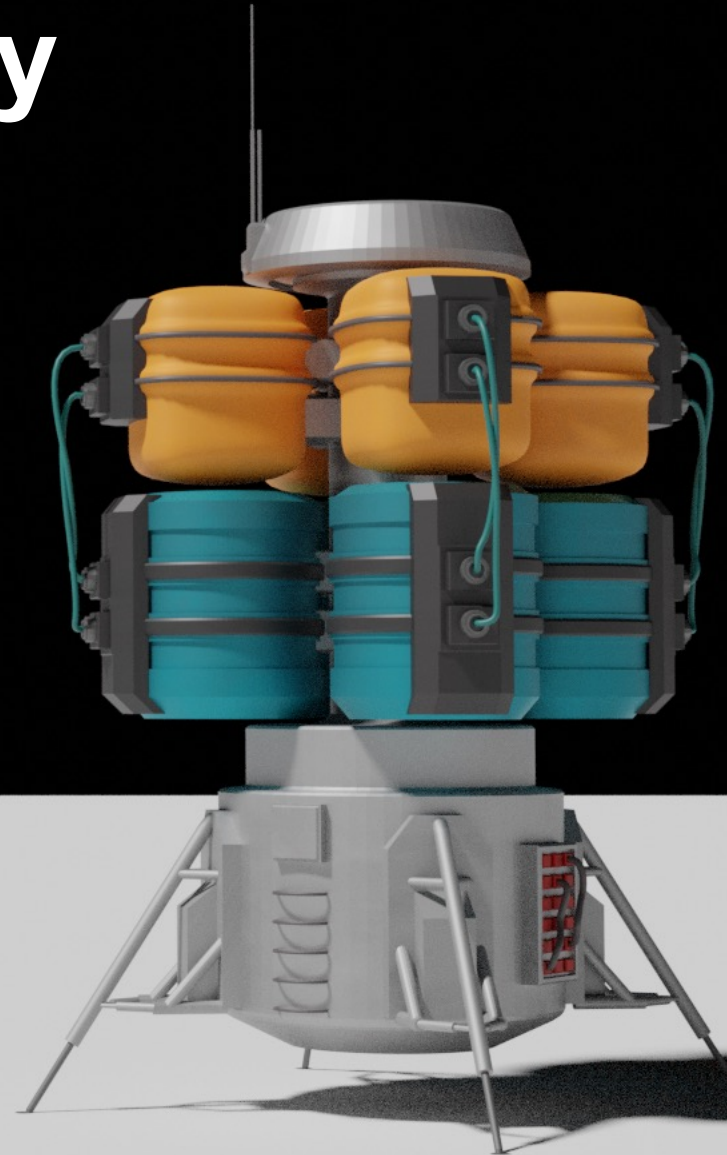


Addressing Uncertainty in Lunar ISRU

An overview of ISRU operations research at
Imperial College London

**Luka Malone / Kosuke Ikeya / Michel-Alexandre Cardin
Jan J. Cilliers / Stanley Starr / Kathryn Hadler
Presenter: Joshua N. Rasera**

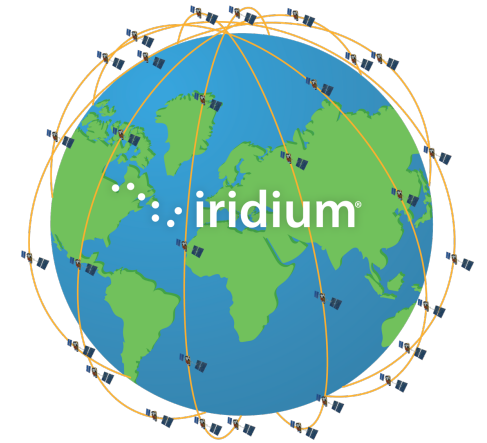


Introduction to Uncertainty

The Future is Uncertain

- Iridium Satellite Constellation (de Neufville, 2011)
 - Satellite phone service
 - Assumed 1 million customers. \$4 billion investment
 - 63,000 customers at max. Sold for \$25 million (~0.6% of the investment)

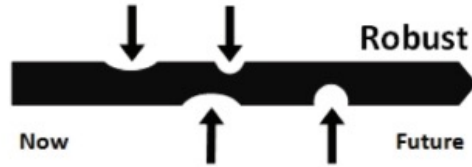
What is of value today may not be so tomorrow, and vice versa



- To tackle uncertain future...
 - Consider uncertainty when designing systems so they do in fact retain value during their lifetime
 - Make sure a system can function in a wide array of future outcomes

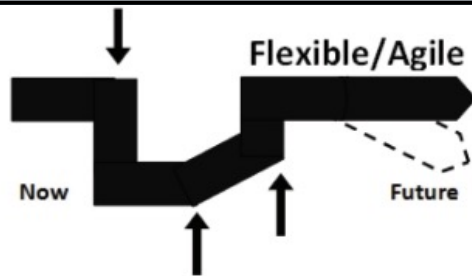
How Can We Respond to Uncertainty?

