Future Lunar Systems, System Dynamics, and *In-Situ* Resource Utilisation

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Summary

System dynamics modelling of lunar resources for a long-term human lunar presence provides insight to the resources that are important for future lunar systems, the role of sustainability, and resilience

1. Background

- Successfully establishing a **long-term** human lunar presence will require implementation of *in-situ* resource utilisation (ISRU)
- What lunar resources and where they can be used can be explored using **Systems Engineering** (SE) and **system dynamics** methods
- Results can provide insight to the role of sustainability and resilience

2. Methods

- A Systems Engineering (SE) and system dynamics method was used (**Figure 1**)
- A literature informed scenario analysis (**Figure 2**) and causal loop diagram (**Figure 3**) were developed to scope possible human lunar activity and ISRU

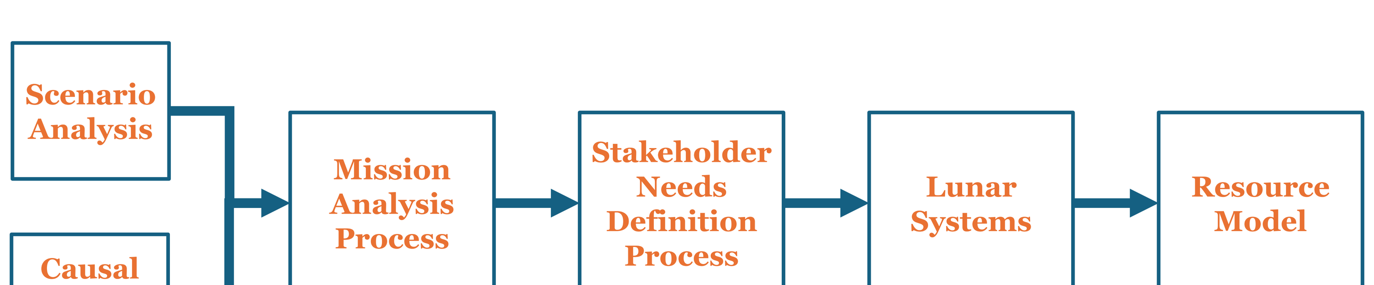

Figure 1. Systems Engineering and system dynamics approach to understand lunar ISRU flows

- Considering possible lunar futures, systems that are important to long-term human lunar operations are identified using tailored SE processes [1]:
  - **Agriculture** – growing of agricultural produce
  - **Energy** – development of a lunar grid
  - **Engineering** – developing lunar infrastructure
  - **Base Operations** – life support and lunar base
  - **ISRU** – lunar resource chain
  - **Transport** – provision of transport
- Lunar resources are mapped to these systems [2-4], and a system dynamics model is developed

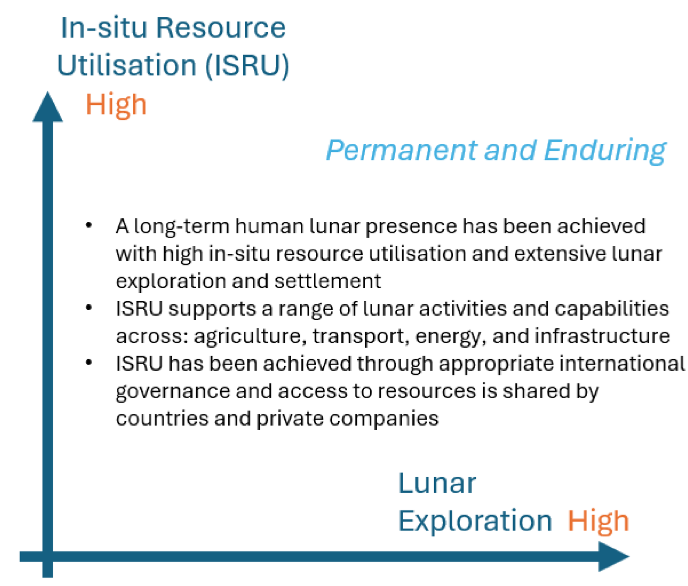

Figure 2. One of four possible future human lunar exploration scenarios developed

