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# CONSTRUCTION

## *"Factor Rating Analysis for Potential Lunar Mining Facility"*

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**Abstract**
Factor rating analysis may be an effective strategy for determining emplacement of a future mining facility on the lunar surface. With NASA and commercial ventures planning new missions to the Moon via the Artemis program, a critical driver will be a long-term liquid oxygen (LOX) processing facility to maintain a permanent presence. While a lunar mining facility is not in NASA's first phase of their return to the Moon program, it is an important operational component in their long-term strategy of permanent presence. The facility at Shackleton Crater was chosen by weighted criteria derived from the analytic hierarchy process (AHP). By assessing the following six key factors: (1) Power, (2) Communication, (3) Site Access, (4) Protection, (5) Transportation and Logistics, and (6) Safety Egress via AHP, a viable solution could be made for determining a proposed facility location, especially when baseline knowledge is limited. While risks in all operational areas are high, a methodical evaluation of the key factors could potentially drive down some of those risks, specifically if site access and manufacturing are co-located with one another to minimize logistical needs. Our analysis assessed a research site on the ridge of Shackleton crater to test out unique mining and manufacturing techniques for lunar ice in the sub-surface soil of the permanently shadowed regions. Future lunar mission planners may use AHP prior to prospecting surveys for site selection of a pathfinder outpost site. This site could then scale up to a full lunar mining facility, thereby potentially satisfying the demands of future lunar surface operations.

**Introduction**
NASA and commercial enterprise are planning on returning to the Moon in this decade (Crane, 2017). Mission planning is currently oriented toward setting up initial transportation and logistics infrastructure (NASA, 2017; 2020). However, future site selections have not been addressed specifically for permanently crewed facilities on the lunar surface. There will be a long-term need for a lunar processing facility of both hydrogen and oxygen to be extracted out of the sub-surface ice at the poles of the Moon. This lunar ice discovered at both lunar poles will be an important resource for future crewed outposts (Spudis & Lavoie, 2011). Lunar ice can provide both water and fuel for expected surface operations and construction. There have been a number of proposed sites for permanent presence on the Moon. Hence, a selection process needs to be developed when there is limited detail of both surface and subsurface conditions at each proposed site. An assessment model will help simplify site selection for future construction on the lunar surface.

**Operational Scenario**
For purposes of this study, a site selection for a future lunar mining facility was proposed. With NASA and commercial enterprise planning to return to the Moon (NASA, 2017), a facility to produce liquid oxygen (LOX) and liquid hydrogen (LH) will be needed for both fuel, potable water, and breathable air (Mankins, 2009). Therefore, a small mining and processing facility will need to be established.

Before conducting a factor-analysis, several assumptions must be made prior to executing the analytical hierarchy process (Table 1). One of the main assumptions for this study is the completion of the Deep Space Gateway (DSG) that NASA plans to put into polar orbit around Moon (NASA, 2017). This would allow a way station for personnel and goods to flow to and from the lunar surface. In addition, there would be a need to have a steady power supply for planned lunar surface operations (Seedhouse, 2009) in addition to a lunar facility undergoing construction. Assuming these challenges are addressed prior to site selection, a factor rating analysis may be properly assessed.

**Table 1**

*Assumptions for all candidate lunar sites*

| |
|---|
| Initial lunar outpost established at the Lunar South Pole is fully operational |
| Initial water processing plant is operational at the outpost |
| Initial LOX/LH fuel plant operational at the outpost |
| Solar power station operational at the outpost |
| NASA's Deep Space Gateway is operational in polar orbit |

*Sources:* Mankinks, 2009; Spudis & Lavoie, 2011; and David, 2018)

The question arises as to the optimal location for such a plant. With a paucity of detailed local data, how do high-level planners narrow the many possible solutions to a set of feasible solutions to assess? A factor-analysis approach may offer an effective method. We hypothesize that the Analytic Hierarchy Process (AHP) may be used effectively for site selection for a future lunar base. AHP can help mission planners reduce the number of site selection reviews from in situ surveys for constructing a remote lunar facility.

