AN OVERVIEW OF LUNAR ISRU OPERATION RESEARCH WITH AN UNCERTAINTY CONSIDERATION AT IMPERIAL COLLEGE LONDON. L. Malone[1], K. Ikeya[1], M.-A. Cardin[1], J.J. Cilliers[1] S.O. Starr[1], and K. Hadler[2], [1]Imperial College London, Exhibition Road, London, SW7 2AZ, United Kingdom (luka.malone19@imperial.ac.uk) for first author, [2]European Space Resources Innovation Centre (ESRIC), Luxembourg Instititute of Science and Technology (LIST), Maison d'Innovation, 5, avenue des Hauts-Forneaux, Esch-sur-Alzette, L-4362, Luxembourg.

Introduction:

In response to the ongoing efforts of humanity's return to the Moon, various lunar in-situ resource utilization (ISRU) technologies and their operations have been researched extensively. These past studies often determined or optimized ISRU plant design and operations based on broad assumptions [1, 2]. However, these assumptions are often oversimplified and devoid of uncertain factors, such as resource content. Such oversimplification can lead the system to be suboptimal when uncertainty unfolds, as it inevitably does in a real-world system [3].

At Imperial College London, the Imperial Strategic Engineering Laboratory and the Space and Terrestrial Resource Group collaborate to develop methods to optimize the design and operations of lunar ISRU plants under uncertainty to help decision-makers make better and more informed decisions. The focus of this collaboration includes practicing flexibility in lunar ISRU design and its operation with sustainability in mind as a key system goal.

Research Overview:

Comprehensive lunar mining simulator and decision support systems. There are now myriad concepts at the ISRU subsystem level, ranging from resource processing to power generation solutions, but there is a general lack of research tools to explore and evaluate how these technologies would work in unison at the system level. This is particularly true when uncertainty in the operating environment is considered despite it posing a considerable threat to the longevity of a lunar ISRU plant. The threat due to uncertain factors is further intensified as the innate harshness and remoteness of the environment creates a situation where responding to unanticipated system problems is extremely difficult. To address this, a research methodology consisting of the development of a simulation game for lunar ISRU has been utilized. This serious game, depicted in figure 1, has been used as a platform to develop decision support systems that aid users in the management of complex systems under uncertainty at the strategic decision level, as well as studying the factors that influence human decision making under uncertainty.

Additionally, it is recognized that there is a lack of a quantitative understanding for what sustainability actually means in an ISRU context. Thus, a set of sustainability indicators for a pilot lunar ISRU plant have been proposed and evaluated within the context of the simulation game developed.

Using these sustainability indicators in the framework of the simulation game, experiments have been run to evaluate the effects of simulation visual fidelity and the presence of emotional cues in managing complex systems under uncertainty, the results of which are summarized in figure 2. It is believed that understanding such factors is especially important for lunar ISRU, where remote operation would play a large part and developing new methodologies for increased situational awareness is vital.

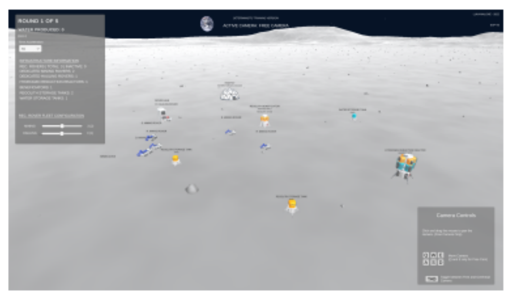


Figure 1: The Comprehensive Lunar Mining Simulator (CLMS)

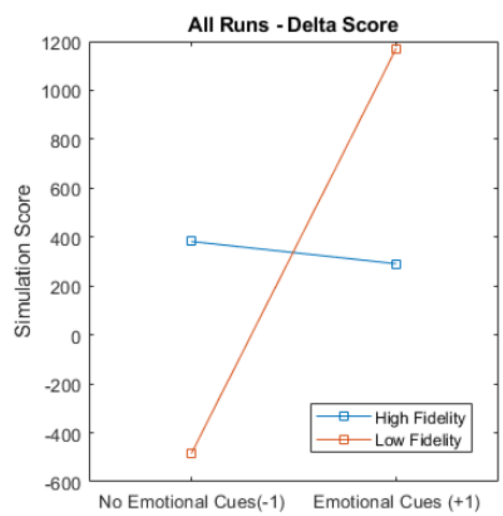
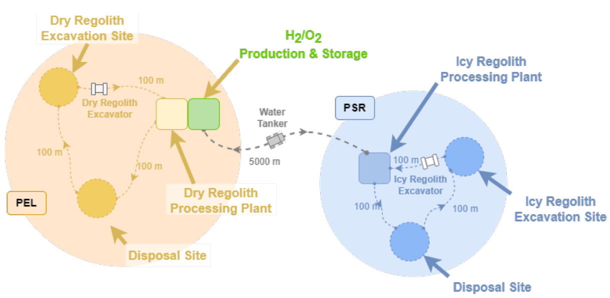