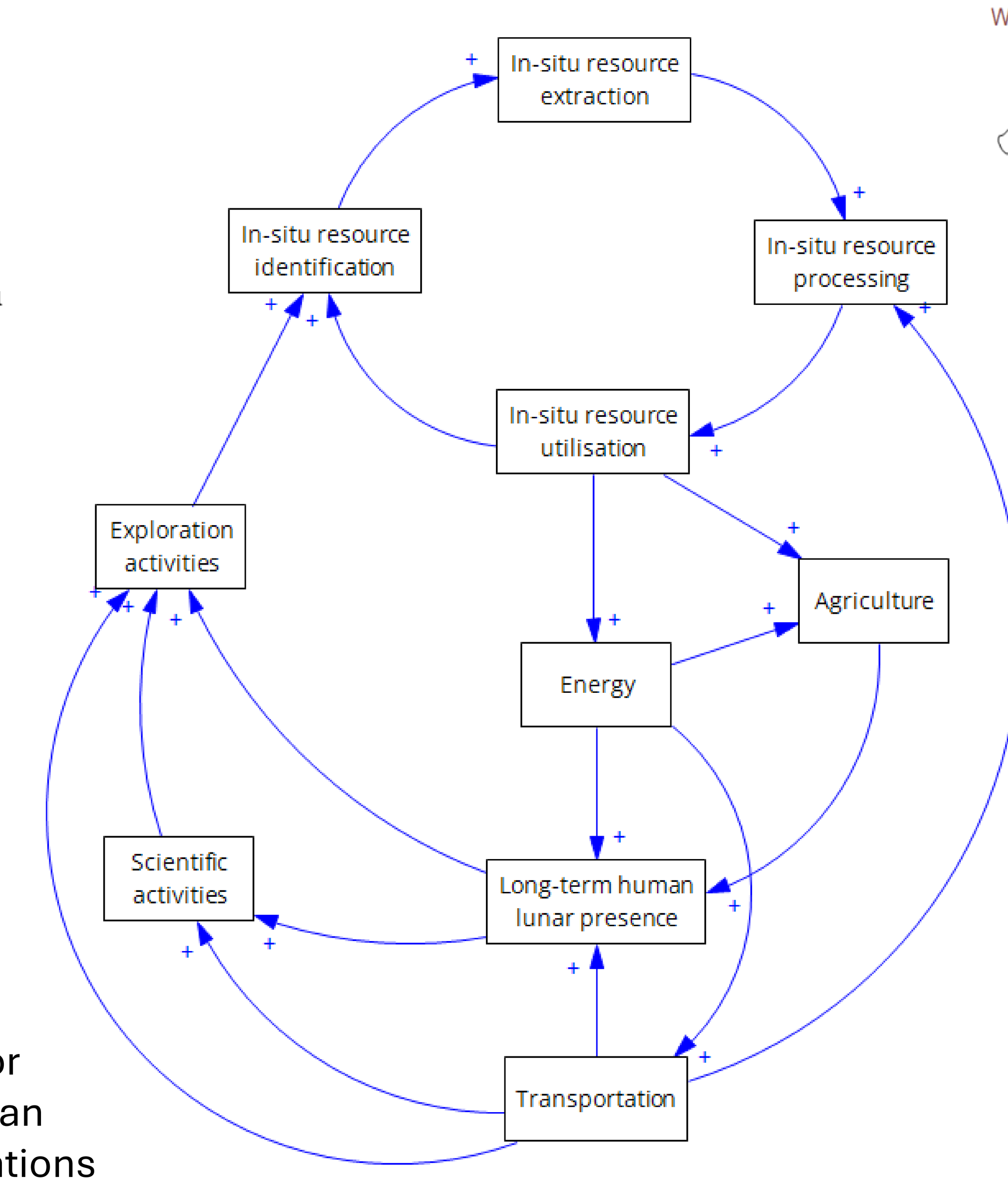

Figure 3. Exploring causality for future human lunar operations

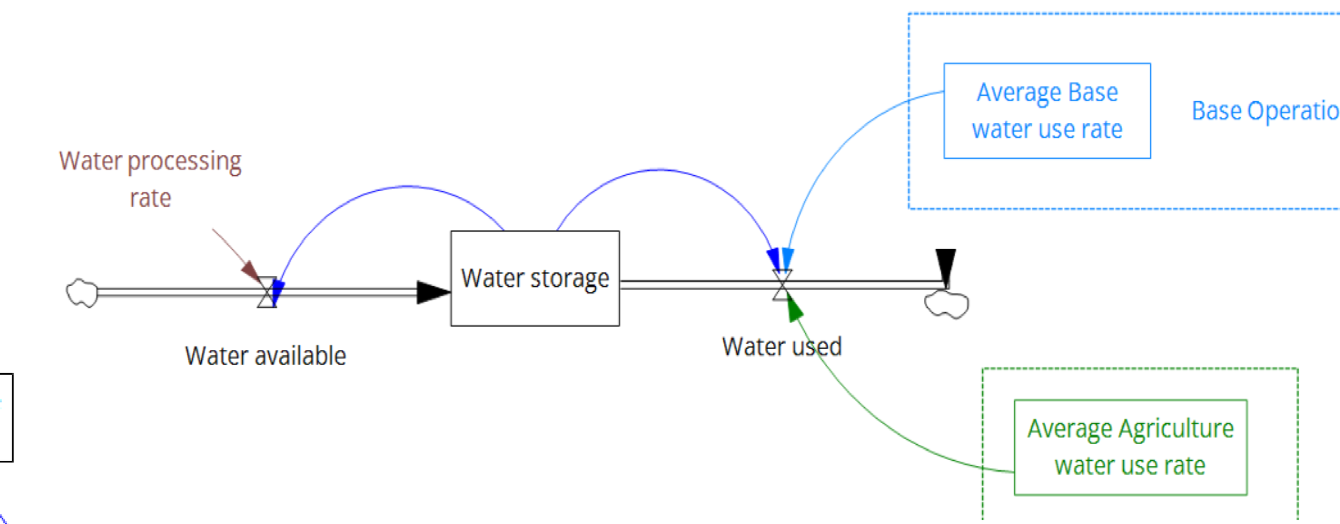

Figure 4. System dynamics model showing water resource

3. Results

- Flow of resources through identified lunar systems is explored using system dynamics software tool *Vensim*
- The initial systems dynamics model, illustrating the representation for water is illustrated in **Figure 4**
- Formulas for resource flows are developed using parameters from the literature
- Initial results for water for a 200-day period from the system dynamics simulation are illustrated in **Figure 5**
- The cyclical behaviour in **Figure 5** is what is expected as storage infrastructure fills to a minimum level before any resource is used

