Journal of Space Operations
Vol. 9, No. 3, July—September 2012

Organization of a Notional Lunar Mining Site

James G. Casler[1]
University of North Dakota, Grand Forks, North Dakota, 58202

Lunar basing concepts to date have not suggested serious consideration in the optimization of base layout for operational productivity, efficiency, safety, and cost, despite wide recognition that such bases are to be engaged in significant industrial operations. The purpose of this paper is to report preliminary efforts to assess potential siting issues for lunar bases. This study attempted to frame the optimization problem posed by the set of variables and constraints and relationships among those variables in the lunar environment. Although a literature survey examines candidate optimization approaches, there is no attempt in this effort to select an approach or to develop an optimization scheme. The results suggest that, while terrestrial analogs of lunar sites are insufficiently developed industrially to offer much insight, there is a substantial volume of literature concerning terrestrial mining and process plants to offer excellent analogs. Additionally, common manufacturing facility layout concerns and optimization approaches are available and appear promising.

Nomenclature

AHP	=	Analytical Hierarchical Protocol
CLESS	=	Closed-loop environmental support system
EPSCOR	=	Experimental Program to Stimulate Competitive Research
ESAS	=	Exploration Systems Architecture Study
EVA	=	Extra-vehicular activity
FACOPT	=	FACility OPTimization
FLP	=	Facility layout problem
FMARS	=	Flashline Mars Arctic Research Station
GA	=	Genetic algorithms
GCR	=	Galactic cosmic radiation
GP	=	Goal programming
HMP	=	Haughton-Mars Project
IDEF0	=	Integration DEFinition
ISRU	=	In-situ resource utilization
L-A	=	Location-allocation
MDRS	=	Mars Desert Research Station
NASA	=	National Aeronautics and Space Administration
NEEMO	=	NASA Extreme Environments Mission Operations project
NP	=	Non-deterministic polynomial
PQRST	=	Product, quantity, routing, supporting services, and timing
QAP	=	Quadratic assignment problem
QFD	=	Quality Function Deployment
SA	=	Simulated annealing
SLP	=	Systematic Layout Planning
SME	=	Society of Mining, Metallurgy, and Exploration
SPLP	=	Static plant layout problem
VSE	=	Vision for Space Exploration

---

[1] Associate Professor, Department of Space Studies, 4149 University Ave Stop 9008, AIAA Associate Fellow.

1. Introduction

With NASA's Vision for Space Exploration (VSE) in 2004, and for sometime prior, lunar and martian bases were contemplated.[1] By late 2006, a lunar architecture had been proposed for a solar-powered base located near one of the lunar poles.[2,3] The rim of Shackleton Crater, located in the Aitken Basin near the South Pole of the Moon, was noted as promising because it has near-continuous access to solar power while offering an opportunity to exploit the water ice captured in the permanently shaded recesses of Shackleton Crater.[4] These plans apparently have been shelved with the termination of the Constellation program. Nevertheless, the vision of lunar bases carries on. More recently, there is a substantially commercial aspect to proposed lunar expeditions as indicated by the competitors for the Google Lunar X Prize.

However, review of these projects does not reveal well-developed plans for growth and sustained presence. Despite an early reference to a zonal approach to lunar base laydown,[5] more recent basing concepts appear to have given little serious consideration to an integrated layout. Yet, eventually these bases are to be engaged in significant industrial activities, e.g., water extraction, propellant production, other in-situ resource utilization (ISRU), and energy generation. The effectiveness and efficiency of these activities depends greatly on the physical and functional relationships of components within the industrial system. Certainly, in light of the relatively high costs of moving humans, materials, and equipment to the Moon, as well as safety concerns, site layout becomes increasingly important to achieve the optimal effectiveness and efficiency under such constraints as limited logistics support and the hostility of the operating environment. Further, these concerns extend beyond lunar basing to operations on other planetary surfaces.

The deployment of ISRU systems such as excavation systems, processing systems for volatiles, etc., has been a critical element in recent expedition architectures. However, site laydown is not explicitly stated, yet an inefficient laydown can increase complexity and cost, reduce performance, lead to awkward works-around, and create unsafe conditions for human operators. For example, concerns, such as management of lunar dust in living areas as well as in industrial support areas such as calibration and metrology laboratories, suggest that such facilities cannot be casually placed with respect to manufacturing and mining areas. Consequently, a capability to optimize implementation of ISRU systems, as well as habitation and logistics support systems to meet the needs of lunar outpost crews, is needed. Development of a laydown methodology can be expected to contribute to engineering and architectural design of lunar basing systems and facilities.

Although approaches and tools are available for optimization of terrestrial facilities, a literature search revealed no known applications of these approaches to lunar basing, or to the more general planetary case. An assumption can be made that these optimization approaches and tools may be applied to the lunar mining problem, but just how the approaches will accommodate the inhospitable environmental conditions remains to be determined. Among other considerations driven by these conditions are life support systems such as shielding from radiation, pressurization, water, food, and waste handling. Furthermore, dust, low gravity, and micrometerorites, among other concerns not found on Earth, may be expected to substantially affect industrial operations.

2. The Problem

This paper investigates the more general problem of identifying and assessing lunar siting issues and begins the development of a methodology by which these issues may be addressed. While specific sites are not examined, the benefits of such a systematic methodology to optimization of site layout include for the example of a first lunar base at Shackleton Crater:

1. Layout to optimize the primary mission of water production in terms of both mass output and efficiency of resources used
2. Layout to permit facility growth in terms of production capability as well as human occupancy
3. Layout considering, but not necessarily optimized for, any secondary missions such as propellant production and/or energy generation
4. Layout considering multiple transportation media
5. Optimized layout constrained by all necessary considerations for human habitation

Similar benefits are expected to accrue for bases located elsewhere on the Moon.

The following questions are relevant. What is the set of design variables and constraints posed by the lunar operating environment that must be considered in order to optimize facility layout for lunar bases, specifically the Shackleton Crater base? What are the general mathematical relationships among these variables? As a test, when applied to terrestrial analogs, are these relationships effective in identifying optimized solutions for industrial layouts? And, what is/are the best generalized optimization approach(s) to basing planetary industrial operations?

This study was limited to framing the eventual optimization problem. Although a literature survey examined candidate optimization approaches, there was no attempt in this effort to select an approach or to develop an optimization scheme. The expectation was that the problem would be reduced to either minimization of a cost function or maximization of an effectiveness function. Whether a unique solution would be possible is not yet known. Framing of the optimization problem posed by the lunar operating environment was accomplished through:

1. Review of the literature of lunar and martian basing concepts
2. Review of siting issues of recent relevant terrestrial analogs, e.g., Antarctica, Biosphere II, and the Devon Island expeditionary site
3. Review of siting issues for relevant terrestrial mining operations
4. Review of siting issues for other relevant industrial operations, such as chemical and petroleum refining plants
5. Development of a preliminary list of considerations emerging from above reviews

Analytical methods such as the transportation linear programming method, systematic layout planning (SLP), Quality Function Deployment (QFD), and Integration DEFinition (IDEF0), among others, were investigated as candidates to explore the relationships among identified variables. A future outcome for this objective is expected to be a preliminary algorithm for lunar base layout.

3. Literature Survey

A review of literature relating to lunar and martian basing over the past 25 years reveals a paucity in consideration of site laydown. DeNike and Zahn provide one of the earliest serious discussions of lunar basing in which they briefly consider layout factors, i.e., "zoned for efficient and compact grouping."[6] Hoffman and Niehoff recognize a distance relationship with respect to a proposed nuclear power plant.[7] The Office of Exploration, Johnson Space Center continues a zonal approach to laydown which involves five zones, i.e., habitat, surface science, ISRU, landing, and nuclear power for a proposed permanent lunar base, as well as a four-zone, i.e., habitat, science, ISRU, and land and launch area, approach for a martian base.[5] However, there has been little apparent advance in the literature. For example, McKee and Sirko apply no method for layout other than that components are "arranged for crew safety."[8] Rather, there is ample consideration of related topics such as structural requirements for habitats and other facilities;[9-11] of estimates of mass, volume, and cost;[4,5,12] and various deployment sequences,[5,13] missions and activities,[4,14-16] and expansive discussions of various candidate technologies. Benaroya and Bernold identify potential sources for layout concerns.[17] Eckhart, et al. describe some environmental and mission factors influencing base design. Using a zonal approach, they do provide some functional relationships for location and sizing of base components or elements.[18] NASA's Exploration Systems Architecture Study (ESAS) is the most extensive recent discussion of lunar basing. Among other considerations, the ESAS defines activities to be conducted on the lunar surface, to include identification of base elements.[4] More extensive discussion of the relationships between/among the various base elements within the base is apparently left to future investigation.

