a comprehensive framework for assessing the total costs associated with each phase of space system development and operation. This analysis encompasses not only initial research and development costs but also manufacturing, assembly, and operational costs, providing decision-makers with a holistic view of the financial implications of space missions. By considering the entire life cycle of space systems, from inception to retirement, LCC analysis enables informed decision-making and the identification of cost-saving opportunities that may arise over time [2]. In parallel,

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sustainability considerations play a crucial role in shaping the design and implementation of future space systems. These considerations encompass a broad range of factors, including resource utilization, waste management, and environmental impacts, with the overarching goal of minimizing ecological footprints and promoting eco-friendly practices in space exploration [3]. By integrating sustainability principles into space system development costs, the SERT tool can ensure that space missions align with long-term sustainability goals, fostering responsible stewardship of celestial resources for all the stakeholders involved.

Numerous tools exist to facilitate LCCA for space systems and they are not without limitations. One of the primary challenges faced by LCCA tools is the integration of comprehensive and accurate data throughout the life cycle of space systems. Often, these tools rely on historical data or assumptions due to the lack of real-time or predictive data sources. Factors such as evolving technology, regulatory changes, and unforeseen events can significantly impact cost estimations. Thus, the inability to incorporate dynamic data sources hampers the accuracy of LCCA. While ALiSSE, the Advanced Life Support Systems for Space Exploration tool developed by the European Space Agency (ESA), offers valuable support for designing and evaluating life support systems for space missions, it also presents several drawbacks. These include its complexity, which may require specialized knowledge to use effectively, and potential limitations in simulating certain aspects of life support systems. Additionally, ALiSSE's resource-intensive nature, both in terms of computational requirements and time, could pose challenges for users with limited resources or tight project timelines. The accuracy and reliability of ALiSSE's predictions may also depend on the quality of input data and assumptions, necessitating validation against real-world data. Furthermore, the user interface may not be user-friendly for all users, impacting usability and accessibility.

On the other hand, the NASA Equivalent System Mass (ESM) is a metric used by NASA to evaluate the mass of various life support systems and consumables required for space missions. ESM quantifies the total mass of a system or set of components needed to provide a certain level of support for astronauts over a specified duration. It encompasses factors such as food, water, air, waste management, and other consumables necessary to sustain human life in space. By calculating ESM, NASA can compare different life support system designs and evaluate their efficiency and feasibility for long-duration missions. However, ESM also has several drawbacks. One limitation is its focus solely on mass, which may not fully capture the complexity and nuances of life support system design. For example, ESM does not account for factors such as volume, power requirements, or the reliability of system components, which are also critical considerations for space missions. Additionally, ESM calculations may oversimplify the complexities of human physiology and behavior, leading to inaccuracies in estimating resource requirements. Furthermore, ESM assessments may not adequately address the integration of life support systems with other spacecraft systems or the dynamic nature of mission scenarios.

Many of these tools focus primarily on direct costs associated with the design, development, and operation of space systems. However, they overlook indirect costs, such as maintenance, upgrades, and disposal, which are integral parts of the life cycle as well. These tools also often struggle to incorporate risk and uncertainty factors adequately. While sensitivity analysis and Monte Carlo simulations can offer some insights, they do not capture the full spectrum of potential risks associated with space missions, leading to overly optimistic or pessimistic cost estimates. Moreover, many existing LCCA tools are designed for specific types of space missions or technologies, lacking scalability and flexibility to adapt to diverse project requirements. As a result, users find it challenging to customize the analysis framework according to their unique needs, limiting the applicability of these tools across different space programs and initiatives. Furthermore, factors such as evolving technology, regulatory changes, and unforeseen events can

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significantly impact cost estimations while often, the existing tools rely on historical data or assumptions due to the lack of real-time or predictive data sources.

Methodology and Expected Results

This project was proposed to address this critical need for comprehensive analysis of life cycle costs throughout the various phases of life support system development, which directly led to the development of the first iteration of Sustainable Exploration Resource Toolkit (SERT) tool that addresses key aspects essential for the success of long-duration space missions. The SERT tool proposed aims to address these issues by assessing existing and commercial technologies relevant to bioregenerative systems by gathering information on available technologies, their capabilities, performance metrics, and limitations within the tool system. In addition, it will also incorporate data from performance testing and validation studies derived from laboratory testing, ground-based simulations, or field trials to assess the functionality, reliability, and resilience of technologies in microgravity, radiation, and extreme temperature environments. Through this integration of comprehensive and accurate data throughout the life cycle of space systems, SERT can provide cost estimates that will be close to actual costs of the missions over time.

