FUTURE LUNAR BASE SYSTEMS, SYSTEM DYNAMICS, AND IN-SITU RESOURCE UTILISATION.

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Introduction: Successfully establishing a long-term human lunar presence that is resilient, sustainable, and achieves mission goals will be highly dependent on the implementation of in-situ resource utilisation (ISRU). To plan and design for future resource needs, an understanding of the potential lunar systems that will exist and the associated system dynamics with respect to resource utilisation is critical.

This presentation uses tailored systems engineering processes informed by possible future scenarios to identify potential future lunar systems. From this, a system dynamics model is created to understand lunar resources consumption associated with the previously identified systems assuming a crew of four people over the course of 200 Earth days (approximately 0.5 years). This process provides insights into potential future resource considerations, and the importance of 'trade-offs' when identifying and using lunar resources.

Tailoring System Engineering Processes: To aid with the identification of possible lunar systems, the approach illustrated in Figure 1 is used.

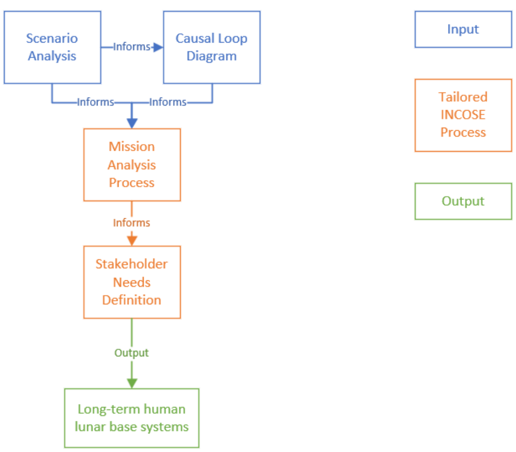

Figure 1: Systems Engineering approach informed by future scenarios and a causal loop diagram.

A 2×2 scenario analysis for what possible futures a long-term human lunar presence could involve is undertaken, which subsequently informs the development of a causal loop diagram. The 2×2 scenario generates four futures, of which Figure 2 illustrates one of these which has high levels of lunar exploration and ISRU.

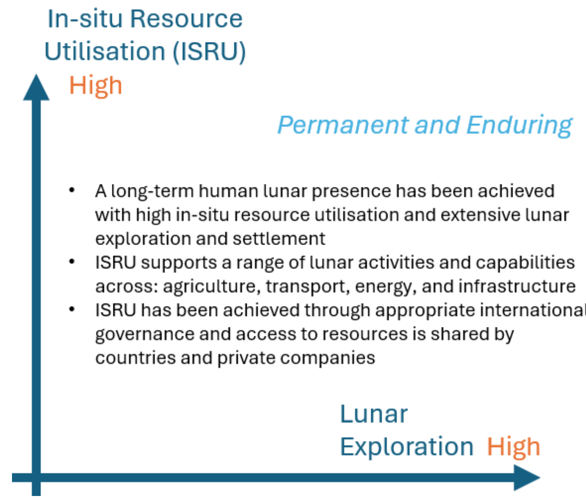

Figure 2: One of the four scenarios developed for a possible long-term human lunar presence considering levels of 'Lunar Exploration' and 'In-situ Resource Utilisation'.

Tailoring of two INCOSE systems engineering processes [1] is undertaken, whereby the *Business or Mission Analysis Process* becomes the *Mission Analysis Process*, and the *Stakeholder Needs and Requirements Definition Process* becomes the *Stakeholder Needs Definition Process*. The tailoring removes unnecessary process inputs, steps, and outputs, subsequently resulting in two processes that are streamlined and suitable for the identification of possible future long-term lunar systems to facilitate a long-term human lunar presence. The process flow for the tailored *Mission Analysis Process* is illustrated in Figure 3.

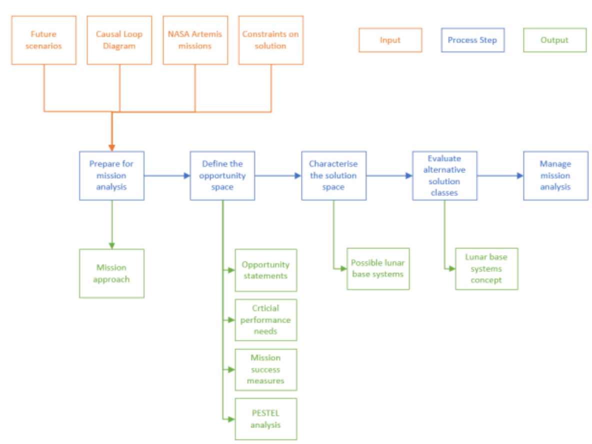

Figure 3: Tailored Mission Analysis Process.

