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Summary of ISRU Trade Study

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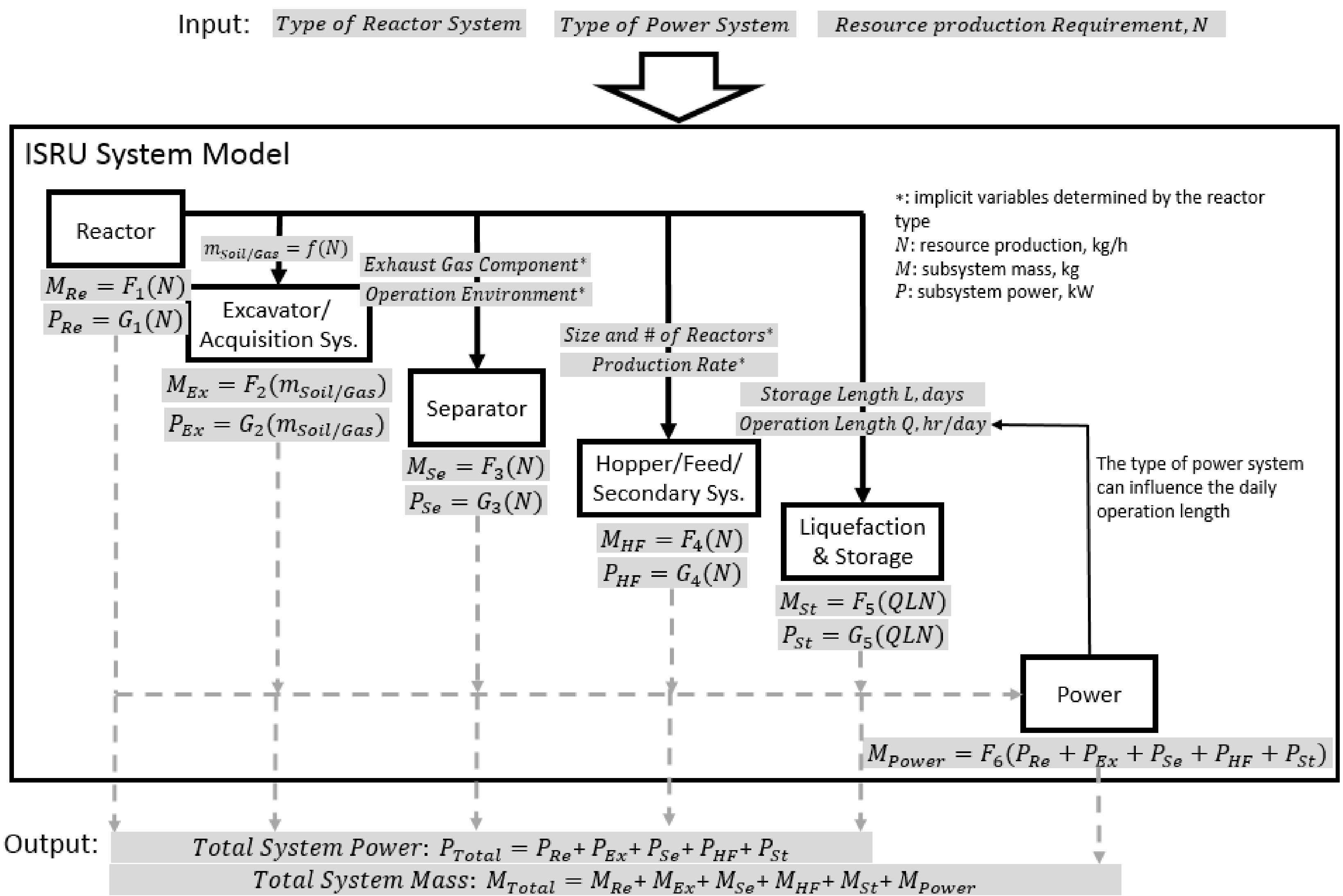
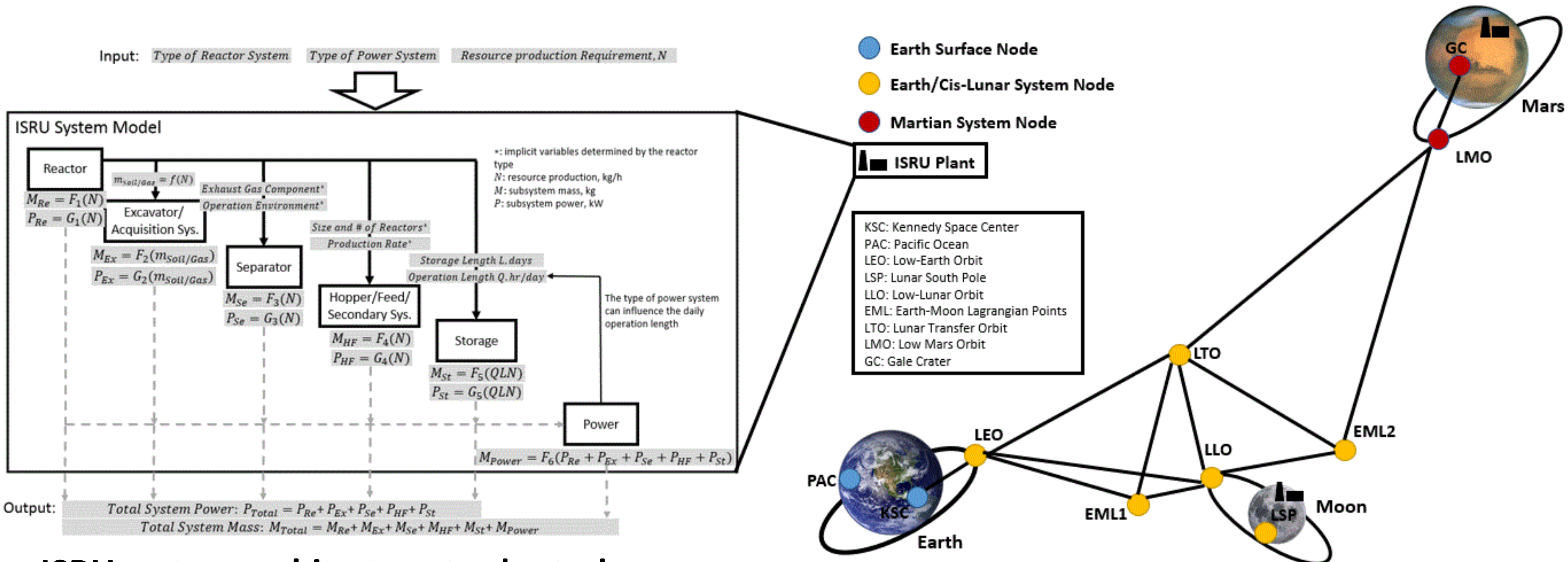
- H. Chen, T. Sarton du Jonchay, L. Hou, and K. Ho, "Integrated In-Situ Resource Utilization System Design and Logistics for Mars Exploration," *Acta Astronautica*, Vol. 170, pp. 80-92, 2020.