As for siting issues of recent relevant terrestrial analogs, such as Antarctica, Bell and Trotti nicely describe how Antarctica provides among the best geographic and environmental analogs to planetary surfaces of interest for human exploration.[19] However, despite their case for using the Antarctic as an Earth-based analog, there is little in the literature to elucidate the rationale for facility design and layout of the over-30 year-round Antarctic stations. While the literature is lacking, there can be no doubt that some degree of planning, at least short-term, is necessary for such large stations as McMurdo, which Collis and Stevens suggest resembles both an urban center and an old-west frontier town.[20] It appears likely that such site planning is buried in internal agency documents, as well as generally being of such small scale relative to the expansive geography as to not require extensive or rigorous planning, although there is no doubt that some efficiencies would be achieved through deliberate laydown planning.

Biosphere II represented a large-scale prototype of the sort of closed-loop environment support systems (CLESS) that may be eventually anticipated for planetary settlements. As such, an opportunity is provided to understand the essential relationships between and among the various biomes (from a system perspective – "components") and to extend such relationships to the hostile planetary environment. The literature reviewed is largely authored by Biosphere II research team members and advocates.[21-23] and does not suggest substantive issues related to the relative locations of the various biosphere system components. One may conclude that any layout issues, if present, were insignificant. However, the literature does not suggest that Biosphere II site design was explicitly optimized to maximize productivity or efficiency, or to minimize energy consumption or other costs. One may speculate that production and efficiency were of little concern within the context of a closed environmental system with no production-related objectives.

The Haughton-Mars Project (HMP) field research camp and associated Flashline Mars Arctic Research Station (FMARS) on Devon Island in Canada are intended to serve as analogs to a Martian base and to support field research in astrobiology and testing of prototype tools, habitats, and planetary suits, as well as procedures and techniques for Martian exploration. Lee provides a geographic description of Devon Island and Haughton Crater in comparison to Mars and describes some science efforts[24] and Zubrin provides a colorful, first-hand account of the raising of the FMARS habitat.[25] However, despite these intimate discussions, there is no mention of site planning or layout relationships and issues. Numerous other papers are available regarding the Devon Island site and its facilities, e.g., the Arthur Clarke Mars Greenhouse. All are silent with respect to site planning and layout.

Arguably, terrestrial mining operations provide the closest analog to the purposes and activities of planetary industrial sites. An extensive body of literature discusses operational issues, many of which influence or are influenced by the relative locations of the various mine components. The Society of Mining, Metallurgy, and Exploration (SME) references provide worthwhile starting points to that body of knowledge,[26,27] as does Hartman's introductory text to mining engineering.[28] More pertinent coverage of specific location allocation methods applied to mining may be found with Zambo,[29] Humphreys and Leonard,[30] and Liebenthal and Mutmansky.[31] These older sources provide relatively simplistic approaches, e.g., sum of weighted distances, graphical, and game-theoretic approaches, respectively, generally to minimize transportation costs, and thereby minimize the cumulative life cycle cost of the mine. For example, related to minimizing transportation costs, Liebenthal and Mutmansky discuss optimization of mine layout specifically as related to a conveyor system.[31]

Other terrestrial industrial operations analogous to those envisioned for planetary bases include chemical processing plants. Planetary surface industrial operations are expected to involve primarily process operations (at least initially) in that the outputs are likely to be products necessary to support the immediate base and are to be derived from local regolith. For example, Gertsch and Gertsch describe a lunar mining scenario to supply gases such as H_2, O_2, and N_2, needed to replenish (or "make-up") losses from closed loop environmental and life support systems.[32] An additional example is production of O_2 as a rocket propellant. These examples are fundamentally process-oriented. Consequently, design considerations for chemical plants, among others, and methods related to process layout are of interest. The literature is replete with discussions of the design concerns in this area and examples are too numerous to mention. Indeed, the journals, *Chemical Engineering and Processing* and *Computers and Chemical Engineering,* are devoted largely to such issues. However, to a large extent, the general considerations of process plant layout, specifically chemical plants, are well captured by Mecklenburgh in his text *Process Plant Layout*.[33] Additionally, one of the frequent design problems for process plants is piping design. While Mecklenburgh touches on piping, Guirardello and Swaney, as well as Bausbacher and Hunt, offer additional design considerations for process plants requiring extensive transportation and handling of fluids.[34,35]

Regarding the literature for site layout methodologies, designing for planetary surface operations engenders two types of problems, i.e., the facility layout problem (FLP) and the location-allocation (L-A) problem. While the literature contains no significant discussion of these problems in relation to space basing, the literature is abundant with theoretical discussions, as well as of practical applications. A multitude of approaches are described, some have general application, others less so. A complete listing of papers is too extensive to be of much value for this current effort. For the moment, it suffices to point out the compilations of methods available to initial study of the planetary surface industrial operations issue.

For excellent reviews of layout methodologies, the reader need look no further than Meller and Gau,[36] Liggett,[37] and Drira, et al.[38] Meller and Gau provide a definition of the facility layout problem and a classification scheme identifying facility layout models and heuristics for block layout, facility layout model extensions, as well as special cases. Over 90 models and algorithms generated between 1986 and 1996 are classified by their schema. They note that the typical objective for these problems is to minimize material handling costs such that cost functions are based on departmental adjacencies and interdepartmental distances. Traditional procedures described include the quadratic assignment problem (QAP), graph-theoretic approaches, and mixed-integer programming. Several commercial software packages are available.[36]

Liggett focuses on automated facilities layout approaches. General methods include optimization of single criterion function, graphic-theoretic, and satisfaction of diverse sets of constraints. This summary discusses the quadratic assignment problem, construction procedures (facility design from a blank sheet), improvement procedures (improvement on existing facility designs), simulated annealing, genetic algorithms, hybrid approaches, unequal area approaches, and expert systems. Interestingly, Liggett notes that despite the interest in the facility layout problem, there are few commercial packages available.[37]

More recently, Drira, et al. go further than providing an update of progress in the field. They describe the facility layout problem, noting that such problems are frequently complex and generally NP-hard. Their approach provides a quite useful taxonomy which characterizes the facility layout problem by manufacturing system features, static and dynamic considerations, continual or discrete representation, problem formulation approaches, and resolution approaches.[38]

Using Drira's, et al., taxonomy, attention to discussions in the facility layout areas most relevant to the planetary surface operations problem, e.g., process layout, irregular facility shapes, construction (rather than improvement) situations, and likely area and budget constraints, is appropriate.[38] Graphical methods for less complex problems include the SLP method.[39,40] Both Tompkins and Konz further discuss SLP and describe several computer applications to automate the solution to the layout problem.[41,42] The classic text of Tompkins, et al. (1996) further provides quantitative models for location allocation.[43]

Heragu's text, *Facility Design*, comprehensively documents and describes, with case examples, the range of methods available from SLP to more recent techniques, such as genetic algorithms, simulated annealing, and tabu search. Heragu addresses service systems, manufacturing, warehouse, and nontraditional layout problems, but does not specifically discuss process plant layout. Heragu discusses both the facility layout problem and the location-allocation problem and notes that the two perspectives represent the micro-design and macro-design levels, respectively. The facility layout problem is characterized as a design problem without optimal solution, while the location-allocation problem is primarily an optimization problem. However, each problem has characteristics of the other and since most of the problems are NP-complete, near-optimal solutions are typically sought unless the problems are small, i.e., for systems of less than about 20 units.[44]

4. Analysis and Discussion

For the purpose of this study, facility layout is defined as the location of system elements (which may be facilities themselves) with respect to each other. The elements within the system can be positioned anywhere within the geographical (more accurately, selenographic) domain of interest, provided that position is unoccupied, to form a feasible solution to the layout problem. For a given set of resources, layout affects material handling cost, safety and health (in some cases), productivity (and probability of mission success), and profit. An assumption is made that, within this set of feasible solutions, there exists an arrangement of the system elements that optimizes one (or more) of the system objectives. There is an expectation that such system objectives can be reflected in mathematical terms, such as in Equation 1.

$$\text{Minimize material handling cost, } Z = \sum_{i=1}^{m} \sum_{j=1}^{n} a_{ij} b_{ij} c_{ij} \qquad (1)$$

Where a_{ij} = mass transported between locations i and j

b_{ij} = distance separating locations i and j

c_{ij} = cost of transportation per units mass and distance on route segment ij

Subject to constraints, e.g., minimum safe separation between facilities.