Design Approaches for Uncertain Futures



Robust design

Performs consistently under various circumstances w/o adapting.



Flexible design

Responds to various situations by adapting, changing, and reconfiguring when necessary.

- A flexible design concept has two key components;
 - System element that can be reconfigured
 - Strategy that determines when, if ever, to do so

‘Provides the right, but not the obligation, to change a project in the face of uncertainty’ – Trigeorgis (1996)

Recognizing Uncertainty and Realizing Flexibility in Lunar ISRU

Lunar ISRU Projects at the Imperial Strategic Engineering Lab

ISRU

- Long project lifetimes (e.g., development & operation)
- Remoteness
- Extreme uncertainty

Exogenous uncertainty examples

- Demand for resources extracted
- Material availability (water ice, metal oxides)

Endogenous uncertainty examples

- Earth/Moon launch failures
- New missions

Because of the long development time for ISRU systems, we need to start considering these approaches NOW

Addressing Lunar ISRU Uncertainty at **IMPERIAL**

Hybrid Lunar ISRU LOX Plant &
Multi-Objective Decision Analysis

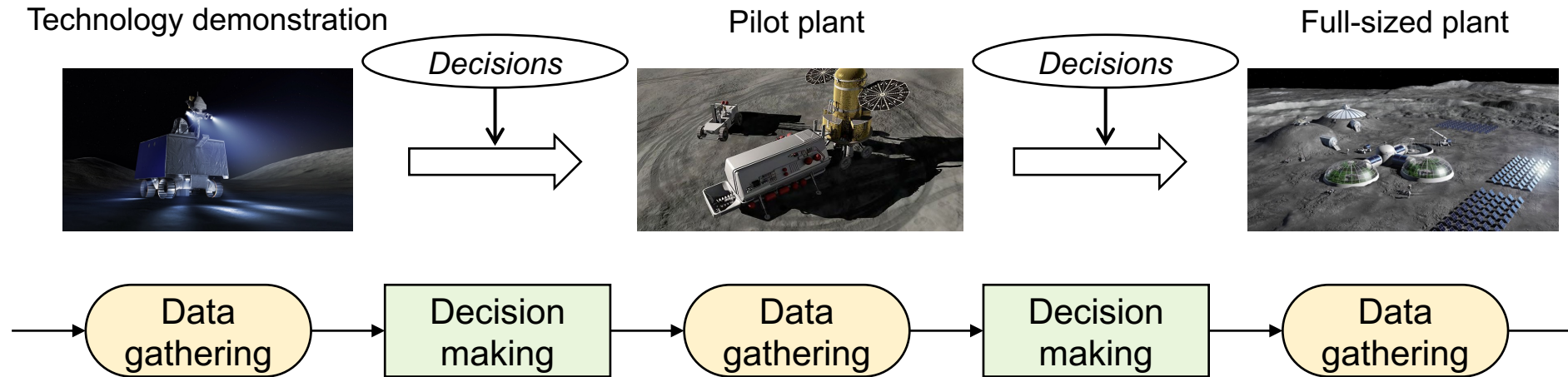
Lunar Mining Simulator To Study Decision
Making Under Uncertainty

Hybrid Lunar ISRU LOX Plant & Multi-Objective Decision Analysis

Addressing Uncertainty with Information Gathering

Sequential Decision Making

- Deployment of lunar ISRU is a *sequential decision making* problem



- Value of Information* & Exploration-exploitation dilemma
 - Potential better decisions by gathering more data vs Gathering more data costs more

What is the expected value of information in lunar ISRU?

