Predictive Modeling for Phased Infrastructure Buildup on the Lunar Surface

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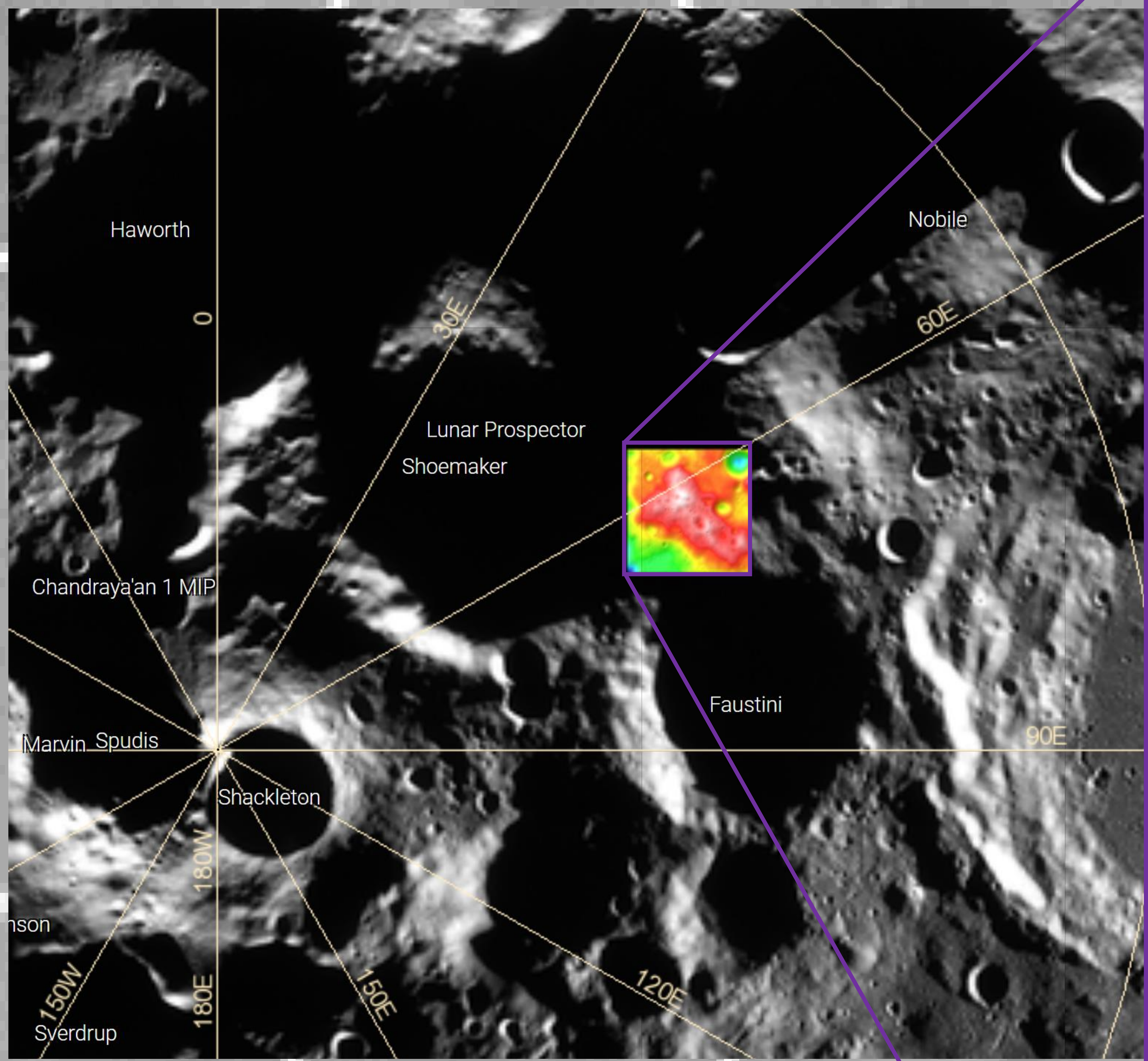
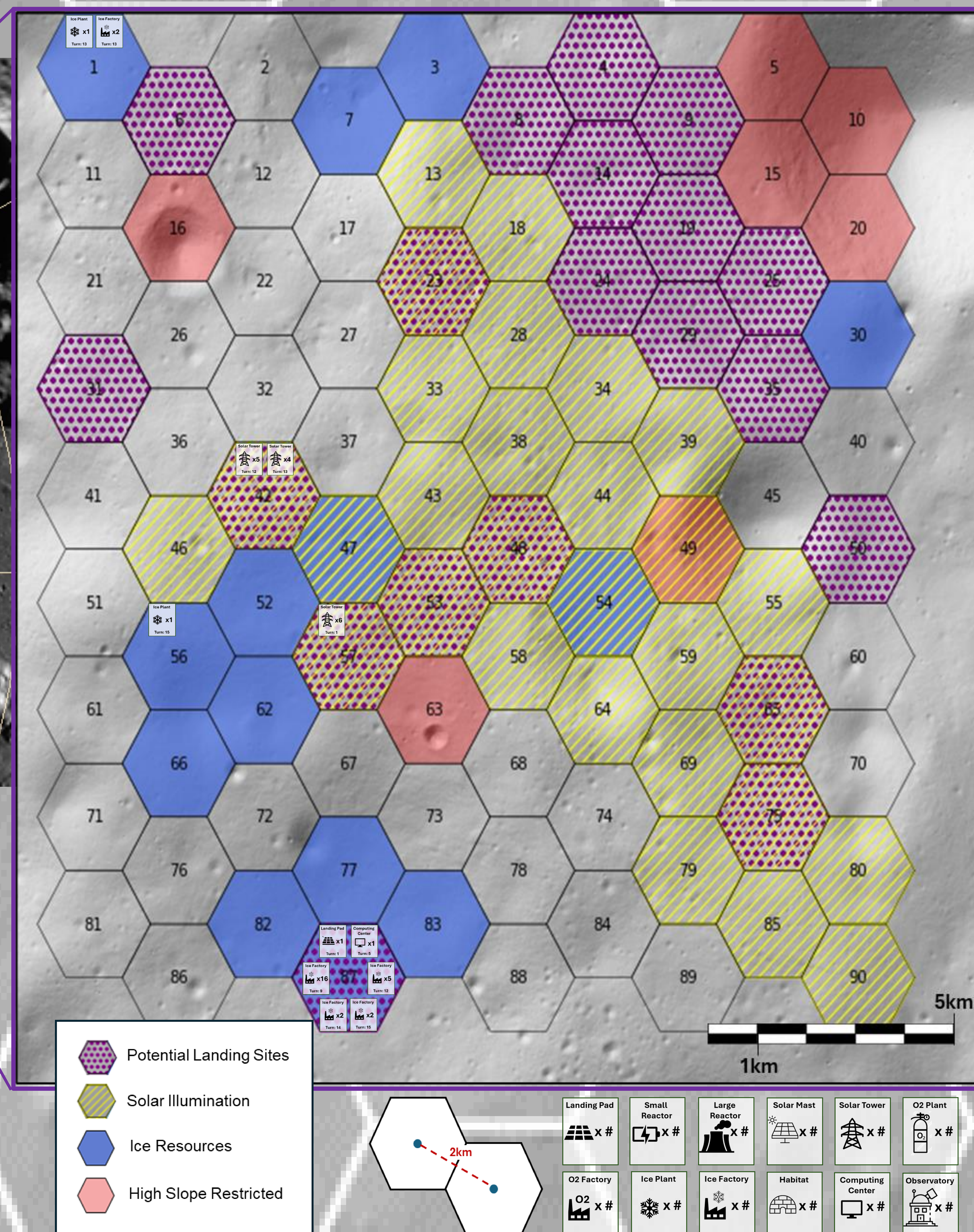