In order to optimize facility layout of a lunar industrial site, the comprehensive set of design variables and constraints posed by the lunar operating environment must be identified. While such a thoroughly comprehensive set is beyond the scope of the immediate discussion, some preliminary considerations are offered.

The lunar outpost envisioned by NASA under the Lunar Surface Architecture was limited in size and production, and more resembled a camp site than an industrial complex. Consequently, without extensive production requirements, such a proposed outpost is not likely to benefit greatly from optimization efforts. However, as lunar surface operations develop and mature, production and efficiency will become more important concerns.

The optimization of material handling in production systems is one of the foremost methods to gain improvements in production and efficiency. Some examples of material handling concerns that are relevant to the lunar surface problem are:

1. Traffic flow to and from the launch and recovery sites, presumably collocated as a "spaceport."
2. Traffic between habitat and other facilities such as labs, mining and manufacturing, processing, and maintenance facilities
3. Traffic between the machine shops, maintenance facility(ies) or equipment pool and field sites.
4. Haul roads, material handling systems (conveyors, piping and conduits, electrical cabling, etc.), and utility systems

While there has been little in the literature concerning planetary basing that suggests consideration of such issues, there may be some benefit to assessing facility layout issues on Earth.

The terrestrial analogs to planetary industrial sites considered in this study include Antarctic stations, the Biosphere II experiment, the Haughton-Mars Project (HMP) on Devon Island, Canada, the Mars Desert Research Station (MDRS) in Utah, as well as the NASA Extreme Environments Mission Operations (NEEMO) project and others. The literature is thin here and offers no specific insights relating to location and relationships among various facility components and activities. One may speculate that these facilities were developed largely ad hoc and are generally too small to benefit substantially from optimization efforts. (Granted that some Antarctic stations, such as McMurdo, are of substantial size, e.g., seasonally grow to 1000 personnel.)

Nevertheless, some observations can be noted. Antarctica is the highest and driest continent, with relatively high levels of solar radiation, temperatures as low as -100 degF, and winds up to 200 mph.[19] Antarctic sites are subject to wind, snow accumulation, ice movement, receding and advancing sea ice, extreme cold, low humidity, surfaces ranging from rock and permafrost to snow and ice. Still, remote research stations must be resupplied. Hence, fuels and other consumables must be warehoused, accessed, loaded, and dispatched. Vehicles and equipment must be maintained and consequently, must be accessible from habitat to some degree in hostile weather conditions. Likewise, laboratories and other research and service sites must be accessible. Conduits and piping between structures must be emplaced and operated. In larger sites, water and sewage treatment must be considered. Power supply systems must be accessible for maintenance but separated from habitats and working areas.

While snow buildup, encroaching sea ice, and buffeting winds are not concerns for the lunar surface, these observations, or considerations, can be related to planetary surface operations in that the planetary astronaut must conduct extravehicular activities (EVA), or transport, in some manner to reach research sites, construction sites, equipment such as the life support system or regolith excavators to be operated or repaired, and sites such as a nuclear power plant or solar panel field that must be inspected and repaired if necessary. In some cases, the astronaut's proximity to the work area is desired to be as close as possible. In other cases, e.g., where safety is involved, a greater distance may be prudent. Likewise, the materials for supporting and sustaining the site must be stored and transported to accomplish the mission.

Table 1 summarizes many of the characteristics of the Antarctic region that offer analogies to planetary surface operations. As can be noted from the related impact on operations, several of the characteristics have direct effects on base layout. Other effects are more indirect, e.g., capacity may be affected by increased requirement for maintenance of equipment, requirement more safety-related equipment and seasonal clothing; inclusion of morale-sustaining facilities, etc. The following characteristics have application to lunar base layout design: extreme cold, surface composition, lengthy periods of darkness (diurnal, rather than seasonal), high levels of solar radiation, low atmospheric pressure (vacuum), lack of vegetation, and isolation. Additionally, we can observe that, similar to what might be anticipated for lunar bases, the objectives of layout optimization for the Antarctic can be summarized by one or more of the following statements:

1. Maximization of safety
2. Minimization of environmental impact
3. Maximization of science productivity

Table 1. Considerations for layout drawn from Antarctic operations.

Analogous Characteristic	Impact on Operations
Extreme cold	Embrittles tools Freezes and cracks piping Reduces lubrication effectiveness Reduces equipment reliability Creates hazard of frostbite & other cold weather medical conditions Increased difficulty of outdoor tasks
Extremely hard surface composition/condition	Increase difficulty of excavation Destabilize roads and foundations May reduce trafficability
Lengthy seasonal periods of darkness	Contribute to increased crew psychological impairment Increased difficulty of navigation Increased difficulty of outdoor tasks
High levels of solar radiation	Increased risk of radiation-related medical conditions
Low atmospheric pressure	Reduced stamina and reduced human productivity
No vegetation available as food source	Importation of virtually all food
Isolation and no industrial capability	Importation of all equipment, building materials, supplies, fuel, etc.

Planetary surface operations intending to utilize ISRU for base support inherently require implementation of process (or functional) plants in which similar operations, e.g., comminution, are grouped together. Exploitation of resources more extensively to produce a product, e.g., oxygen or hydrogen for propellant or helium 3 as an export, has an even greater requirement to consider process plants. One could also argue that even science missions, and support thereof, employ functions and processes that must be appropriately located to achieve desired effectiveness and efficiency. Consequently, a review of those factors often considered in the facility layout decisions of process plants, i.e., those properties of the system that are affected by the facility design, is worthwhile. On a higher level and offering appropriate insight for the current effort, Mecklenburgh lists the following considerations for process plant layout: process requirements, economics, ease of operations, ease of maintenance, ease of construction, ease of commissioning, ease of future expansion, ease of emergency response, operator safety, hazard containment, and environmental impact.[33]

Additional perspectives offered by Tompkins, as well as Parks and Bhat, exhibit some differences in levels of detail, areas of emphasis, and categorization schemes, but also serve to enrich the input set for such decisions.[41,45] For example, Tompkins notes that the level of quality achievable is affected by the layout of the manufacturing facility.[41] Guirardello and Swaney offer additional design considerations, e.g., division in modules, use of rectangular patterns, use of centralized piperacks, and employing free space for safety and operations.[34] These perspectives by the various authors are generally consistent. The process plant design decision making considerations relevant to lunar basing are presented in Table 2.

As with the previous Antarctic analogy, several objectives are relevant. For process plant facility design, Tompkins outlines the following typical objectives:[41]

1. Minimize backtracking, delays, handling
2. Maintain flexibility
3. Utilize manpower and space effectively
4. Promote high employee morale
5. Provide for good housekeeping and ease of maintenance

But we are most keenly interested in the exploitation of lunar resources, because it is here that we see the invocation of a process, or processes, to transform the raw material of the lunar surface, in combination with imported resources, to a product, or products, of value to the base inhabitants. For lunar surface applications, these operations appear to be most likely to resemble terrestrial surface mining operations.

Table 2. Process plant design considerations relevant to lunar basing.