Case Study: ISRU Technology Selection

Carbothermal Reduction



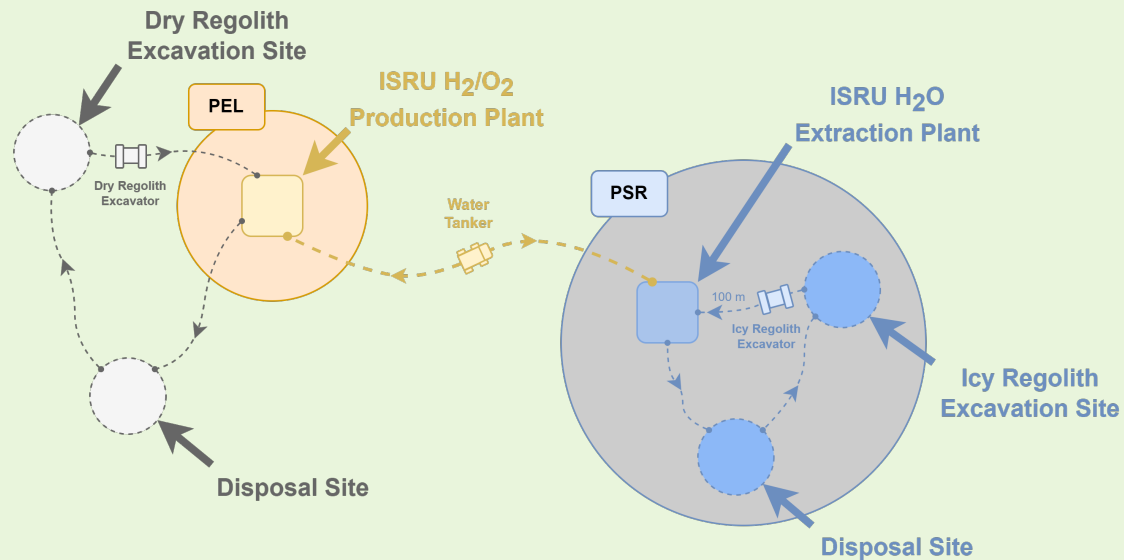
- Extract oxygen from metal oxides in regolith
- Requires very high temperature (1250-2000 °C)
- Complicated process

Water Extraction from Icy Regolith

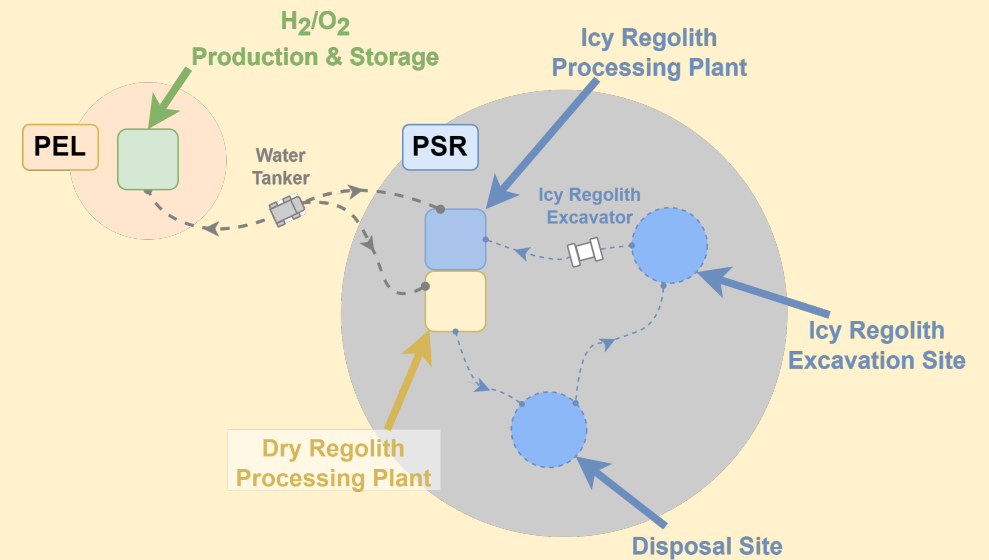


- Extract water from icy regolith in Permanently Shadowed Regions (PSRs)
- Water content is highly uncertain
- Requires material transport