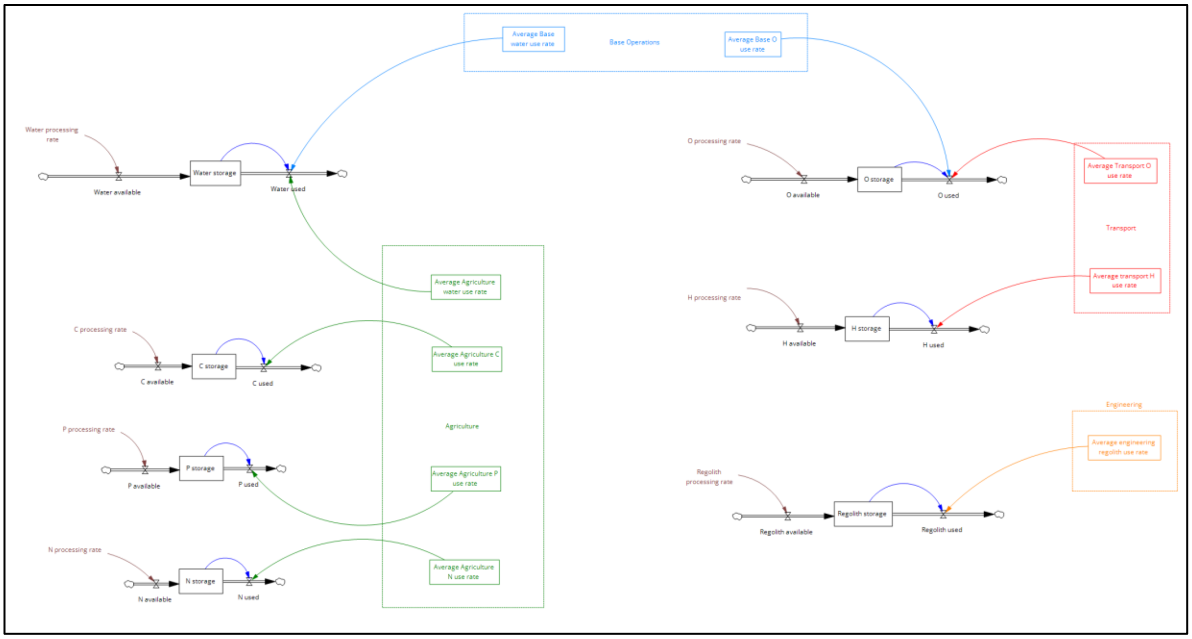

Figure 4: Understanding the system dynamics of future lunar systems and resource use

Lunar Systems and System Dynamics: From the tailored *Stakeholder Needs Process* an output was the lunar base systems concept. The identified lunar base systems are: Agriculture, Energy, Engineering, Base Operations, ISRU, and Transport.

Using lunar resource information in the literature [2] [3], resources that are likely to be key for the operation of these systems were used to inform the development a system dynamics model using Vensim's stock and flow capability. Lunar resource use is modelled using variables associated with the systems. Where possible, the system dynamics model is informed by the literature, e.g., NASA's Human Integration Design Handbook [4], and considers an average lunar operation. The stock and flow model is shown in Figure 4, with result graphs illustrating resource flow.

From the system dynamics model, several important considerations emerged:

- Resource processing rate is a leverage point with delays here impacting usage.
- Resource storage needs to facilitate periods of increased demand but not result in excessive infrastructure.
- Water is a key resource, with consumption closely associated with human lunar exploration activities, i.e., the more often and longer astronauts are out on the lunar surface, the more water is required.
- Resource processing could be minimised through identifying suitable locations for resource extraction.
- Circularity and sustainability can reduce the need for ever-increasing resource extraction and introduction into the overall system.

Future Considerations: From consideration of future scenarios and the system dynamics that exist, the importance of forward planning when developing lunar systems and prioritising resources to be extracted emerges. Considering this, a trade-off study has the potential to inform resource site selection for optimising resource extraction and processing rates. Such a trade-off study would consider, at a minimum: Scarcity of Resource, Existing Infrastructure, Lunar Activities, Energy Demand, TRL, and Sustainability.

Future considerations include further development of the system dynamics model, in particular, focusing on water as a key resource. This involves further expanding the variables associated with this resource, and understanding extraction and processing techniques [5] with the overall aim of improving resource flow.

References: [1] INCOSE (2023) *Systems Engineering Hanbook. Wiley, 5th Ed.* [2] Crawford, I. A. et. al. (2023) *Lunar Resources, Reviews in Minerology and Geochemistry,* 89. [3] Crawford, I. A. (2015) *Lunar resources: a review*, *Progress in Physical Geography*, 39(2). [4] NASA (2014) *Human Integration Design Handbook*. [5] Kiewiet L. Fälker S. and Zabel P. (2025) *A review of lunar water extraction technologies: comparison, classification, and research gaps*, *Space and Planetary Resources*.