Consideration	Description	Functional Constraint Example(s)
Process requirements	Relevant specifications such as process sequence, timing, temperature, pressure, mixture proportions, containment, etc.	Limitations in pressure or temperature drop in transfer lines.[33]
Economics	Impact of layout on revenues and expenses. For given facilities, equipment, subsystems, vehicles, considers efficient use of space in layout, proximity to raw materials and customers, overhead expenses, taxes and insurance expenses, etc.	1. Limitation in launch resources to resupply and support lunar base. 2. Market price available for goods produced.
Operations	Impact of layout on operational costs and productivity. For given facilities, equipment, subsystems, vehicles, considers access frequency, task duration, safety, administration and control, logistics support, reduction of waste, communication and information transfer, etc.	Tradeoff between cost of equipment monitoring visits by operators and cost of automated monitoring for various operations locations.
Maintenance	For given facilities, equipment, subsystems, vehicles, considers access time, repair time, number of repair stations (capacity), etc. Well-laid out maintenance facilities enable better reliability, better safety, and higher mission readiness.	Limitations on mean waiting time (to include transit time) for mission-critical equipment.
Construction	Impact of layout on access, sequence, safety, etc., of construction activities, perhaps generally reducing to construction costs and time.	Design tradeoff between whether surface or subsurface construction.
Commissioning	Impact of layout on conduct of pre-production activities and acceptance testing of facilities, reducing to test time, cost, and accuracy.	Limitation on production delays due to delayed, or ineffective, inspections resulting from inaccessibilities.
Flexibility	Impact of layout on facilitating or interfering with growth of system. May also include negative growth, or “downsizing” of system or other adjustments to accommodate market changes. Considers cost of acquisition of additional space.	1. Limitation in current production downtime for rerouting of pipeworks. 2. Prohibition of expansion due to inopportune position of existing facility.
Safety & health	Impact of layout on crew health and safety, emergency response effectiveness, and hazard containment. Considers accident severity and probability; probable cost of prevention, response, medical treatment, lost production, etc.	1. Minimum separation between habitat, and other occupied facilities, and nuclear power plants, explosive events, and contaminated areas. 2. Limitation on emergency response time.
Environmental impact	Impact of layout on generation of environmental contamination and on effectiveness in carrying out social and legal responsibility to conserve environment. Considers construction of containment areas, probability and severity of spills, etc., generally reducing to cost of compliance.	1. Limitations on acceptable locations for tailings piles. 2. Requirement for reclamation of mined surfaces.
Staffing	Impact of layout on recruitment, employment, training, support, and termination of labor force. Considers costs of employing, specially trained labor categories, accommodation of range of labor force, provision of facilities for morale and comfort.	Limitation on size of skilled labor force available.
Quality	Impact of layout on quality of goods and services produced. Considers costs of prevention, inspection, salvage, rework, and scrap as affected by layout.	Limitation on acceptable losses due to scrap.

The mining analogy offers a few more considerations. Facility locations for terrestrial mining operations are affected by the target ore grade (tenor) and distribution, as well as both geological and geographic considerations. Hartman offers a more expansive listing of factors, or considerations to be made, regarding location and mine facility design. General factors include location characteristics, climate, history, ownership, land status, and transportation concerns. Hartman goes on to list environmental concerns, geologic factors, mining reserves, processing requirements, auxiliary and support factors, staffing, and economic factors.[28] Caffrey and Ladd (1992) offer a similar categorization of geographic, technical, business, legal, and political considerations.[46] For tailings facilities, Flint adds several factors, to include location and elevation relative to the mill, topography, hydrology and catchment areas, geology, and groundwater.[47] Each of these factors incorporates several more detailed concerns such as environmental considerations include pollution, reclamation, subsidence, noise, and blasting damage. Several of the mining considerations are common with those of process plants. A review of the design considerations for mine location and facility layout adds the following concerns relevant to lunar basing, as presented in Table 3.

Table 3. Mining design considerations relevant to lunar basing.

Consideration	Description	Functional Constraint Example(s)
Natural and geologic (selenologic) factors	Considers effects of extreme cold (combined with severe temperature cycles), difficult surface composition/conditions, lengthy diurnal periods of darkness, high levels of solar radiation, and galactic cosmic radiation (GCR), atmospheric pressure of vacuum, micrometeorite incidence, abrasive dust, no local food source, isolation, no natural industrial capacity, etc..	Minimum shielding thickness as protection from micrometeorite impact, and solar radiation and GCR.
Auxiliary and support requirements	Impact of layout on provision of support functions, such as energy, life support, land/launch activities, administration and control, etc. Includes maintenance and logistics.	Minimum separation of habitat from nuclear power plant and launch pad.
Technical factors	Considers availability of technical solutions and technical maturity of systems, etc. Includes capacity of transportation system in terms of number of launchers, single-vehicle payload capacity, etc.	Limitations in single-vehicle payload mass and dimensions for launch from Earth to Moon constrain size of excavation equipment, processing facilities, nuclear power plants, etc. and thus constrain nature, capacity, and efficiency of operations.

Taken together, Tables 2 and 3 provide a list of relevant considerations for lunar base layout. Note that while social, political, and legal factors are likely to be present to some degree, such factors were assumed to be minimal for this discussion.

While minimization of transportation costs is typically the primary objective of most facility location optimization approaches, other considerations may also arise with respect to mining operations. Tompkins notes that multiple, often conflicting, objectives may apply to layout optimization.[41] Layout decisions affect total costs in that facility and operation placement may dictate facility sizing as well as more or fewer services, as represented by capacity of maintenance, information systems, energy, etc. Further, layout decisions also affect productivity. Certainly, the objective of profit maximization, e.g., as expressed as the maximization of ore processing throughput or refined product output, is in some ways complementary to minimizing transportation costs and is often used. Related to profit maximization might be minimization of costs due to environmental and regulatory concerns. For example, geological structure may constrain locating holding ponds and tailings piles to certain areas to prevent contamination of ground water. A candidate listing of objectives may now be summarized as:

1. Minimization of transport costs
2. Maximization of profit
3. Maximization of ore processing throughput
4. Maximization of refined product output
5. Minimization of environmental and regulatory costs
6. Minimization of fixed costs

7. Minimization of variable costs (or minimization of fixed costs while balancing variable costs)

Mining operations involve facilities such as haul roads, conveyor systems, beneficiation plants, topsoil stockpiles, tailing collection, holding ponds, as well as maintenance and administration facilities, etc. A more expansive, but still not comprehensive, listing of terrestrial mining facilities may be found in Table 4. Notionally, many of these facilities are presented by the plan view representation in Figure 1. As such, beneficiation plants and tailings piles and holding ponds must be located to minimize the costs of transporting materials to and from these facilities. Transportation costs include the construction costs, as well as operations costs, of haul roads and conveyor systems. Presumably, the longer the road, the greater the construction costs and the greater the cost of equipment, fuel, maintenance, and time (labor) in transporting material along these haul roads. However, shorter roads are not necessarily less expensive to construct if cut through rock, nor cheaper to operate if over difficult terrain or through areas requiring continual road maintenance to ensure trafficability.

Table 4. Common terrestrial mining functions and associated facilities and usage areas.

<table>
<tr><th>Functions</th><th>Related Facilities or Usage Area</th><th>Functions</th><th>Related Facilities or Usage Area</th></tr>
<tr><td>Overburden removal</td><td>Topsoil stockpile
Waste pile</td><td rowspan="7">Auxiliary operations
Administration
Planning & control
Health & safety
Environmental control
Dispatching
Power supply distribution
Water & flood control
Waste disposal
Material control
Purchasing & receiving
Vehicle & equipment control
Maintenance & repair
Communications
Personnel transport
Sample analysis
Security & visitor control
Reclamation</td><td rowspan="7">Administrative offices
Residences (for remote locations)
Laboratory facilities
Maintenance facilities
Equipment wash bay
Oil storage containment
Fuel storage containment
Vehicle pool
Receiving facility
Warehouse
Sedimentation ponds
Pump stations
Diversion ditches
Explosive locker
Power generation systems
Entrance & exit
Visitor control point</td></tr>
<tr><td>Ore fragmentation (rock breakage)</td><td>Ore deposit</td></tr>
<tr><td>Excavation</td><td>Ore deposit</td></tr>
<tr><td>Haulage</td><td>Haul roads
Conveyor system</td></tr>
<tr><td>Comminution</td><td>Truck unloading & sizing area
Crushing plant
Conveyor system</td></tr>
<tr><td>Sizing</td><td>Classification plant (screening)
Conveyor system</td></tr>
<tr><td>Beneficiation</td><td>Sorting plant
Consolidation facility
Tailings pile
Product stockpile
Product loading</td></tr>
</table>

For the moment confining the lunar mining problem to surface mining, the following phases of open pit and open cast mine operations are identified: ore fragmentation (drilling and blasting), excavation, haulage, beneficiation, processing, and reclamation.[26]

Consideration of the lunar environment enables refinement (at a top level) of this list of factors to: vacuum, absence of liquid water, radiation, gravity, diurnal cycle, dust, micrometeorite bombardment, extreme temperature variation, as well as view of Earth, etc. Specific to Shackleton (and similar polar sites), while the polar location provides near continuous sunlight, the incidence angle is nearly tangential. Consequently, effective use of solar panels for power generation would require mounting the panels vertically and rotating the panels to continuously face the sun. Consideration of the additional structural and mechanical complexity leads to a selection decision between a solar-powered alternative and a nuclear-powered alternative. Applying such concerns to the functions described in Table 4 leads to functions and facilities that might be found in a notional lunar mining operation, such as summarized in Table 5. We also note that explosives are not likely to be used on the moon because low lunar gravity and absence of atmosphere would make containment of blast debris and dust a rather difficult problem.