Parallel Production Plant

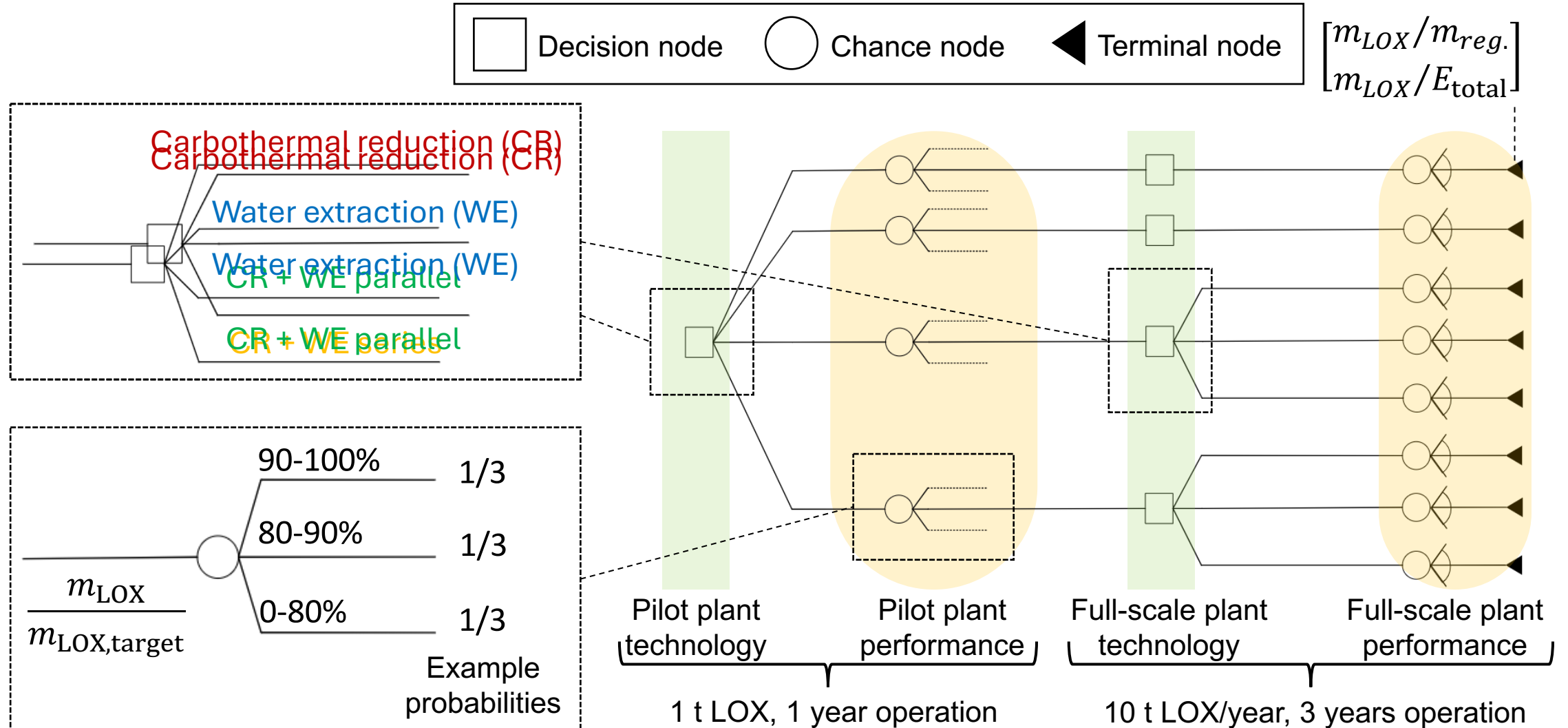


Series Production Plant



Decision Analysis

Two Stage Decision Tree for Pilot & Full-Scale Deployment

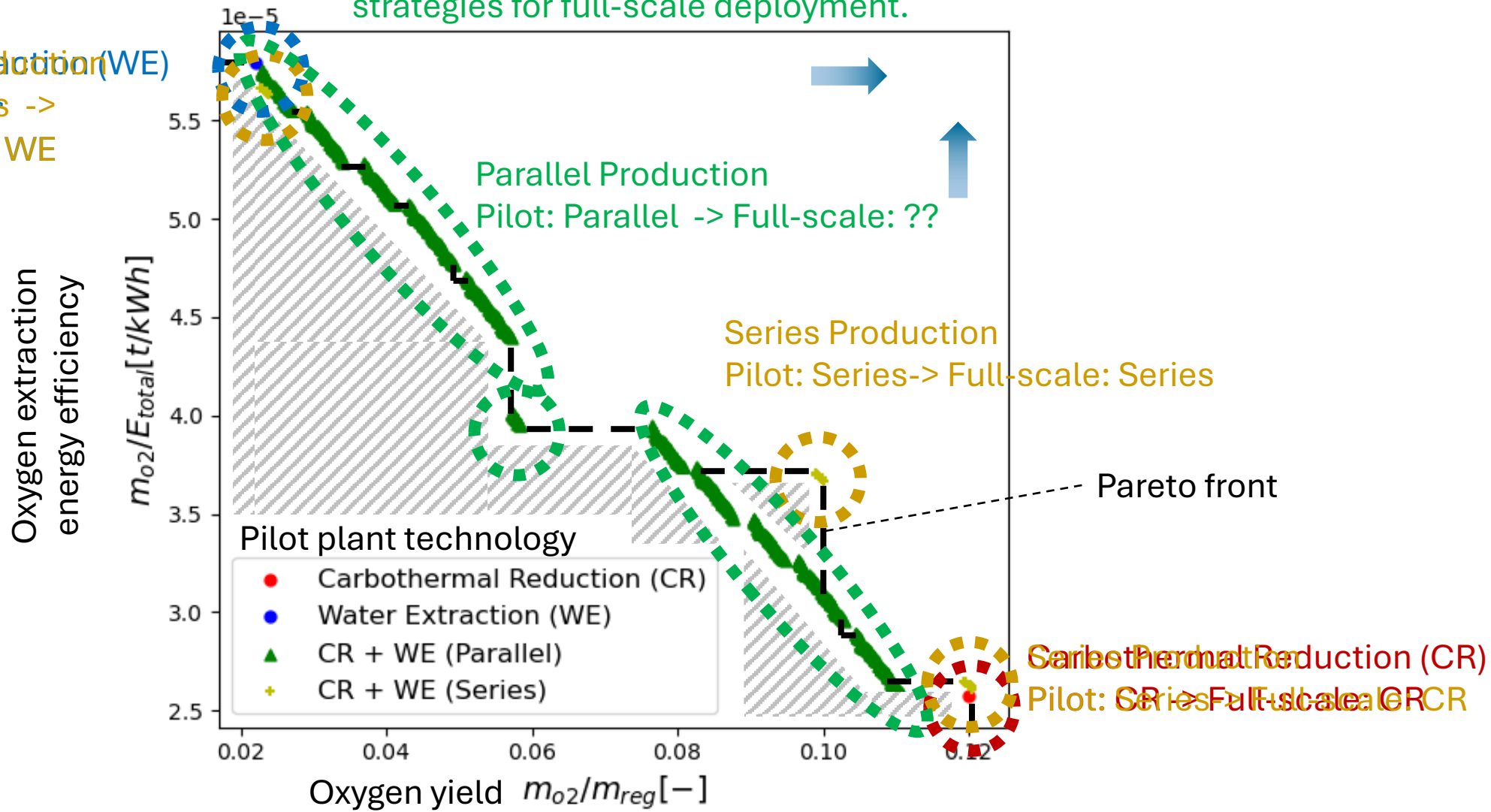


Result

Pareto Front

Series Production (WE)
Pilot: WE ->
Full-scale: WE

Parallel Production can change its production ratio between CR and WE.
Therefore, by deploying Parallel pilot plant, we can have the most flexible strategies for full-scale deployment.