Background

Missions face numerous challenges related to resource management. These include limited budgets, logistical complexities, harsh environmental conditions, and long-term sustainability. Traditional resource management strategies in space missions have relied heavily on Earth-based resupply missions. However, these approaches are not sustainable for prolonged missions or permanent settlements. Recent advancements in in-situ resource utilization (ISRU) have shown promise in addressing some of these challenges by enabling the extraction and processing of local resources. There remains a need for comprehensive models that can optimize the allocation and utilization of resources to ensure mission success.

Motivation for Optimization Models

The development of optimization models for space resource utilization is driven by the need to overcome these challenges and enhance the feasibility of long-term space missions. By incorporating factors such as launch costs, cargo capacities, resource production, and transportation logistics, these models can provide strategic insights into the effective allocation of resources.

Optimization models can help address key questions such as:

- How can resources be allocated efficiently to support mission objectives?
- What are the optimal strategies for deploying assets and equipment?
- How can the sustainability of missions be ensured through effective resource management?

This study presents a Mixed-Integer Programming (MIP) model that aims to optimize the allocation and utilization of space resources. By considering a range of factors that impact resource management, the model provides an initial framework for enhancing the sustainability and feasibility of space missions.

Selected References: [1] Rardin (2017) *Optimization in Operations Research*. [2] Wosley (2020) *Integer Programming*. [3] Bae et al., (2022) *Littoral Commander: Indo-Pacific.* [4] Menges & Cannon (2022), *SRR XXII.*

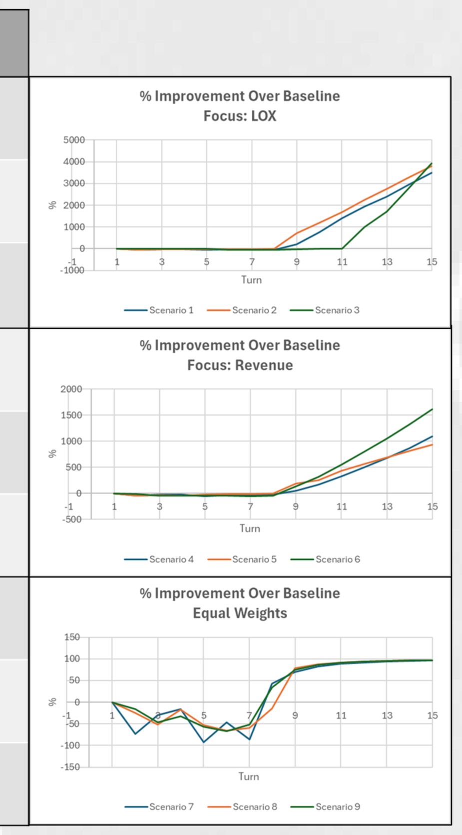
Results

To evaluate the performance of the optimization model, we tested it under various scenarios with differing budgets and time horizons. The scenarios are designed to simulate real-world conditions and challenges encountered during space missions.

Optimization Results

The optimization model was run for each scenario to determine the optimal allocation and utilization of resources. Key results include the number of spacecraft launched, assets deployed, resources produced and consumed, and the total victory points achieved. The results demonstrate the model's effectiveness in maximizing resource utilization and mission sustainability.

Scenario	Budget (Tokens)	Weights	Spacecraft Launched	Assets Constructed	Total Points
1	20 (low)	Tokens: 1 LOX: 2 Power: 0	S: 33 M: 9 L: 9	CC: 2, IF: 9, IP: 2, LP: 2, OF: 3, ST: 12	10807
2	*50 (med)*	*Tokens: 1 LOX: 2 Power: 0*	*S: 16 M: 6 L: 5*	*CC: 1, IF: 27, IP: 2, LP: 1, ST: 15*	*29276*
3	100 (high)	Tokens: 1 LOX: 2 Power: 0	S: 79 M: 45 L: 2	CC: 16, IF: 99, IP: 2, LP: 2, OB: 3, SR: 1, ST: 52	60499
4	20 (low)	Tokens: 2 LOX: 1 Power: 0	S: 4 M: 3 L: 14	CC: 3, IF: 17, LP: 1, SM: 3, ST: 10	7160
5	50 (med)	Tokens: 2 LOX: 1 Power: 0	S: 4 M: 4 L: 6	CC: 1, IF: 29, LP: 1, ST: 20	15558
6	100 (high)	Tokens: 2 LOX: 1 Power: 0	S: 0 M: 8 L: 49	CC: 19, IF: 115, LP: 2, ST: 68	51380
7	20 (low)	Tokens: 1 LOX: 1 Power: 1	S: 0 M: 3 L: 16	CC: 3, IF: 17, IP: 1, LP: 2, ST: 10	7379
8	50 (med)	Tokens: 1 LOX: 1 Power: 1	S: 1 M: 1 L: 17	CC: 7, IF: 51, LP: 2, ST: 22	23387
9	100 (high)	Tokens: 1 LOX: 1 Power: 1	S: 0 M: 10 L: 48	CC: 17, IF: 108, IP: 1, LP: 2, ST: 49	47244



Model

Sets

$T = \{1,2,\dots,20\}$ set of time periods indexed by *t*
$H = \{1,2,\dots 90\}$ set of hexes indexed by *h*
$U = \{rover, hauler, raw\ cargo\}$ set of launched cargo indexed by *u*
$S = \{small, medium, large\}$ set of spacecraft/lander types indexed by *s*
$A = \{solar\ mast, solar\ tower, small\ reactor, large\ reactor, ice\ plant, ice\ factory, O2\ plant, O2\ factory, landing\ pad, habitat, observatory, computing\ center\}$ set of constructable assets indexed by *a*