Integrated ISRU Models

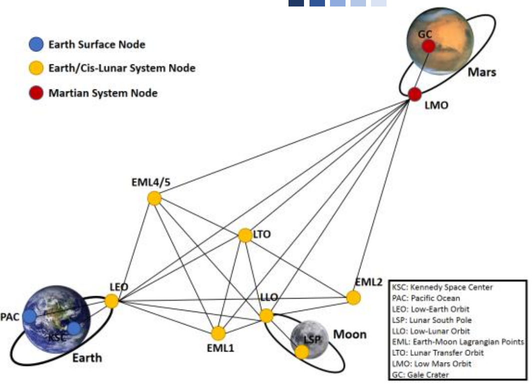


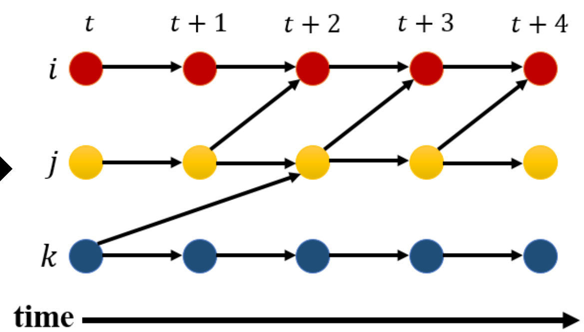
ISRU Trade Studies



- **ISRU system architecture trade study:**
  - Reactor type(s) selection for demands
  - Power subsystem selection: PV vs nuclear
- **ISRU operational trade study**:
  - Daytime-only operation or deploy additional batteries/fuel cells for night
  - Frequency of logistics missions and its impact on storage size
- **ISRU deployment timeline/location trade study:**
  - Deploy ISRU in 1 stage or multiple stages? If multiple stages, how many?
  - Could lunar ISRU be beneficial to Mars mission?
  - What if there is a space station, such as Deep Space Gateway?