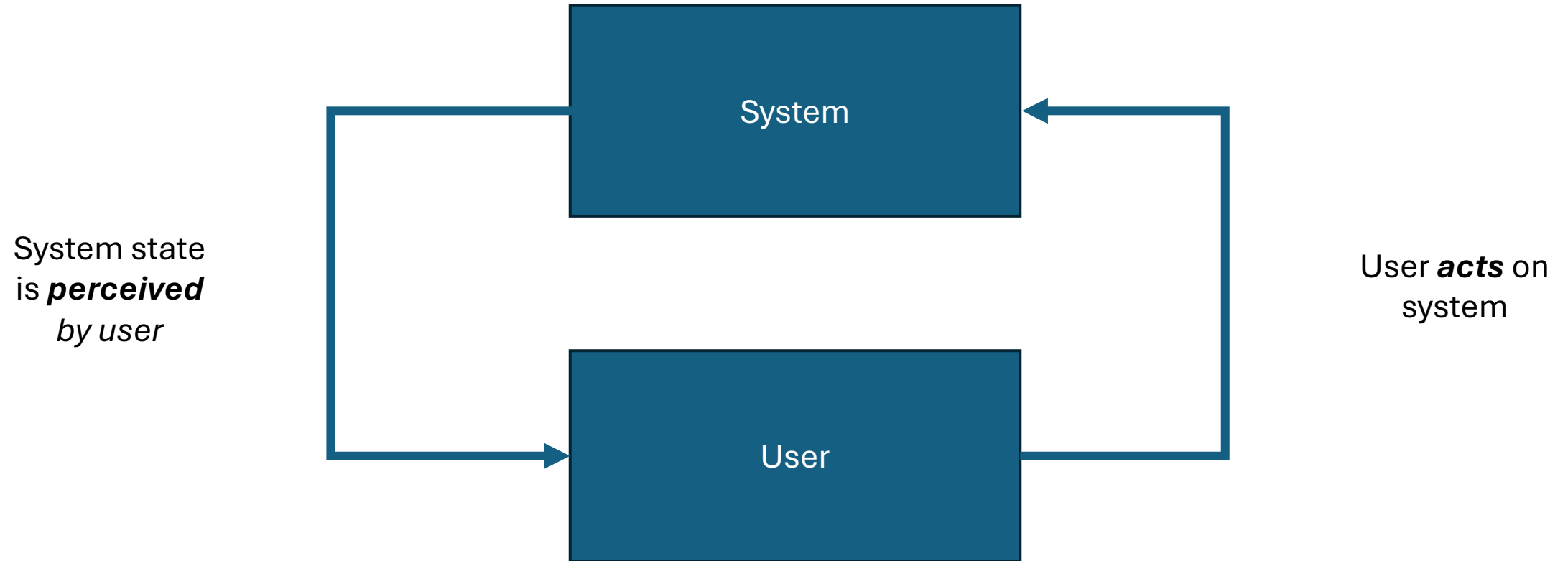


A Lunar Mining Simulator To Study Decision Making Under Uncertainty

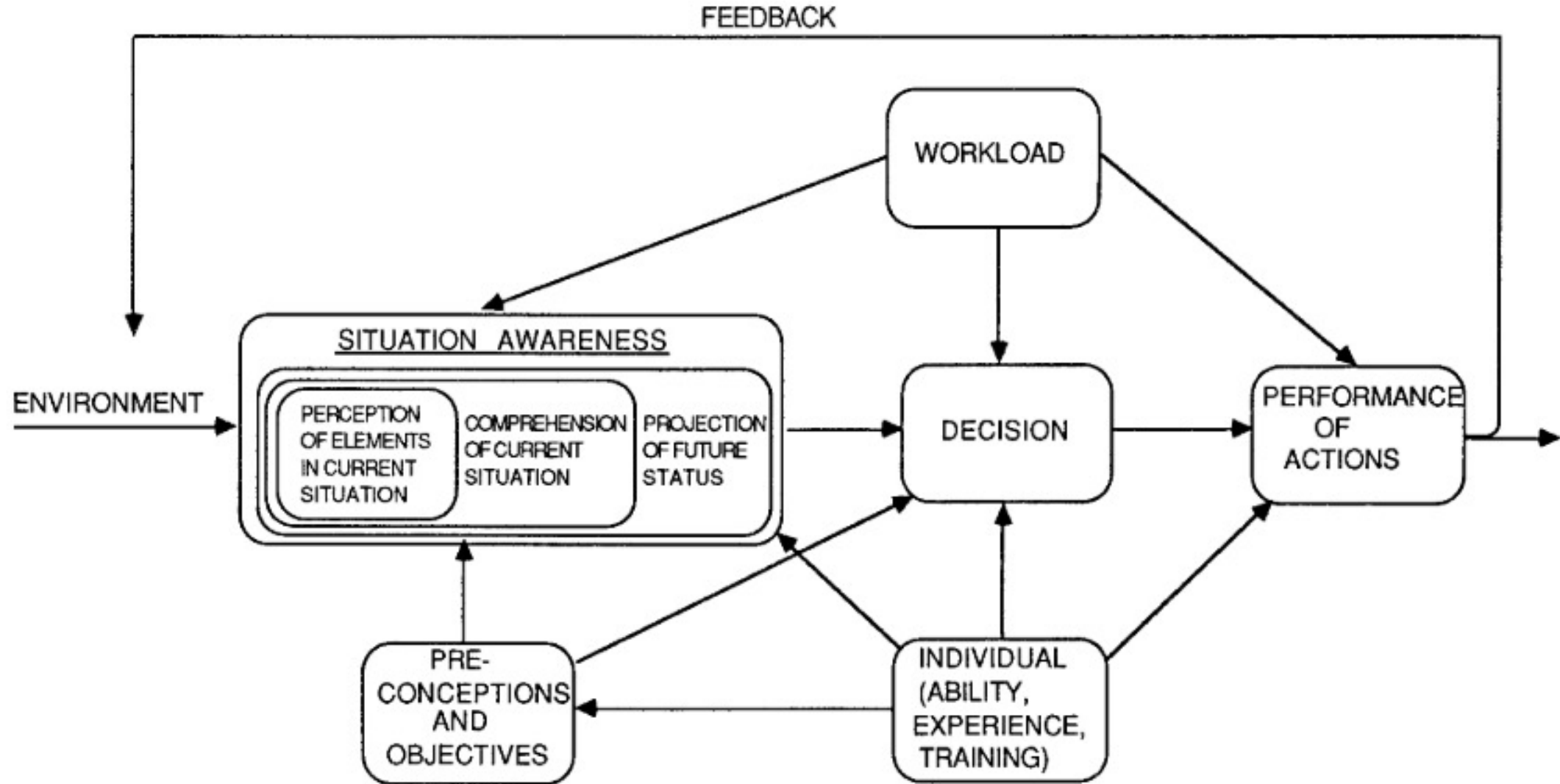
Using Serious Games to Study Decision Making Under Uncertainty

- Strategic level decisions are made by **people**, not control algorithms
- Including human operators 'In the loop'
- Aiding user's in making decisions in extremely uncertain contexts, such as Lunar ISRU