Several system requirements will need to be taken into consideration prior to both factor analysis and in-situ prospecting (Table 2). Feeling that Siegfried's (1999) projection for a permanent facility was too low, we doubled the crew complement so that this facility will be permanently manned with a minimum of 50 crewed personnel on 6-month rotations. Access to NASA's Deep Space Gateway is also an important system requirements for both establishing and sustaining operations and maintenance (O&M) of the mining facility. In anticipation of engineering requirements creep to expand from its initial role, a pathfinder facility will be established first. A "pathfinder" is a space systems engineering term used to denote an initial engineering test case before transitioning to full production of that particular engineering model (Stone, 1996; Golombek, 1997). Once the pathfinder mining facility has been founded and evaluated, it can then expand to full mining production.

**Table 2**

*System Requirements for an operational lunar facility*

| | |
|---|---|
| Support 50 x personnel on 6-month rotations | |
| Have an overall life expectancy of 20+ years | |
| Be accessible to nearby launch facility | |
| - | Access to orbit of DSG (NASA, 2017) |
| Access route from research station/plant to launch facility | |
| - | < 50 km distance |
| Use crew return vehicle at initial outpost | |
| - | For onsite emergencies |
| Abundance of local material for in-situ processing | |
| - | Ease of extraction for LOX |
| Advantage of constant illumination for solar power | |
| - | Polar crater rims have near-continuous view of the sun |

*Sources:* Siegfried, 1999; Willenberg & Siegfried, 2001; Spudis & Lavoie, 2011

Construction on the lunar surface has never been attempted in the harsh lunar environment, yet it proved challenging just to conduct short duration activities during the Apollo missions. (Kawamoto & Miwa, 2011). Therefore, considerations of the environmental design challenges are of paramount importance for future long duration missions (Table 3). Temperature fluctuations are dramatic between 127o C down to – 173o C, but also vary between the lunar limbs and the permanently shadowed regions (Heiken et al., 1991). Further, characteristics of partial gravity, variable topography, and extreme lighting changes will complicate construction processes on the lunar surface.

**Table 3**
*Environmental Design Considerations*

| | |
|---|---|
| Partial gravity | The 1/6 gravity of the Moon may be an advantage for manufacturing due to lower mass |
| Temperature Extremes | Objects in direct sunlight can get very warm; whereas objects in shadow can get very cold |
| Temperature Fluctuations | Even operating on daylit side, moving to region of shadow cause significant temperature decrease |
| Topography | Traversing crater walls via personnel & equipment may prove operationally challenging |
| Lighting | Lunar surface has 2 weeks of either continual day or night which will require visors and headlamps |

*Sources:* Heiken et al., 1991;Willenberg & Siegfried, 2001; and Mankins, 2009

**Facility Location Options**
While a number of candidate sites have been selected for initial crewed missions to return to the Moon (David, 2018), this study selected three nominal end-member candidate locations, which should be sufficient to effectively demonstrate a factor analysis using the Analytic Hierarchy Process (AHP) for preliminary site selection. The three end-member exemplars (Table 4) represent the following lunar environments: north lunar pole, south lunar pole, and the lunar limb.

**Table 4**
*Facility Location Options*

| Option | Description | Name | Coordinates |
|---|---|---|---|
| 1 | Near-side equator | Riccioli Crater | 3.0 S, 74.3 W |
| 2 | North Pole region | Ridge or Peary Crater | 88.63 N, 24.4 E |
| 3 | South Pole region | Ridge of Shackleton Crater | 89.9 S, 0.0 E |

*Site Options:* Riccioli Crater (Lowman, 1996); Peary Crater (Detsis et al., 2013); Shackleton Crater (David, 2018)

Each candidate option is distinct in that each represents different parts of the planetary body. The two polar regions would have easy access to the lunar gateway, as well as co-located with trapped lunar ice near the permanently shadowed craters. However, it appears that the distribution of lunar ice may be different in terms of deposition and entrainment in the regolith (Spudis & Lavoie, 2011). Whereas the lunar limb may offer better of line of sight access for satellite communication system and more equatorial sunlight (Lowman, 1996). Due to the unique nature of these candidate sites, a robust and proficient factor rating analysis needed to be employed.