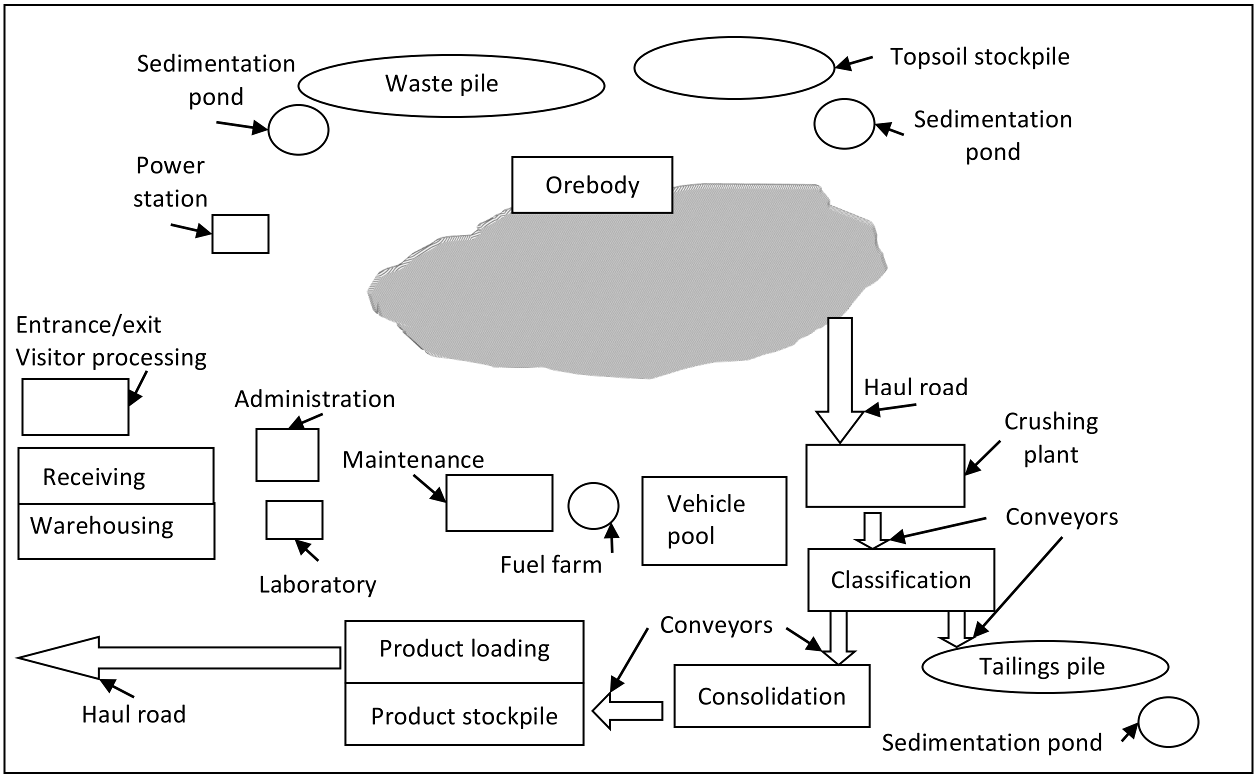

Figure 1. Notional terrestrial mining operation.

Figure 2 adapts the terrestrial mining representation to consider a notional lunar mining operation. Note that substantial variations in layout are anticipated as specific minerals and processes are specified. For example, the average grade of solar wind-driven ^{3}He is 3 – 4 ng ^{3}He/g regolith concentrated in the most mature regolith. To obtain 1 metric tonne of ^{3}He would require the excavation of 2000 km^{2} at a depth of 10 cm.[48] This excavated area, which is about two-thirds the size of Rhode Island, considerably exceeds any terrestrial experience and will drive extensive haul road requirements to transport the "ore," or regolith, to processing and to distribute the processing waste, e.g., as shielding build-up or as surface reclamation. Other products are not likely to require excavation of such a vast area but rather will be confined to more localized deposits. On the other hand, these products, e.g., oxygen, may have greater energy demands or involve more complex refinement processes.

Table 5. Mining functions and associated facilities and usage areas applied to a lunar mining operation.

<table>
<tr><th>Functions</th><th>Related Facilities or Usage Area</th><th>Functions</th><th>Related Facilities or Usage Area</th></tr>
<tr><td>Overburden removal</td><td>Regolith stockpile
Waste pile</td><td rowspan="8">Auxiliary operations
Administration
Planning & control
Health & safety
Environmental control
Dispatching
Power supply distribution
Waste disposal
Material control
Receiving
Vehicle & equipment control
Maintenance & repair
Fabrication & assembly
Communications
Personnel transport
Sample analysis
Reclamation</td><td rowspan="8">Administrative offices
Habitat
Laboratory facilities
Maintenance facilities
Equipment cleaning bay
Vehicle pool
Machine shop
Receiving facility
Warehouse
Pump stations
Power generation systems
Land/launch pad
Communication antenna</td></tr>
<tr><td>Ore fragmentation (rock breakage)</td><td>Ore deposit</td></tr>
<tr><td>Excavation</td><td>Ore deposit</td></tr>
<tr><td>Haulage</td><td>Haul roads
Conveyor system</td></tr>
<tr><td>Comminution</td><td>Truck unloading & sizing area
Crushing plant
Conveyor system</td></tr>
<tr><td>Sizing</td><td>Classification plant (screening)
Conveyor system</td></tr>
<tr><td>Beneficiation</td><td>Sorting plant
Consolidation facility
Conveyor system
Tailings pile
Waste pile</td></tr>
<tr><td>Processing</td><td>Processing facility
Product stockpile
Product loading</td></tr>
<tr><td colspan="4">Note: Aspects of the lunar environment considered include vacuum, absence of liquid water, radiation, gravity, micrometeorite bombardment, diurnal cycle, dust, extreme temperature variation, and Earth view.</td></tr>
</table>

The notional lunar mining operation, with (at present) eighteen units to be located, marginally remains a comparatively small-sized problem. However, with greater detail in discrimination of activities, e.g., adding subsystems such as airlocks, crushers, screens, pumps and compressors, tanks, piping and piperacks, heaters and coolers, loading ramps, etc., it can easily become a problem of much more complexity. Although the assessment of the efficacy of the various optimization techniques is the subject of future research, it is worthwhile to briefly explore a common technique as a prelude of that future line of research.

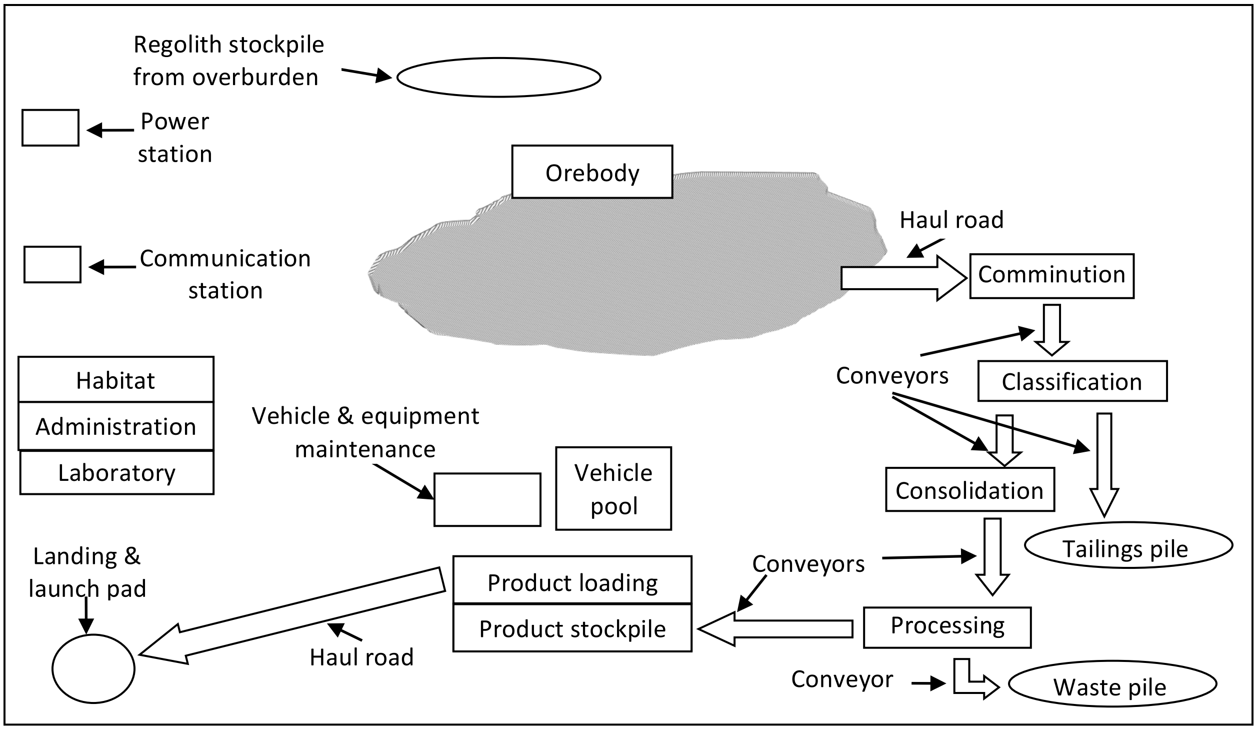

Figure 2. Notional lunar mining operation.