Using Serious Games to Study Decision Making Under Uncertainty



Situational Awareness

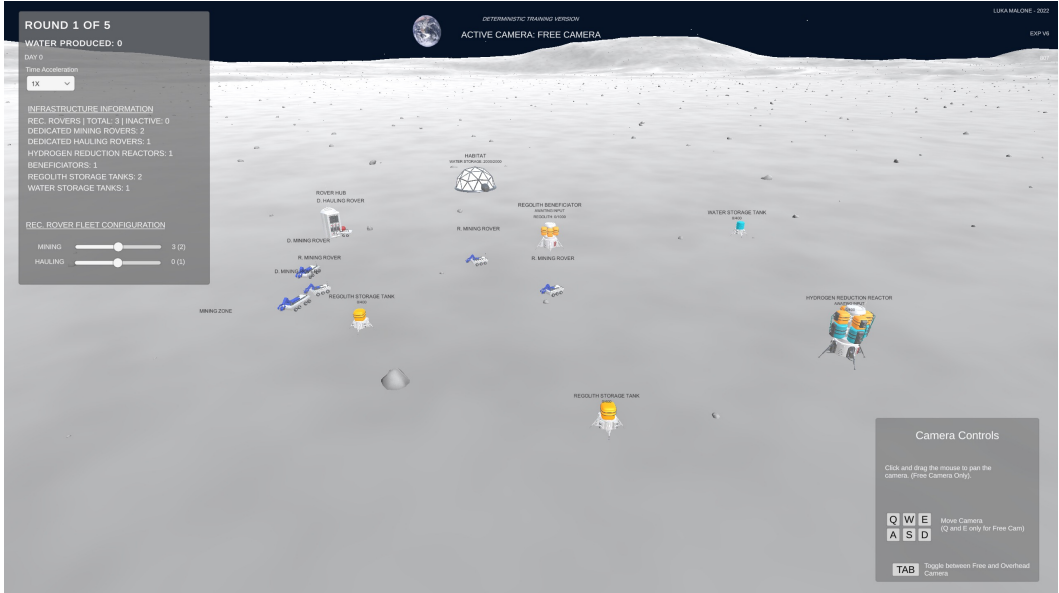


Adapted from Endlsey, M. R. (1988), *SITUATION AWARENESS GLOBAL ASSESSMENT TECHNIQUE (SAGAT)*.

