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ECLSS が月圏物資輸送需要に与える影響の評価：再生システムと自立システムのシステムダイナミクス的比較

Evaluating the Impact of ECLSS on Cis-Lunar Logistics Demand: A System Dynamics Comparison of Regenerative and Autonomous System

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1. Background

As cis-lunar space activities expand in the coming decades, the number of stakeholders is projected to increase significantly, driving a corresponding rise in material transportation demand. However, robust methodologies for forecasting this logistics demand remain underdeveloped. This challenge stems from the growing complexity and diversity of use cases—ranging from human exploration and resource extraction to space tourism and Mars mission staging—driven by an expanding array of actors, including private enterprises and emerging space agencies[1,2]. Quantitatively assessing the impact of closed-loop operations, such as in-situ resource utilization (ISRU) and the regeneration of life-support consumables, on logistics demand remains a particular challenge.

This study investigates how Environmental Control and Life Support System (ECLSS) architectures influence future cis-lunar logistics. We focus on crewed orbital platforms and surface bases planned for near-term development, adopting a system dynamics modeling approach. This approach is used to compare a regenerative ECLSS architecture, similar to that of the International Space Station (ISS), with an autonomous ECLSS architecture, which represents a key area of ongoing research and development.

2. System Dynamics Approach

The system dynamics methodology adopted in this study is a simulation-based approach, grounded in feedback systems theory, used to analyze complex systems and support strategic decision-making. We employ this methodology to compare the systemic implications of regenerative and autonomous ECLSS architectures. As an initial step, we constructed a causal loop diagram (CLD) to visualize the causal relationships between ECLSS implementation and logistics demand. A CLD maps these relationships using links that represent either reinforcing (positive) or balancing (negative) feedback loops. Reinforcing loops amplify change, while balancing loops promote stability. A double slash on a link indicates a significant time delay in the causal effect.

3. Causal Loop Diagram

Figure 1 presents the Causal Loop Diagrams (CLDs) developed in this study. The left panel details the feedback structure for a regenerative ECLSS, where the storage at lunar or orbital facilities is augmented by inter-orbital transportation and depleted through resource consumption. A balancing feedback loop is generated by the recovery of resources from consumption, whereas the interplay between logistics demand and storage constitutes a reinforcing loop. The right panel illustrates an autonomous ECLSS architecture. This model incorporates local food production and In-Situ Resource Utilization (ISRU) on the Moon and Mars, both of which serve to mitigate overall logistics demand. Nevertheless, the implementation of in-situ food production necessitates the launch of additional modules relative to a regenerative ECLSS, potentially elevating the overall logistics demand.

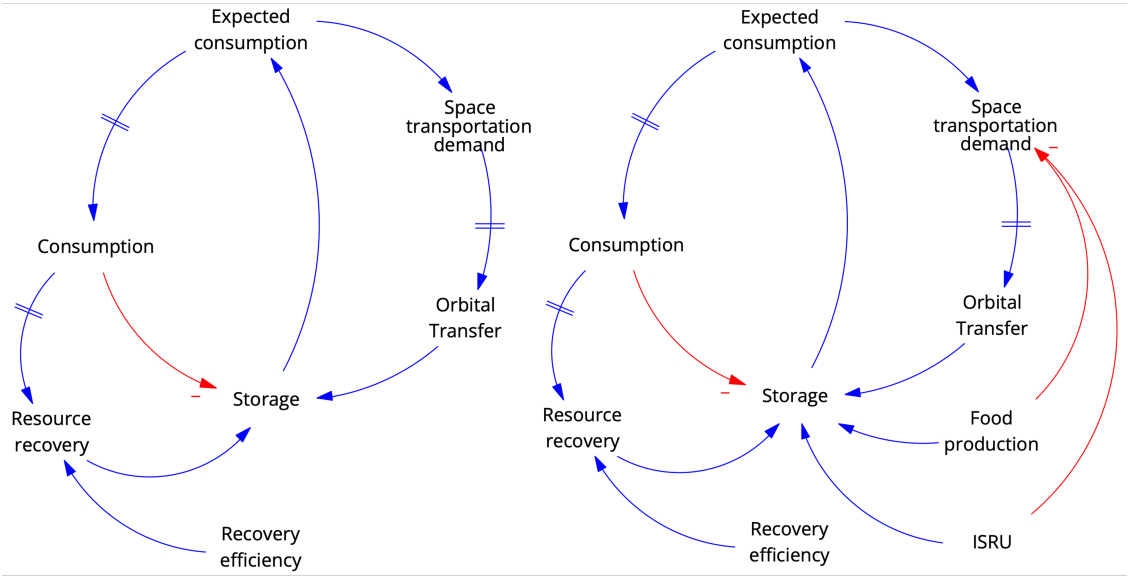

Figure 1. Causal Loop Diagram between Transportation Demand and ECLSS

4. Future Work

This study presents a preliminary Causal Loop Diagram (CLD) that elucidates the causal relationships between cis-lunar logistics demand and the architecture of Environmental Control and Life Support Systems (ECLSS). Subsequent research will extend this qualitative framework by constructing a quantitative stock-and-flow model tailored to realistic, near-term human spaceflight programs. The quantitative analysis aims to evaluate the impacts of regenerative and autonomous ECLSS on logistics demand and to estimate the requirements for implementing such systems on the lunar surface. Furthermore, the interdependencies between these ECLSS requirements and other logistical drivers, such as lunar infrastructure and relay satellites, will be examined. Ultimately, this research trajectory seeks to establish a comprehensive predictive model and methodology for forecasting future cis-lunar logistics demand.

References

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