While not an optimization approach per se, SLP is a graphical technique commonly used to optimize facility layouts. Simplistically, the process involves:[39]

1. Identify the product, quantity, routing, supporting services, and timing (PQRST) of the project
2. Identify alternatives
3. For each alternative approach, determine or develop:
4. Flow of materials
5. Activity relationships
6. Relationship diagram
7. Space requirements
8. Space available
9. Space relationship diagram
10. Modifying considerations
11. Practical limitations
12. Evaluation of alternatives
13. Decision/selection of alternative

As such, SLP provides a usable guide regardless of whether graphical or analytical methods are employed.

From the notional example, we note that, at this level of detail, the number of units remains relatively small and the problem is likely to remain tractable using graphical techniques. Drawing from the mining operation of Figure 2, Figure 3 presents a relationship chart. Note that the relationships indicated in Figure 3 are notional and depend on the specific operation plan under consideration. Although beyond the scope of the current effort, the relationship chart can then be developed into further graphical presentations leading to a layout design. Further, it is expected that the relationship chart can be translated into a series of constraint equations comprising part of a linear programming solution. As more elements and detail, e.g., additional processing lines, are added to this base system, this initial constraint matrix becomes larger and cumbersome to manage. Further, Figure 3 (and the related derived matrix) does not necessarily reflect the range of constraints identified above. Rather, it is primarily related to process sequence, material flow, operator activity, and safety. For example, in this case, it does not address how layout would be affected by the constraints on the size of the excavation or processing equipment that can be lifted to the lunar surface.

Within each consideration identified above, constraint models, as well as independent variables, are anticipated. Selected examples of constraints are offered Tables 2 and 3.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	Orebody	--																	
2	Regolith stockpile	C/1	--																
3	Comminution plant	C/1	E	--															
4	Classification plant	E	E	B/1	--														
5	Consolidation plant	E	E	E	B/1	--													
6	Tailings pile	E	E	E	C/1	E	--												
7	Processing plant	E	E	E	E	B/1	E	--											
8	Waste pile	E	E	E	E	E	E	C/1	--										
9	Product stockpile	E	E	E	E	E	E	C/1	E	--									
10	Product loading	E	E	E	E	E	E	E	E	A/1	--								
11	Landing/launch pad	F/3	E	F/3	F/3	F/3	E	F/3	E	E	D	--							
12	Vehicle/equipment maintenance	C/5	E	C/5	C/5	C/5	E	C/5	E	E	D	D	--						
13	Vehicle pool	C/4	E	D	D	D	E	D	E	E	D	D	A/5	--					
14	Laboratory	C/4	E	E	E	C/4	E	C/4	E	E	E	F/3	E	E	--				
15	Administration	D	E	D	D	D	E	C/2	E	E	D	F/3	D	D	A/2	--			
16	Habitat	E	E	E	E	E	E	F/6	E	E	E	F/3	B/2	C/4	A/2	A/2	--		
17	Communication station	E	E	F/3	F/3	F/3	E	F/3	E	E	F/3	F/3	C/5	E	E	E	E	--	
18	Nuclear power plant	E	E	G/6	G/6	G/6	E	G/6	E	E	G/6	G/6	G/6	G/6	G/6	G/6	G/6	G/6	--

Closeness Desired		
A	< 10m	Absolutely necessary
B	< 20 m	Especially important
C	< 40 m	Important
D	< 80 m	Average
E		Unimportant
F	> 80 m	Not desirable
G	> 200 m	Unacceptable

Reasons for Desired Closeness	
1	Flow of material
2	Personal contact
3	Avoid dust & blast effect
4	Contact frequently
5	Service urgently
6	Safety

Figure 3. Relationship chart for notional lunar industrial site.

A very short list of variables of potential interest is shown in Table 6.

Table 6. Selected variables of potential interest relevant to lunar base layout

Number of facilities
Size of facilities (physical footprint)
Capacity of facilities (maximum throughput)
Service life of facilities & equipment
Strength of relationship among facilities
Direction of relationships (monodirectional or bidirectional)
Criticality of individual facility
Transportation rates & volume (material flowrate)
Haul road gradient, width, bearing, surfacing
Vehicle capacity, speed
Energy transmission (direction & volume)
Maintenance & repair requirements
Life support requirements
Fuel & power consumption
Number of ports
Command/control/administration
Waste management
Hazards
Storage & warehousing
Ground control & support characteristics

However, it is clear that a comprehensive set of general variables and constraints cannot be determined within the scope of this preliminary investigation. This point should not be surprising as Eckart suggests that, just for resupply mass estimates alone, several thousand input parameters and boundary conditions are required. Nevertheless, Eckart's parametric lunar base model appears to provide a starting point for eventual tabulation of these variables and constraints. His parametric model includes the following submodels: lunar surface environmental model, crew metabolic load model, lunar base modules model, shielding model, communication system model, EVA/airlock operation model, lunar surface transportation systems model, life support system model, low-temperature thermal control system model, in-situ oxygen production model, power supply system model, and high-temperature thermal control system model.[49]

This parametric model provides a scheme to "manipulate hundreds of input parameters to determine their impact on the overall system mass and the interdependencies among the different systems."[49] When the basic data are input, for example, crew size and makeup, environmental properties, etc., the constituent modules presumably can be appropriately sized. The resultant appears to produce mass requirements which can be then translated to lift and cost requirements. However, this method does not appear to incorporate layout concerns, e.g., affinity or closeness requirements, etc., and, consequently, goes only part way to address the optimization issue.

The Facility Layout Problem (FLP) can be largely classified in two types, i.e., construction and improvement type problems. At present, since no layout currently exists, the candidate methods are considered with regard to applicability to the construction problem. Preliminary assessments appear most appropriate in addressing the smaller (less than 20 units), less complex scenarios first. Hence, although not an optimization method per se, SLP has been briefly demonstrated with the intent of gaining early insight into the nature of the larger problem. It is expected that as planetary bases grow in size and complexity, SLP will give way to other techniques.

Another graphical method of passing interest due to its use in laying out mining operations is described by Humphreys and Leonard. Here, the overall objective is to minimize the cumulative life cycle cost of the mine through the minimization of transportation cost.[30]

Among the candidate approaches posited early in this investigation, the well-known linear transportation method is expected to be challenged on at least two counts. First, the transportation method is intended to optimize material handling, i.e., to minimize transportation cost. As has been discussed above, many considerations other than material handling, e.g., safety, are important aspects of the lunar industrial base layout problem. Second, the many factors involved are not all independent, nor are they necessarily linear. Hence, the linear transportation method would seem to be inappropriate in all but the most simplified problem structures.

Quality Function Deployment (QFD) is a systematic process intended to translate customer needs (expressed and unexpressed) into product and process specifications that can be applied to ensure the customer receives what he/she really needs. It was included among the initial candidate methods because it provides the structure to move from subjective expressions of needs that the lunar base must accommodate to the process specification, which has a significant bearing on layout. As a graphical method, QFD would be limited to addressing relatively small and simple scenarios. Furthermore, it is not an optimization technique and, as such, does not ensure that the best solution is achieved. Several software applications are available to relieve some of the tedium involved in fully deploying this technique for a given problem.