Visual Fidelity



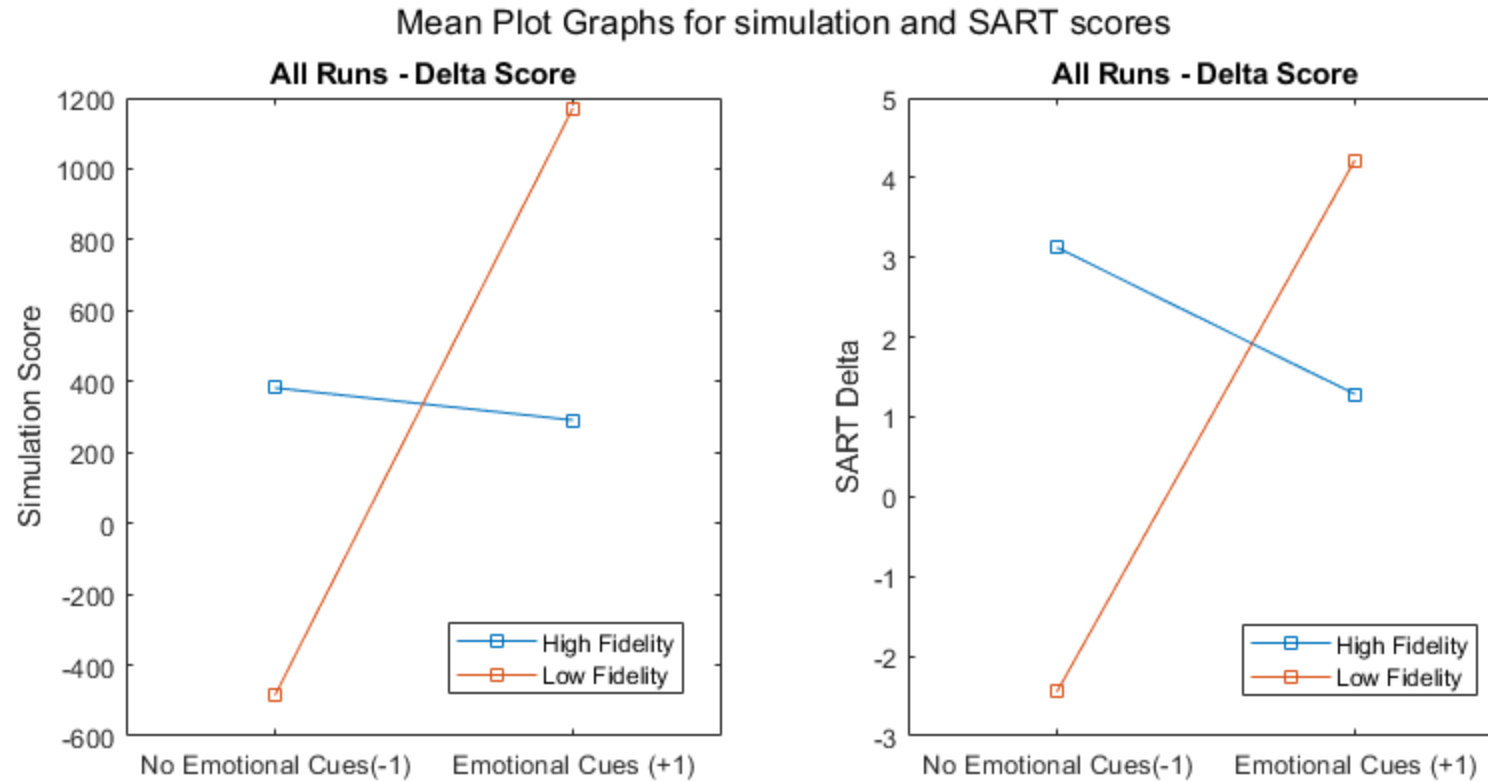
Low Visual Fidelity



High Visual Fidelity

Study Results

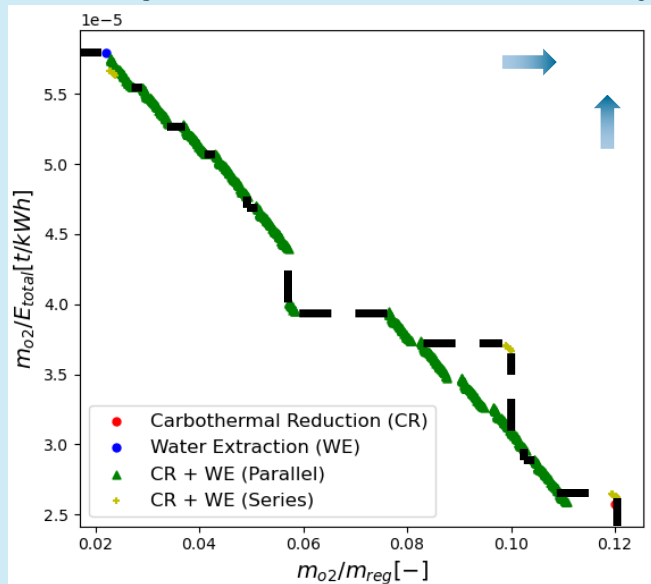
The effect of simulation fidelity and emotional cues



Summary

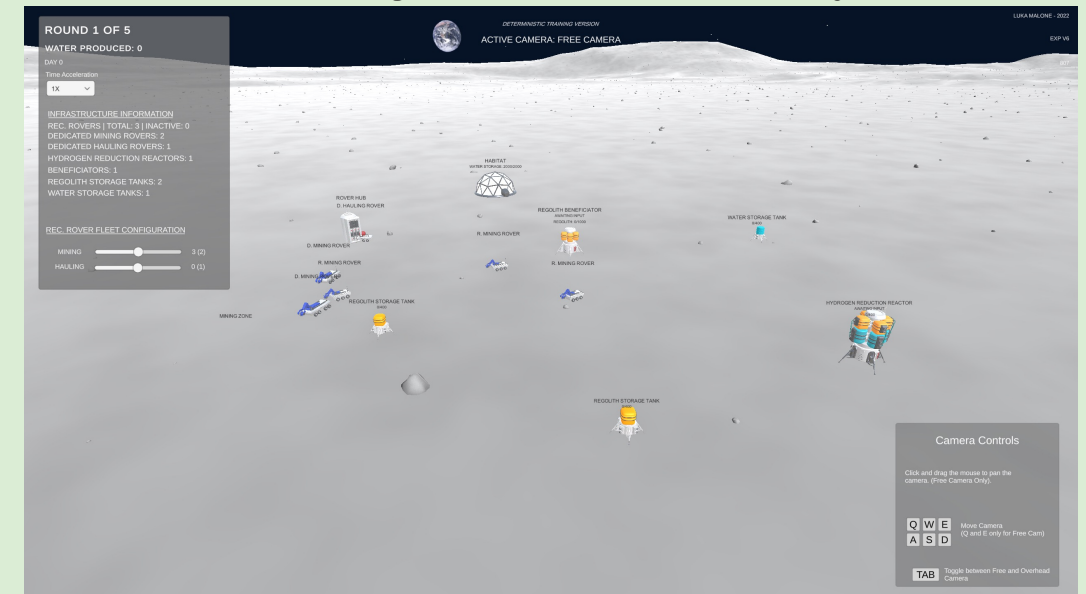
Lunar ISRU can greatly benefit from flexible approaches due to its uncertainty and long lifetimes.

Hybrid Lunar ISRU LOX Plant & Multi-Objective Decision Analysis



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Lunar Mining Simulator To Study Decision Making Under Uncertainty



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Thank you