Decision Variables

$X_{s,h,t} \geq 0$ (Number of spacecraft *s* launched to hex *h* in turn *t*)
$Z_{u,s,h,t} \geq 0$ (Number of launched assets *u* on spacecraft *s* launched to hex *h* in turn *t*)
$B^{rover}_{h1,h2,t} \geq 0$ (Number of rovers moved from hex *h1* to hex *h2* in turn *t*)
$B^{hauler}_{h1,h2,t} \geq 0$ (Number of rovers moved from hex *h1* to hex *h2* in turn *t*)
$C^{rover}_{h1,h2,t} \geq 0$ (Units of raw cargo moved by rovers from hex *h1* to hex *h2* in turn *t*)
$C^{hauler}_{h1,h2,t} \geq 0$ (Units of raw cargo moved by haulers from hex *h1* to hex *h2* in turn *t*)
$G_{h,t} \geq 0$ (Units of LOX produced at hex *h* in turn *t*)
$K_t \geq 0$ (Total tokens available at beginning of turn *t*)
$L_t \geq 0$ (Total LOX units available at beginning of turn *t*)
$P_t \geq 0$ (Power units available at beginning of turn *t*)
$D^{rover}_t \geq 0$ (Number of new rovers deployed in turn *t*)
$D^{hauler}_t \geq 0$ (Number of new haulers deployed in turn *t*)
$Q^{rover}_t \geq 0$ (Cumulative number of rovers available in turn *t*)
$Q^{hauler}_t \geq 0$ (Cumulative number of haulers available in turn *t*)
$N_{a,h,t} \geq 0$ (Number of newly constructed assets *a* in turn *t*)
$Y_{a,h,t} \geq 0$ (Cumulative number of constructed assets *a* available in turn *t*)
$R_{h,t} \geq 0$ (Units of raw cargo, $a \in \{raw\ cargo\}$, available for construction at hex *h* in turn *t*)

Parameters

lc_s – cost to launch spacecraft type *s* [tokens]
cap_s – cargo capacity of spacecraft type *s* [cargo units]
b – constant budget per turn [tokens]
lp_a – LOX production per turn for asset *a* [LOX units]
pg_a – power generated per turn by asset *a* [power units]
pu_a – power used per turn by asset *a* [power units]
r_a – revenue generated per turn by asset *a* [tokens]
$blue_h$ – binary indicator for ice at hex *h*
red_h – binary indicator for restrictive (high) slope at hex *h*
$yellow_h$ – binary indicator for sufficient solar illumination at hex *h*
$purple_h$ – binary indicator for landing site candidate at hex *h*
rc_a – raw cargo required to construct asset *a* [cargo units]
bc_a – cost to construct asset *a* [tokens]
$mcap_u$ – cargo capacity of mover $u \in \{rover, hauler\}$ [cargo units]
cc_u – amount of space (cargo cost) cargo type *u* occupies in spacecraft [cargo units]
$M = 1000$ (big-M constant)
w_K – token weight
w_L – LOX weight
w_P – power weight

Objective Function

$$Maximize\ VictoryPoints:$$
$$w_K K_{|T|} + w_L L_{|T|} + w_P P_{|T|}$$

The model incorporates various constraints to ensure the feasibility and logical consistency of the space resource optimization problem. Initially, the model sets the initial values for budget. The budget constraint ensures that the total expenditure on launching spacecraft and constructing assets in each turn does not exceed the available tokens. This is complemented by a constraint that updates the tokens available for subsequent turns, accounting for launch costs, construction costs, and revenue generated from assets.

To manage the movement of resources, constraints are included to govern the movement of cargo by rovers and haulers. These constraints ensure that the amount of cargo moved does not exceed the capacity of the rovers and haulers and that no cargo is moved to red hexes (high slope areas). Additionally, there are constraints that limit the launch capacity of spacecraft, ensuring that the total cargo loaded does not exceed the spacecraft's capacity.

The deployment constraints track the total number of rovers and haulers deployed over time, ensuring cumulative consistency across turns. Power generation and usage are carefully managed through constraints that update the stored power based on the power generated and used by the constructed assets, ensuring assets only operate if sufficient power is available.

For the production of LOX, the model includes constraints that calculate the amount of LOX produced based on the assets constructed in each hex and turn. This is followed by a constraint ensuring that the total LOX available is updated correctly each turn. The construction of assets is also restricted by the availability of raw cargo, and specific assets can only be constructed on appropriate hexes (e.g., ice plants on blue hexes and solar towers on yellow hexes).

Finally, landing constraints ensure that spacecraft landings are feasible based on the construction of landing pads and the suitability of the hexes for landing. Together, these constraints create a comprehensive framework for optimizing the deployment and operation of assets in a space utilization scenario, balancing resource availability, logistical considerations, and operational constraints to maximize the overall victory points.