However, a similar approach, Analytical Hierarchical Protocol (AHP), does appear to hold promise. Badri in discussing location-allocation problems points out that "Location-allocation decisions involve substantial capital investment and result in long-term constraints on production and distribution of goods." Badri notes that factors for these decisions may be both quantitative and qualitative and proposes AHP as an approach that considers both types of factors and provides a subjective, but systematic (rather than arbitrary) process to rank these factors in importance. Goal programming (GP) is incorporated to enable consideration of budgetary and resource constraints. Candidate factors for location-allocation decisions include availability of transportation facilities, cost of transportation, availability of labor, cost of living, availability and nearness of markets, attainment of favorable competitive position, anticipated growth of markets, income and population trends, cost and availability of industrial lands, closeness to other industries, cost and availability of utilities, government attitudes, tax structure, community related factors, environmental considerations, assessment of risk, and return on assets.[50]

As briefly mentioned above, Eckart has developed a parametric model for lunar basing.[49] The depiction of this model is at least visually reminiscent of the IDEF0 method commonly used in systems engineering to enable a structured depiction of the functions of a system. This method provides a means by which activities of a system, as defined by inputs, controls, outputs, and mechanisms, can be progressively refined to the level necessary. As such, IDEF0 has some potential to describe the system in terms of activities which can then be related in terms of affinities, or locations, relative to other activities.[51]

The zonal approach taken by Ref. 5, 6, 9, and 18 gathers various base activities or facilities into groups, or zones, as an attempt to simplify the layout problem. As mentioned above, these sources go no further in optimizing the layout than arranging these zones to satisfy high level engineering and safety concerns. However, this zonal layout has a resemblance to the block layout design problem which has the objective to minimize the cost associated with interactions between departments, or facilities. Given the notional lunar operation depicted in Figure 2, one can recognize that these facilities are very likely to have substantially different footprints. Hence, any block layout undertaken is likely to employ blocks of unequal areas. Castillo, et al. address this more general problem using decision variable transformation and symmetric convex lower bounds to enable exact representation of the underlying area restrictions. That this approach is claimed to be readily applicable to both process plant layout and piping design is encouraging for the lunar industrial operations case.[52]

Balakrishnan, et al. note that the static plant layout problem (SPLP) is NP-complete and suggest that problems with more than 20 facilities cannot be solved optimally if modeled as a quadratic assignment problem (QAP). They suggest that the SPLP for more than 20 facilities is better solved with heuristic algorithms, e.g., simulated annealing (SA) or genetic algorithms (GA), and recommend application of FACility OPTimization (FACOPT).[53]

Finally, noting that laying out process plants must find an "economically acceptable balance [among] … often conflicting constraints" and that these constraints are often derived from environmental, construction, maintenance, and operational constraints, Georgiodis and Macchietto take a mathematical programming approach. Of note, for problems with greater than 30 units, they suggest heuristic methods be used for preallocation of some units. Alternatively, equipment of facility modules of similar operating characteristics can be aggregated to initially simplify the problem.[54] This discussion is extended to a more general formulation by Georgiodis, et al.[55]

5. Conclusions

To date, authors discussing space basing have not delineated location and layout design considerations as found in the processing plant and mining literature discussed. One may speculate that this paucity may be due to several factors. First, the body of knowledge of planetary basing is not as rich in empirical or experiential evidence nor as lengthy as for mining and process plants. Second, the more serious considerations of lunar or martian bases have been more oriented to small temporary science and exploration outposts rather than viewing the bases as production systems. Consequently, there has been little attention to the production processes and a far greater attention to candidate technological systems. Further, many of these systems, e.g., habitat, laboratories, life support systems, and airlocks, have been highly integrated into single modules. While consideration of the layout of these modules in itself is highly relevant, it overlooks the greater problems to be encountered in a much larger production-oriented system.

In considering the terrestrial processing plant and mining operation as analogs for future planetary industrial operations and projecting to the lunar surface, several conclusions may be drawn. First, in the context of an optimization problem, the analogs suggest that several objective functions may be relevant. For example, the layout of a lunar base to minimize transportation, or material handling, cost for the production system seems as appropriate for lunar bases as it is for terrestrial counterparts.

Additionally, a gleaning of the space-based literature suggests a greater emphasis on safety, most significantly represented by EVA safety. Hence, that emphasis should be reflected in the problem objective statement, e.g., maximize astronaut safety, as well as in constraints that may apply maximum traverse distances and exposure times. Such statements influence layout by maximizing adjacencies between human-attended units, where possible, and by requiring pressurized and shielded passageways where not.

Second, a preliminary list of fourteen factors is offered (summarized as Table 7) for consideration for lunar base layout design. A future objective is to develop these considerations into a tentative, but usable, list of variables and constraints to more fully describe the optimization problem. From a practical standpoint, an assessment of a planetary production system with a more defined purpose, e.g., propellant oxygen production, than the generic, notional approach taken here is more likely to bear fruit. That being said, it is believed that a reasonable framework has been established by which to view the lunar (or planetary) base layout problem.

Table 7. Considerations for Lunar Basing Layout

Process requirements	Staffing
Natural and selenologic factors	Environmental impact
Economics	Construction
Operations	Commissioning
Auxiliary and support requirements	Flexibility
Technical factors	Quality
Safety and health	Maintenance

That framework is demonstrated by the partial application of SLP. A conclusion drawn from this demonstration suggests that even this simplistic, well-used, graphical method can offer a better rationalized approach than seen in the literature to date. Further, this approach may be completely satisfactory for most lunar production systems envisioned in the near-term. However, additional approaches are available. Because the lunar industrial operation may be expected to well-exceed 20 units, several heuristic methods may be appropriate. Which one of these is best is subject to further research.

This preliminary assessment of the lunar base layout problem indicates that there are numerous avenues of research to be pursued. A specific line of research for the near-term is to select a likely production objective, such as production of oxygen as a propellant for vehicles leaving the Moon. For this given production objective, using SLP (as a starting point) may be used to more thoroughly define the relevant objective function, define the operational flow, consider auxiliary and support functions, identify the appropriate variables and constraints, and ultimately develop an optimal layout for that process.

Additional lines include applying other methods, notably goal programming, block layout, simulated annealing, and genetic algorithms, to the selected production objective to assess which of these methods might be more efficient. Further research areas include determining an optimized layout for the Shackleton Crater basing case, as well as developing more general approaches for the range of basing scenarios and production objectives on the Moon, Mars, and other planetary surfaces.

6. Acknowledgment

This research effort was funded by a grant from North Dakota NASA Experimental Program to Stimulate Competitive Research (EPSCOR).

7. References

[1]National Aeronautics and Space Administration, "The Vision for Space Exploration," NP-2004-01-334-HQ, 2004.

[2]Dale, S., "Exploration Strategy and Architecture," AIAA 2nd Space Exploration Conference, Houston, 2006.

[3]Braukus, M.; Dickey, B.; and Humphries, K., "NASA Unveils Global Exploration Strategy and Lunar Architecture," NASA Release 06-361, URL: http://www.nasa.gov/home/hqnews/2006/dec/HQ_06361_ESMD_Lunar_Architecture.html [cited 7 November 2011].

[4]National Aeronautics and Space Administration, "NASA's Exploration Systems Architecture Study: Final Report," NASA-TM-2005-214062, 2005.

[5]National Aeronautics and Space Administration, "Office of Exploration FY 1989 Annual Report. Exploration Studies Technical Report Vol III: Planetary Surface Systems," NASA TM-4170, 1989.

[6] DeNike, J. and Zahn, S., "Lunar Basing," *Aerospace Engineering*, Vol. 21, 1962, pp. 8-14.

[7]Hoffman, S. J. and Niehoff, J. C., "Preliminary Design of a Permanently Manned Lunar Surface Research Base," *Lunar Bases and Space Activities of the 21st Century*, edited by W. W. Mendell, Lunar and Planetary Institute, Houston, 1985. pp. 69-75.

[8]McKee, J. W. and Sirko, R. J., "Lunar Base Design: The Links Between Power System, Life Support System, and Site Selection," Presented at AIAA Space Programs and Technology Conference, Huntsville, AL, AIAA 93-4782, 1993.

[9]Boles, W. W., Ashley, D. B., and Tucker, R. L., "Lunar-Base Construction Equipment and Methods Evaluation," *Journal of Aerospace Engineering*, Vol. 6, No. 3, 1993, pp. 217-235.

[10]Toklu, Y. C., "Civil Engineering in the Design and Construction of a Lunar Base," *Proceedings of Space 2000, Seventh International Conference on Engineering, Construction, Operations, and Business in Space*, edited by S. W. Johnson, K. M. Chua, R. G. Galloway, and P. I. Richter, ASCE, Reston, VA, 2000, pp. 822-834.

[11]Benaroya, H., Bernold, L., and Chua, K. M., "Engineering, Design, and Construction of Lunar Bases," *Journal of Aerospace Engineering*, Vol. 15, No. 2, 2002, pp. 33-45.

[12]Duke, M. B., Blair, B. R., and Diaz, J., "Lunar Resource Utilization: Implications for Commerce and Exploration," *Advances in Space Research*, Vol. 31, Nol 11, 2003, pp. 2413-2419.