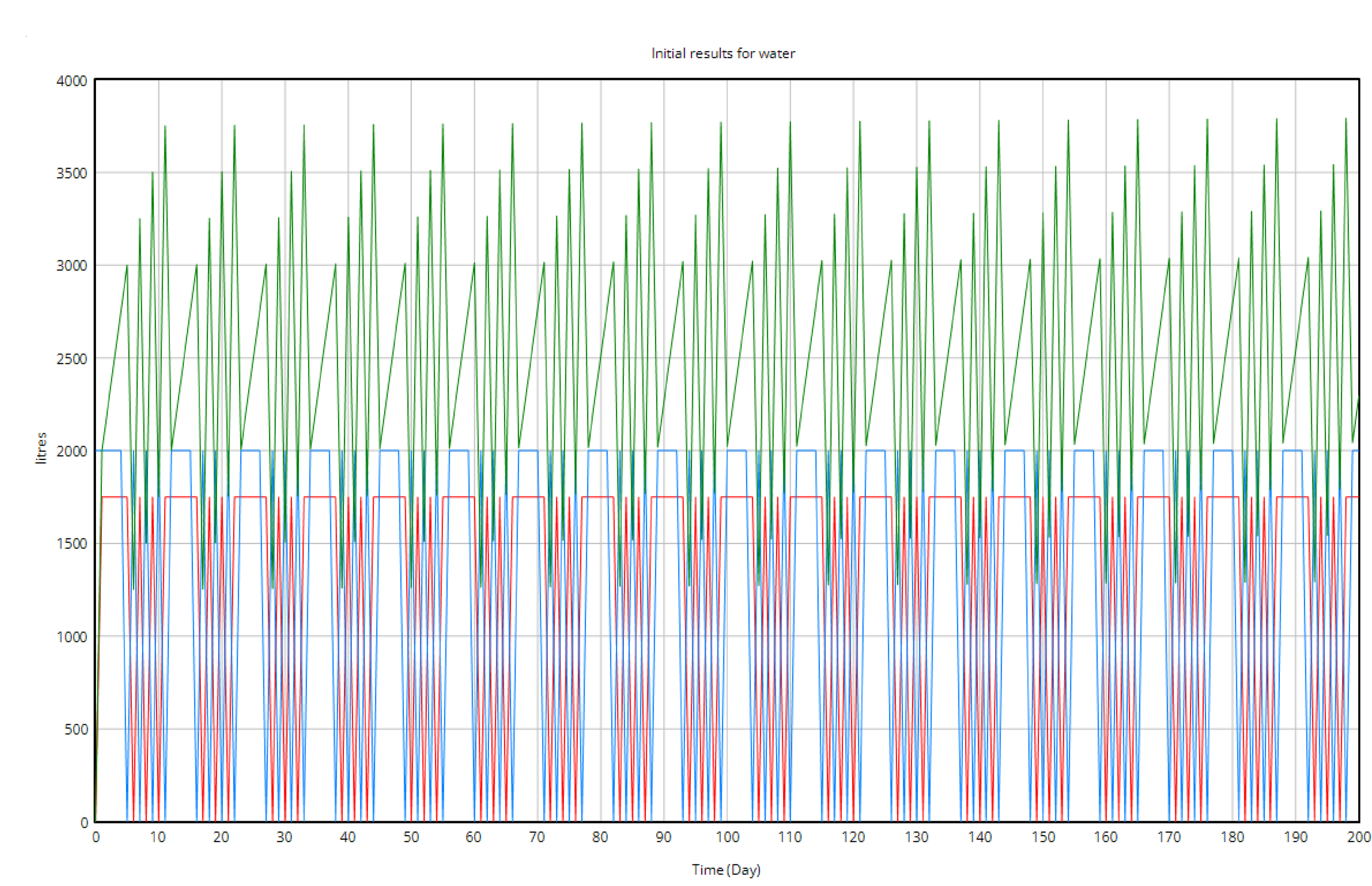

Figure 5. Initial results for lunar water-ice resource flow from the system considering water storage, water available (post-processing) and water used (subject to human lunar activities) over 200 days

- For the duration of the simulation, resource can only be used if the storage level is above a minimum value
- This is one way to develop resilience in the system
- Lunar water-ice use in transportation (as a fuel) is not included, which significantly increases resource demand
- Initial delays for storage are caused by time taken for resource extraction and processing

4. Discussion

- Lunar **resource processing rate** is a leverage point. Delays here impact overall usage
- Storage needs to facilitate periods of increased demand, whilst not resulting in **excessive infrastructure**
- Water is a key resource, with consumption closely associated with human lunar exploration and transportation requirements
- Resource **processing and transportation delays** can be addressed through appropriate lunar site selection
- Circularity and **sustainability** can reduce the need for-ever increasing resource extraction and introduction into the overall system
- A trade-off study can help guide resource site selection for optimising resource extraction and processing rates

5. Future Work

- Further **development of the system dynamics model** to include more variables and flows to better reflect complexity within and **between critical lunar systems**
- Development of a **trade-off study** that helps with site selection and planning for lunar ISRU
- Explore how **sustainability and resilience** can be achieved in the lunar systems
- Consideration of more scenarios, e.g., stress testing and sensitivity analysis

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.