**Analytic Hierarchy Process**
The Analytic Hierarchy Process (AHP), described in Saaty (1990) and operationalized in the software package Expert Choice, has been a relatively simple decision-making tool in use for over forty years (Goodwin & Wright, 2009, 73). Vargas, de Felice, and Petrillo (2017) indicate that AHP has been implemented in many applications, to include industrial engineering, manufacturing engineering, disaster readiness, strategic planning, risk modelling (in steelmaking), and production improvement (in tobacco). Other authors, e.g., da Silva, Belderrain, and Pantaja (2010) and Dong and Cai (2017), describe the broad use of AHP in aerospace engineering applications, such as selection of research and development projects in Brazil and optimization of trajectories for hypersonic glide vehicles, respectively.

The simplicity of AHP lies in its systematic process of identifying attributes, or factors, relevant to a decision-making objective, weighting the relative importance of these factors, as well as of the decision-maker's preferences regarding alternatives, and through pairwise comparisons of the alternatives, computing a value for each alternative across all attributes. A hierarchy of objectives exists such that these attributes, or factors, should be considered as subordinate objectives. As the number of attributes increases or the number of subordinate levels of objectives increases, i.e., as the hierarchy gets taller, the computation becomes more complex (Goodwin & Wright, 2009, 85; Tang et al., 2004) – hence, the software package clearly becomes beneficial. However, for the relatively simple scenario posed here, Expert Choice was not invoked. Writing for the construction industry, Tang, et al. (2004) provide an excellent description of treatment of extensive numbers of factors, up to four levels of hierarchy, and four alternatives.

**Methodology**

This research focused on employing AHP and employing weighted criteria to influence scoring for both reliability and safety. The study used six factors to address the aforementioned system requirements and environmental design considerations that would need to be addressed prior to construction of this scale and remoteness (Shrunk et al., 2008) (Table 5).

AHP used a high-level factor weighting for each of the facility location options. The purpose of the weighting was to establish optimal conditions that would enable success for mining operations at each respective site. This would set the threshold for the appropriate clearance value for an acceptable score. Values below the weighted score would be a detrimental element to site selection. The weighting trended from STRONG to EXTREME due to the high degrees of scrutiny that would likely be derived from an investment of resources by the public and private sectors. Hence, safety egress and transportation logistics were the heavily weighted factors. Not to trivialize the other important elements, but the heavily weighted factors would have severe consequences to the overall program if there was a catastrophic failure. Hence, the importance of identifying the important factor elements prior to assessment.

**Table 5**
*Factor Rating Analysis Criteria and Weighting*

| Factor | Description | Weight | Considerations |
|---|---|---|---|
| Access to power | Availability of abundant, safe, economical, and uninterrupted power | 5 | –Illumination % can be very high at poles<br>–Multiple options – solar panels, nuclear, batteries provide options anywhere at a cost |
| Communications | Reliable, dedicated, and uninterrupted Earth-Moon communications link | 5 | –Cost of lunar relay satellites vs. surface only<br>–DSG used as a relay satellite |
| Access to site | Close proximity to areas of scientific interest | 7 | –Support of scientific community important<br>–Radio and optical telescope options |
| Protection | Some degree of natural protection from the harsh environment of space | 5 | –Unless underground (lava tubes) very little provided anywhere<br>–Sun angle of incidence comparison |
| Transportation and logistics | Both to and from base should if not be simple, at least have the minimal amount of obstructions or obstacles | 7 | –Assumption of DSG used as a tug<br>–Dust from landing zone<br>–Obstructions |
| Safety degrees | Crew evacuation operation may be conducted without difficulty | 9 | –Risk and public perception very important<br>–Funding tied to above |

*Factor Weighting:* 1 - Equal; 3 - Moderate; 5 - Strong; 7 - Very strong; 9 - Extreme
(Handfield et al., 2002; Schrunk et al., 2008)

The evaluation process involved determining a set of mean scores for each site location for the proposed lunar mining facility. This was conducted via manual process of human reviewers. The concept of employing software to run the AHP was discounted to demonstrate the feasibility of a factor-rating analysis by small research teams. Apollo landing sites were selected by consensus of small teams (Willenberg & Siegfried, 2001). Hence, if there is value in successfully demonstrating site selection through the AHP method, this could be employed by future lunar mission planners.