[13]Siegfried, W. H., "Lunar Base Development Missions, *Acta Astronautica*, Vol. 44, No. 7-12, 1999, pp. 755-767.

[14]Mendell, W. W., (ed.), *Lunar Bases and Space Activities of the 21st Century*, Lunar and Planetary Institute, Houston, 1985.

[15]Waldron, R. D. and Criswell, D. R., "Overview of Lunar Industrial Operations," *Conference on Alternative Power from Space*, edited by M. S. El-Genk, AIP, New York, 1995, pp. 965-971.

[16]Sirko, R. J., Renton, M. B., McKee, J. W., Siegfried, W. H., and Cutler, A. H., "Lunar Base Design for Resource Utilization," *A Lunar-Based Analytical Laboratory: Proceedings of the Second Lunar Analytical Laboratory Workshop*, edited by C. W. Gehrke, Deepak, Hampton, VA, 1997, pp. 16-33.

[17]Benaroya, H. and Bernold, L., "Engineering of Lunar Bases," *Acta Astronautica*, Vol. 62, 2008, pp. 277-299.

[18]Eckart. P., Ishikawa, Y., and Kennedy, K. J., "Designing, Sizing, and Integrating a Surface Base," *Human spaceflight: Mission analysis and design*, edited by W. J. Larson and L. K. Pranke, McGraw-Hill, New York, 1999, pp. 421-446.

[19]Bell, L. and Trotti, G., "Earth-based Analogs of Lunar and Planetary Facilities," *Second Conference on Lunar Bases and Space Activities for the 21st Century*, edited by W. W. Mendell, NASA Conference Publication 3166, Vol. 1, 1992, pp. 243-247.

[20]Collis, C. and Stevens, Q., "Cold Colonies: Antarctic Spatialities at Mawson and McMurdo Stations," *Cultural Geographies*, Vol. 14, 2007, pp. 234-254.

[21]Allen, J., *Biosphere 2: The Human Experiment*, Penguin, New York, 1991.

[22]Dempster, W. F., "Biosphere II: Engineering of Manned, Closed Ecological Systems," *Journal of Aerospace Engineering*, Vol. 4, No. 1, 1991, pp. 23-30.

[23]Eckart, P., "Biosphere 2 – Lessons Learned for Future CELSS Research," *Spaceflight Life Support and Biospherics*. Microcosm, Torrance, CA, 1996, pp. 365-396.

[24]Lee, P., "Mars on Earth: The NASA Haughton-Mars Project," *Ad Astra*, Vol. 3, No. 14, 2002, pp. 12-17, 51-53.

[25]Zubrin, R., "North to Mars!" *Scientific American*, Vol. 284, No. 6, 2001, pp. 66-69.

[26]Hartman, H. L., (ed.), *SME Mining Engineering Handbook*, Vol. 1, 2nd ed., SME, Littleton, CO, 1992.

[27]Lowrie, R. L., (ed.), *SME Mining Reference Handbook*. SME, Littleton, CO, 2002.

[28]Hartman, H. L., *Introductory Mining Engineering*, Wiley, New York, 1987, pp. 7-12, 98.

[29]Zambo, J., *Optimum Location of Mining Facilities*, translated by B. Balkay, Akademiai Kiado, Budapest, 1968, (Original work published 1966).

[30]Humphreys, K. K. and Leonard, J. W., "Technical Note: Optimizing Location of Mining Facilities, Coal Research Bureau, Report No. 85, Morgantown, WV, 1972.

[31]Liebenthal, A. M. and Mutmansky, J. M., "An Approach to Optimal Design of a Multi-Source, Single-Destination Conveyor and Beneficiation Plant Network," edited by A. Weiss, *World Mining and Metals Technology: Proceedings of the Joint MMIJ-AIME Meeting*, AIME, New York, 1976, pp. 998-1019.

[32]Gertsch, L. S. and Gertsch, R. E., "Surface Mine Design and Planning for Lunar Regolith Production," edited by M. S. El-Genk, *Space Technology and Applications International Forum – 2003*, CP654, AIP, 2003, pp. 1108-1115.

[33]Mecklenburgh, J. C., *Process Plant Layout*, Wiley, New York, 1985, pp. 7, 29.

[34]Guirardello, R. and Swaney, R. E., "Optimization of Processing Plant Layout with Pipe Routing," *Computers and Chemical Engineering*, Vol. 30, 2005, pp. 99-114.

[35]Bausbacher, E. and Hunt, R., *Process Plant Layout and Piping Design*, Prentice Hall, Englewood Cliffs, NJ, 1993.

[36]Meller, R. D. and Gau, K.-Y., "The Facility Layout Problem: Recent and Emerging Trends and Perspectives," *Journal of Manufacturing Systems*, Vol. 15, No. 5, 1996, pp. 351-365.

[37]Liggett, R. S., "Automated Facilities Layout: Past, Present, and Future," *Automation in Construction*, Vol. 9, 2000, pp. 197-215.

[38]Drira, A., Pierreval, H., and Hajri-Gabouj, S., "Facility Layout Problems: A Survey," *Annual Reviews in Control*, Vol. 31, 2007, pp. 255-267.

[39]Muther, R., *Systematic Layout Planning*, 2nd ed., Cahners, Boston, 1973.

[40]Muther, R. and Hales, L., *Systematic Planning of Industrial Facilities – S.P.I.F.*, Vol. 1., Management and Industrial Publications, Kansas City, 1979.

[41]Tompkins, J. A., "Facilities Layout," edited by G. Salvendy, *Handbook of Industrial Engineering*, 2nd ed., Wiley, New York, 1992, Chap 67.

[42]Konz, S., *Facility Design: Manufacturing Engineering*, 2nd ed., Publishing Horizons, Scottsdale, AZ, 1994.

[43]Tompkins, J. A., White, J. A., Bozer, Y. A., Frazelle, E. H., Tanchoco, J. M. A., Trevino, J., *Facilities Planning*, 2nd ed., Wiley, New York, 1996.

[44]Heragu, S. S., *Facilities Design*, 3rd ed., CRC Press, Boca Raton, FL, 2008.

[45]Parks, G. M. and Bhat, V. N., "Facilities Size and Location," *Handbook of Industrial Engineering*, edited by 2nd ed. G. Salvendy, Wiley, New York, 1992, Chapter 66.

[46]Caffrey, J. E. and Ladd, M. J., "Plant Siting and Construction," edited by H. L. Hartman, *SME Mining Engineering Handbook*, Vol. 1, 2nd ed., SME, Littleton, CO, 1992, Chap 7.2.

[47]Flint, B. F., "Site Structures and Hydrology," edited by R. L. Lowrie, *SME Mining Reference Handbook*, SME, Littleton, CO, 2002, Chapter 18.

[48]Heiken, G. H., Vaniman, D. T., and French, B. M., (eds.), *Lunar Sourcebook: A User's Guide to the Moon*. Lunar Planetary Institute, Houston, 1991, p. 647.

[49]Eckart, P., "Lunar Base Parametric Model," *Journal of Aerospace Engineering*, Vol. 10, No. 2, 1997, pp. 80-90.

[50]Badri, M. A., "Combining the Analytic Hierarchy Process and Goal Programming for Global Facility Location-Allocation Problem," *International Journal of Production Economics*, Vol. 62, 1999, pp. 237-248.

[51]Knowledge Based Systems, "IDEF0 function modeling method," URL: http://www.idef.com/idef0.htm [Cited 10 Sep 2010].

[52]Castillo, I., Westerlund, J., Emet, S., and Westerlund, T., "Optimization of Block Layout Design Problems with Unequal Areas: A Comparison of MILP and MINLP Optimization Methods," *Computers and Chemical Engineering*, Vol. 30, 2005, pp. 54-69.

[53]Balakrishnan, J., Cheng, C.-H., and Wong, K.-F., "FACOPT: A User Friendly FACility OPTimization system," *Computers and Operations Research*, Vol. 30, 2003, pp. 1625-1641.

[54]Georgiodis, M. C. and Macchietto, S., "Layout of Process Plants: A Novel Approach," *Computers and Chemical Engineering*, Vol. 21 (Suppl.), 1997, pp. S337-S342.

[55]Georgiodis, M. C.; Schilling, G.; Rotstein, G. E.; Macchietto, S., "A General Mathematical Programming Approach for Process Plant Layout, *Computers and Chemical Engineering*, Vol. 23, 1999, pp. 823-840.