Space Logistics Optimization





Minimize: $\mathcal{J} = \sum_{(v,i,j,t)\in\mathcal{G}} \boldsymbol{c}_{vijt}{}^{T} \boldsymbol{x}_{vijt}$

Subject to:

$$\sum_{(v,j):(v,i,j,t)\in\mathcal{G}} \boldsymbol{x}_{vijt} - \sum_{(v,j):(v,j,i,t)\in\mathcal{G}} F_{vji}\boldsymbol{x}_{vji(t-\Delta t_{ji})} \leq \boldsymbol{d}_{it} \quad \forall i \in \mathcal{N} \;\; \forall t \in \mathcal{T}$$ → Mass balance

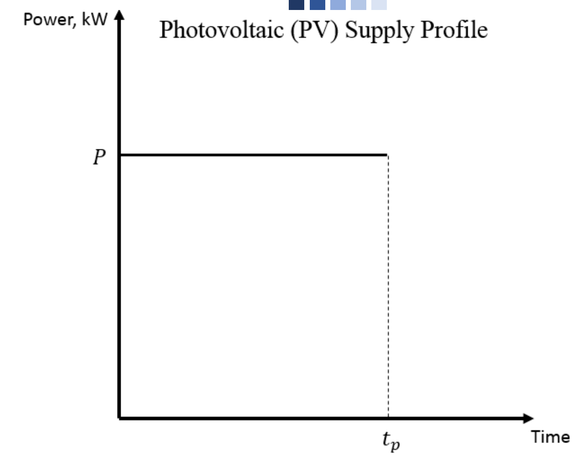
($F_{vji}\boldsymbol{x}_{vji(t-\Delta t_{ji})}$ → Flow Transformation)

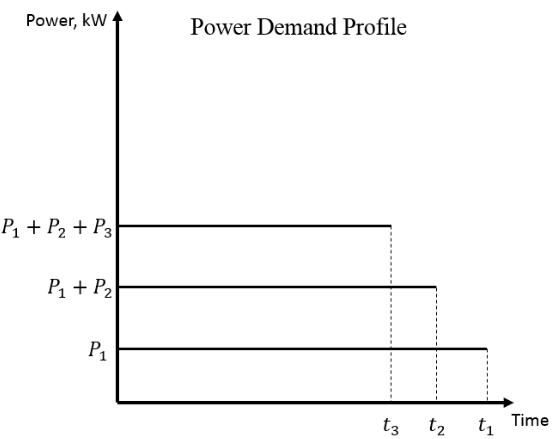
$$H_{vij}\boldsymbol{x}_{vijt} \leq \boldsymbol{0}_{l\times 1} \quad \forall (v,i,j,t) \in \mathcal{A}$$ → Flow Concurrency

$$\begin{cases} \boldsymbol{x}_{vijt} \geq \boldsymbol{0}_{p\times 1} & \text{if } t \in W_{ij} \\ \boldsymbol{x}_{vijt} = \boldsymbol{0}_{p\times 1} & \text{otherwise} \end{cases} \quad \forall (v,i,j,t) \in \mathcal{A}$$ → Flow bound

$$\boldsymbol{x}_{vijt} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_p \end{bmatrix}_{vijt}, x_n \in \mathbb{Z}_+ \; or \; \mathbb{R}_+ \quad \forall n \in \{1, \dots, p\} \quad \forall (v,i,j,t) \in \mathcal{A}$$

Power System Analysis Example





Define the commodity flow variables as,

$$\boldsymbol{x}_{vijt} = \begin{bmatrix} x^{I_1}\text{: infrastructure system 1, kg} \\ x^{I_2}\text{: infrastructure system 2, kg} \\ x^{I_3}\text{: infrastructure system 3, kg} \\ x^{P}\text{: power generation system, kg} \\ x^{E}\text{: energy storage system, kg} \end{bmatrix}_{vijt}$$