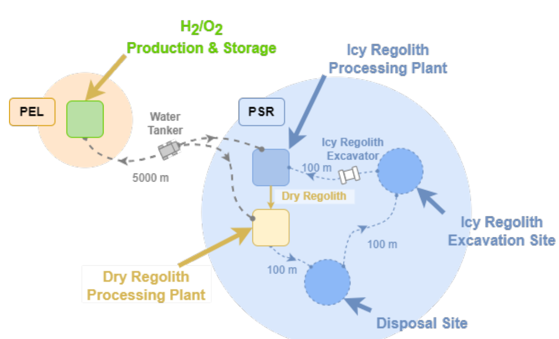
Figure 2: The effects of different treatment conditions on the sustainability score obtained in the CLMS

Hybrid lunar ISRU oxygen plant and multi-objective decision analysis. To address uncertainty stemming from limited information availability in the lunar environment and ISRU operations, an Expected Value of Information (EVoI) methodology, which is commonly used in the terrestrial extraction industry [4], has also been adopted. Utilizing multi-objective decision analysis for lunar ISRU plant deployment, EVoI highlights the importance of gathering more data to better understand the potential benefits and risks associated with ISRU system design and planning. Monte Carlo simulations are used to build a decision tree estimating the impact of uncertain parameters on ISRU plant performance using metrics capturing cost, efficiency, and power consumption.

A case study deploying pilot and full-scale ISRU oxygen production plants in the lunar southern polar region demonstrates the practicality of the EVoI approach. This case study examines four plant architectures: carbothermal reduction of dry regolith, water extraction from icy regolith, and two types of hybrid combinations of both technologies (Types A and B). Type A involves mining and processing in both a permanently shadowed region (PSR) and a peak of eternal light in parallel, while Type B with mining solely in a PSR (Fig. 3). In this Type B hybrid architecture, the dry regolith tailing from water extraction is further processed by carbothermal reduction.



(a) Type A hybrid plant.



(b) Type B hybrid plant.

Figure 3: Two different hybrid ISRU production plant architectures.

A two-stage decision tree is built to examine this case (Fig. 4). The first and the second decisions correspond to the design of the pilot and the full-scale plant, respectively. A multi-objective decision analysis defines a trade-space between each combination of decisions regarding plant design as a Pareto frontier. Figure 5 illustrates a two-dimensional Pareto frontier generated from three objectives: oxygen yield, and mass payback. As can be seen, the Pareto frontier consists of both hybrid plants indicating the proposed hybrid plant helps gather more information on system performance and supports decision-makers to make more informed choices regarding the deployment of a full-scale plant in a subsequent phase.

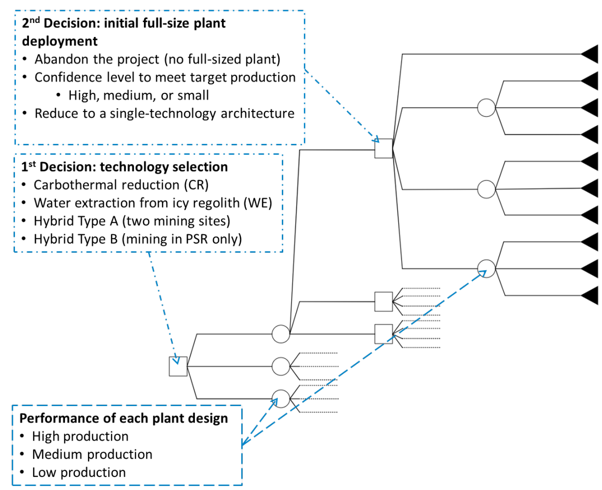


Figure 4: System Decision Tree

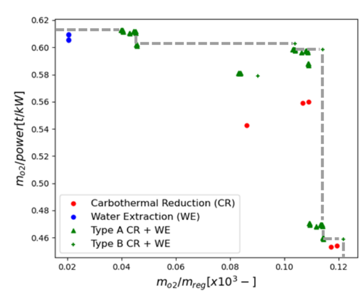


Figure 5: Two-dimensional Pareto frontier.

References: [1] H. Chen et al. (2020) *Acta Astronaut., 170,* 80–92. [2] F. J. Guerrero-Gonzalez. and P. Zabel (2023) *Acta Astronaut., 203,* 187–201. [3] J.J. Cilliers et al. (2020) *Planet. Space Sci., 180,* 104749. [4] J. Savolainen (2016) *Resour. Policy., 50,* 49–65.