**Results**
The factor analysis using the AHP method selected the Shackleton Crater for a proposed lunar mining facility. It met most of the system requirements and environmental conditions based on its weighted scoring (Table 6). While the rating was a mean score, there was less than 1.0 standard deviation (1-sigma) differential between the different scoring. Therefore, the review of

the initial criteria and weighting helped minimize discrepancies that could have manifested itself in this type of assessment. The scoring during the AHP process was a two-component process: (1) weighting the corresponding factors in terms of significance, and (2) scoring each respective factor element that addresses system and design requirements. Initially each reviewer had to be familiar with the assumptions of NASA and commercial space ventures for the near future. Next each reviewer had to understand the system requirements and environmental design considerations for constructing a lunar facility. Once that was completed, an assessment of each element of factor-rating criteria was defined and reviewed for a shared and common understanding by the review team. Then, an agreed upon weighted number was assigned to each factor in terms of importance for that specific element set (Table 5). That weighted factor would then be applied as a product to the mean score of each corresponding factor to the respective site location. The overall scores were tallied and rated with respect to one another (Table 6). This two-component process employed for the AHP factor analysis helped to both prioritize the important factor elements as well as minimize any significant extent of standard deviation in the mean scoring.

**Table 6**

*Location Factor-Rating Analysis useful*

| Factor | Near-Side Equator (Riccioli Crater) | North Pole (Ridge of Peary Crater) | South Pole (North rim of Shackleton) |
|---|---|---|---|
| Access to power | 5(3) | 5(7) | 5(7) |
| Communications | 5(8) | 5(4) | 5(4) |
| Access to site | 7(3) | 7(7) | 7(7) |
| Protection | 5(5) | 5(2) | 5(2) |
| Transportation & logistics | 7(2) | 7(3) | 7(7) |
| Safety egress | 9(3) | 9(3) | 9(4) |
| Overall Mean Score | 122 | 162 | 199 |

*Scoring:* The weighted values from Table 4 are the left integer. The average mean score of each factor is the right bracketed integer. Their product is part of the summation of the overall mean score.

A pairwise comparison of each scored factor element respective to each site location would provide a constructive assessment. Access to power factor was scored VERY STRONG for both polar regions due to the near-continuous sunlight at the topographically high crater rims for solar power. Riccioli had a MODERATE scoring due to the recurring day/night cycle of 14-days. Counter. A similar pairwise comparison also was scored similarly for the site access factor. Both polar regions scored VERY STRONG to Access to Site due to the proximity of nearby water ice. Again, Riccioli scored MODERATE even though there was less variable topography that crews would encounter there, the remote distance from trapped water ice in the lunar regolith brought the mean score down for this site. An inverse of similar scoring occurred for both communication and protection factors respectively. The polar site locations scored MODERATE-STRONG due to a fair amount of SATCOM access with LOS oriented low along the horizon. Whereas Riccioli crater can establish remote SATCOM sites with communication relay lines networked to the parent site due to its unique position along the lunar limb. As for the protection factor, there is a narrowing of the scores in that all the sites face similar radiation and meteorite hazard. However, the polar regions will receive more sunlight on the rims than at the lunar limb. Hence the differential between SLIGHTLY MODERATE to STRONG between the two sets of scores for the protection factor. The breakout in scores of the pairwise comparisons transpire at the transportation and logistics factor and to a lesser extent the safety egress factor. Shackleton crater scored VERY STRONG over Peary Crater (MODERATE) and Riccioli (SLIGHTLY MODERATE). This is due to planned transportation hubs being planned for the lunar South Pole (David, 2018). This translates into Shackleton scoring higher MODERATE-STRONG versus the other two candidate locations of a MODERATE factor rating.

**Conclusions**

Developing a set of selection criteria for future lunar facilities is a critical analytical process that needs to be instituted into long-term planning when there is limited baseline knowledge at remote candidate sites. This AHP study selected a site at the edge of Shackleton Crater which can scale up from a pathfinder site to a full mining facility. Using weighted criteria of the AHP, some of the high operational risks may be reduced. This analytical process may be useful to mission planners in future lunar site selections prior to in situ prospecting and subsequent construction and maintenance costs. AHP or similar factor analysis will need to be employed for future site selection of future lunar operations.

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