Operations and systems modelling of a sustainable, human-centred lunar settlement via the integration of state-of the art ISRU technologies

NASA's goal is to establish a sustainable human presence on the Moon by 2028 with the Artemis Base Camp. Another proposal for a lunar settlement is the ESA's Moon Village, supported by the MELiSSA (Micro-Ecological Life Support Alternative) project. The aim of a sustainable human lunar presence is heavily dependent on the development of life support systems. As such, in-situ resource utilization (ISRU) of lunar regolith is crucial to long-term and cost-effective life support. Current technologies include NASA's hydrogen reduction plant and lunar prospectors to produce water and oxygen, successfully demonstrated at field tests in Hawaii in 2010, and Aqua Factorem for ultra low-energy lunar water extraction, proposed in 2020. The implementation of these technologies can make a lunar habitat feasible as they can provide the necessary consumables and propellant for long-duration crewed missions. Another key indicator of future success of these lunar missions is the abundance of water in the form of ice on the permanently shadowed floors of polar craters.

In conjunction with designing and validating technologies to extract consumables from lunar regolith, an equally important area of research is their integration within human settlements. Although much work has been done to design and innovate lunar habitats and ISRU technologies, little work has been done to systematically connect these together. Even if literature has explored some of the challenges and consequences of ISRU technologies, specific solutions to manage their interfaces and interactions, including operators and proposed habitat designs, remain relatively unexplored. Specifically, technologies of high priority are those that produce the necessities for life: water and oxygen. These particular systems are prone to producing wastes such as reduced metals and can incur risks such as dust displacement. As such, it becomes important to investigate the interactions between these components in tandem with a focus on waste management and risk mitigation, as they will directly impact the sustainability of the system and the wellbeing of the operators.

To address this need, this paper proposes a concept of operations and a systems model that synthesizes the interfaces and interactions among habitats, excavation technologies, and operators in a lunar settlement with a key design focus on safety and sustainability. First, the operational policies and constraints are established from space treaties and technical standards. The environmental characteristics are summarized based on the findings of lunar science missions. Then, the functions of individual components in the system, along with their relationships to each other, are identified and grouped into operational scenarios to illustrate how the system will operate. Within these scenarios, potential risk factors and opportunities for waste generation are highlighted. By developing functional flow block diagrams, systems-level requirements, and conducting trade studies to define system components and operations, this paper introduces novel procedures to mitigate risks to human health and critical equipment as well as handle the by-products of oxygen and water extraction. The results in this paper provide new perspectives and considerations to inform the development of lunar ISRU systems that emphasize safety and sustainability. In the future, the operations and systems models presented in this paper can be applied to integrate other capabilities, such as energy generation and food production, in lunar settlements.