In addition, to mitigate the development risks associated with sustainable and cost-effective bioregenerative systems, SERT also incorporates the evaluation of existing and commercial technologies. By leveraging existing expertise and infrastructure, space agencies can reduce complexity in system components and processes, optimize operational efficiency, and minimize costs. Collaborations with terrestrial agriculture research centers offer invaluable opportunities to tap into the wealth of knowledge and experience in agricultural science, enabling the adaptation of proven technologies and methodologies for space applications. Moreover, the feasibility of utilizing existing technologies and collaborations with terrestrial agriculture research centers serve to optimize operational efficiency and minimize costs. By harnessing existing expertise and infrastructure, space missions can accelerate technology development, reduce research and development costs, and enhance the reliability and performance of bioregenerative systems. Since interdisciplinary collaborations have become the cornerstone of innovation in today's interconnected world by bridging the gap between industries, these partnerships have fueled progress, driven efficiency improvements, and unlocked new opportunities for growth and development. In that regard, healthcare has witnessed a revolution with the collaboration between medical professionals and 3D printing companies, leading to the creation of custom-made implants that reduce surgery time, improve outcomes, and save costs. Retailers partnering with tech companies utilize big data analytics to optimize supply chains, resulting in streamlined logistics, reduced inventory, and improved customer satisfaction. The aerospace industry's expertise in lightweight materials, transferred to automotive manufacturing, has yielded fuel-efficient vehicles that meet emission regulations. Therefore, integrating expertise from terrestrial agriculture research centers and utilizing existing technologies allows space missions to optimize operational efficiency and maximize yields, while minimizing resource consumption and waste generation. This ensures the long-term sustainability of space habitats while supporting the nutritional needs of astronauts during extended missions. Therefore, this SERT tool will also feature options to integrate the current, as well as up-coming technologies in the form of their Technology Readiness Levels (TRLs) to give an estimate of costs involved at various step-intervals.

Conclusion

In conclusion, the proposed SERT tool aims to underpin the development of space systems that are not only robust and economically viable but also environmentally responsible. By integrating life cycle costs (LCC) analysis, sustainability considerations, and complexity reduction strategies, SERT strives to address the multifaceted challenges inherent in space exploration. Through the tools' extensive analysis, decision-makers gain a comprehensive understanding of the total costs associated with each phase of system development and operation, enabling informed decision-making and resource allocation instead of being limited by ESM or overstimulated by ALiSSE tools. Moreover, by systematically evaluating the feasibility of utilizing existing and commercial technologies, space agencies and organizations can identify low-risk, cost-effective solutions for developing sustainable and resilient bioregenerative systems for space missions. Thereby, these sustainability considerations ensure that space systems align with long-term environmental goals, minimizing ecological footprints and promoting eco-friendly practices. Additionally, complexity reduction strategies mitigate development risks and optimize operational efficiency, further enhancing the economic viability of space missions. Furthermore, by fostering cross-industry collaboration, businesses can unlock a wealth of potential for cost savings and efficiency gains. This collaborative approach not only strengthens individual companies but also propels technological advancements that benefit entire sectors and, ultimately, society as a whole. Implementing these methodologies into the tool holds the potential to revolutionize future space exploration missions, particularly in meeting the sustainable exploration needs of astronauts during extended missions. By deriving upon innovation, efficiency, and environmental responsibility, SERT paves the way for a new era of estimating costs for space exploration missions that is both technologically advanced and environmentally sustainable.

References:

[1] Hauschild, M. Z., Olsen, S. I., & Rosenbaum, R. K. (Eds.). (2018). Life cycle assessment. SpringerLink. https://link.springer.com/book/10.1007/978-3-319-56475-3

[2] Seedhouse, E. (2020). Life Support Systems for Humans in Space. In Springer eBooks. https://doi.org/10.1007/978-3-030-52859-1

[3] Dominoni, Annalisa. “Design for Sustainability in Space: Future Nature.” SpringerBriefs in Applied Sciences and Technology, 1 Jan. 2024, pp. 25–48, https://doi.org/10.1007/978-3-031-56004-0_2. Accessed 2 Apr. 2024.