Power generation capacity constraint can be written as,

$$\begin{bmatrix} P_{I_1}(1+\frac{Q_{I_1}-Q_p}{\varepsilon Q_p}) & P_{I_2}(1+\frac{Q_{I_2}-Q_p}{\varepsilon Q_p}) & P_{I_3}(1+\frac{Q_{I_3}-Q_p}{\varepsilon Q_p}) & -P_0 \end{bmatrix}_{vij} \begin{bmatrix} x^{I_1} \\ x^{I_2} \\ x^{I_3} \\ x^{P} \end{bmatrix}_{vijt} \leq 0$$

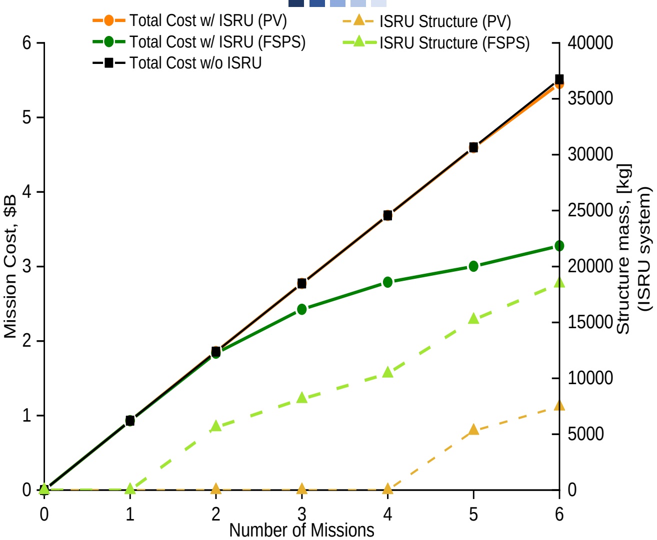
where Q is the system operation time per solar day.

The **energy storage capacity constraint** can be written as,

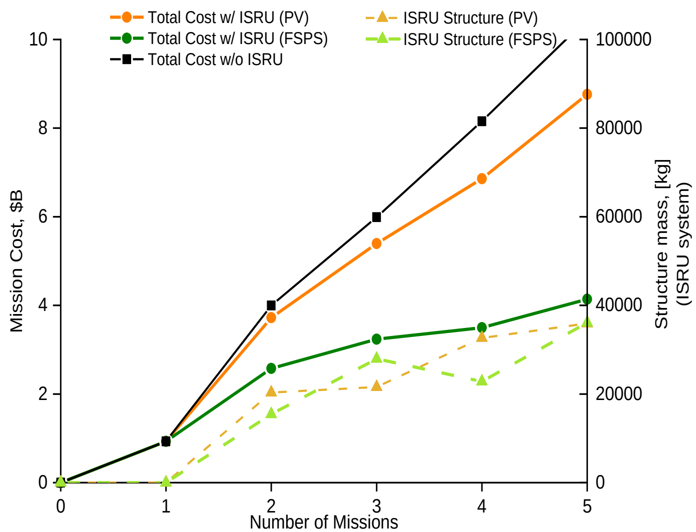
$$\begin{bmatrix} -P_{I_1} & -P_{I_2} & -P_{I_3} & P_0 & -\frac{\gamma}{\varepsilon Q_p} \end{bmatrix}_{vij} \begin{bmatrix} x^{I_1} \\ x^{I_2} \\ x^{I_3} \\ x^{P} \\ x^{E} \end{bmatrix}_{vijt} \leq 0$$

where P is the system power demand or supply.

Example Results



Cargo transportation mission (One-way)



Human exploration mission (Round-trip)

- ISRU is more effective for round-trip missions than one-way cargo missions;
- FSPS (Fission Surface Power Systems) has a better performance than the PV (Photovoltaic) power system (i.e., solar panels) in this case.

- **Developed optimization framework can be used for**
  - ➢ Design of large-scale space exploration campaign considering the interaction between space infrastructure design and space transportation planning.
  - ➢ Fast evaluation of potential performances of space architectures and spacecraft in large-scale campaign