LUNAR MATERIALS PROCESSING SYSTEM INTEGRATION

Brent Sherwood

Boeing Defense & Space Group

Abstract

The theme of this paper is that governmental resources will not permit the simultaneous development of all viable lunar materials processing (LMP) candidates. Choices will inevitably be made, based on the results of system integration trade studies comparing candidates to each other for high-leverage applications. It is in the best long-term interest of the LMP community to lead the selection process itself, quickly and practically.

The paper is in five parts. The first part explains what systems integration means and why the specialized field of LMP needs this activity now. The second part defines the integration context for LMP -- by outlining potential lunar base functions, their interrelationships and constraints. The third part establishes perspective for prioritizing the development of LMP methods, by estimating realistic scope, scale, and timing of lunar operations. The fourth part describes the use of one type of analytical tool for gaining understanding of system interactions: the input/output model. A simple example solved with linear algebra is used to illustrate. The fifth and closing part identifies specific steps needed to refine the current ability to study lunar base system integration. Research specialists have a crucial role to play now in providing the data upon which this refinement process must be based.

SYSTEM INTEGRATION

Among technical specialist, System Integration (SI) is often considered an "impure" form of engineering, consisting principally of "paper studies". But SI is a vital part of the engineering process, without which the whole of a project reverts to a mere sum of its parts. SI's function is to tie together all the specialty engineering, ensuring that what results is a coherent, well-balanced project or design. SI is therefore a technical activity one logical type higher than the specialty engineering disciplines. Subsuming all of them, it addresses issues beyond the scope of any one specialty.

Specifically, SI coordinates the unique needs and contributions of the project's distinct parts. It clarifies the resulting interactions among them, revealing and resolving conflicts and mismatches in their performance and their resource needs. By working in the "spaces between" the specialty fields, SI identifies and exploits opportunities for synergy that might otherwise remain unknown in a partitioned field of specialties. By nudging each piece into a seemingly nonoptimal state, it seeks to create a balanced system, one which is overall optimal and yields a cost-effective use of system resources.

Figure 1 tabulates the life cycle phases of a space project, starting with the end product and working backwards to outline what each phase consists of and what it tries to accomplish. Success in each phase requires the coordination that SI provides. *Performance* is the driver during project execution, where achievement within resource constraints is the measure of success. Here SI limits recurring costs by optimizing "value added" and facilitating "total use". The approach of value added attempts to derive multiple benefits from work performed, and to avoid doing the same job more than once. A lunar materials processing (LMP) example is the value added to a grain of regolith merely by having moved it. Even if that grain is part of the "tailings" rather than the "ore", taking advantage of the unavoidable investment in its processing facilitates a more efficient overall operation. Mechanical work (transportation) and state changes (thermal and chemical treatments) should be captured by subsequent disposition. In the limit, this kind of conservation leads to total use. The operation capitalizes on the investment of limited resources, maximizing the incorporation into useful products of anything to which value has already been added. On the Moon, disposal becomes stockpiling; refuse is really an already partially-processed resource. In the example above, the sieved but then rejected fraction of regolith feedstock becomes valuable as well-sorted radiation shielding.

For the planning phase of a project, *synergy* is the driver, enabling selection of cost-effective capital options favored for project implementation. SI facilitates synergy in four ways. First, it matches performance to requirements in a balanced way across all component systems. An LMP example is the proper sizing and duty factor of surface operations equipment for modestly scaled oxygen (LLOX) production. Roughly 100 t of LLOX enables four lander round trips. Even with a poor-yield process like ilmenite reduction, a 100t/yr production rate translates to an excavation rate of about 2 kg/s, roughly equivalent to "two good guys with shovels" operating continuously. For this purpose, the typically imagined lunar "bulldozer" may be a nonoptimal miner concept. Second, SI tries to achieve commonality and standardization across systems where practical. Designing modular power packs -- using dynamic or thermophotovoltaic isotope sources, for example -- into mobile applications allows both ganging (for power-intensive applications) and interchangeability (which maximizes duty factor for these limited-half-life subsystems and simplifies redundancy scenarios).

Third, SI seeks to incorporate or adapt existing systems, which can save money and time over baselining "clean sheet" designs. Adapting Space Station *Freedom* modules for lunar outpost habitation takes advantage of national investments in engineering development and qualification testing. Fourth, SI determines the resulting tradeoffs -- as between expediency and optimization -- by assessing the performance penalties of non-optimal solutions. LMP will generate many cases for which less efficient of less elegant solutions may nonetheless trade favorably against high-

Project Phase	What Goes On	Objective
Execution	• Fabrication & testing • Launch & flight • Deployment • Operations • Data collection & evaluation	• Capable, robust system emplaced successfully • Every kg, W, min enhances return • Longevity, knowledge, progress
Conception & Planning	• Requirements development • Trade studies • Preliminary design • Experimental validation • Detailed design & system specification	• Good system selections • Designs with "think ahead" responsiveness • Incorporation of multiple paths to success • Efficient use of project resources (time, $)
Enabling Research	• Basic research • Application development • Proof-of-concept	• Discover interesting things • Identify and pursue promising options • Understand performance characteristics

Figure 1 Success in all three project lifecycle phases requires the coordination which SI provides.

Objective	Description	Basic Needs	LMP Focus
Operations Enhancement	• Reduced transp. cost • Improved base efficiency • Reuse/recycling of imported material	• Modest quantitites of propellant • Simple paving, sheltering	• Primarily LLOX; perhaps Al, sw-H2 • Simple bulk feedstock or *in situ* processing
Lunar Settlement	• High human traffic rate • Large population • Long-distance surface transp. • Productive economy	• Large habitable volume • High-rate, precision manuf. and recycling infrastr.	• Life elements (HCNOP) • Structure systems • Wide spectrum of technological products • Agricultural substrate
Interplanetary Industrialization	• Provides high-value exports (energy, precious products or large supplies of mat'l) • Advanced automation • Regular space transportation	• Large specialized *in situ* industry, and/or... • High mining rate • High efficiency, rapid-fire launch	• 3He; solar power plant materials • Special-purpose processing in lunar environment

Figure 2 Potential LMP-supporting lunar base functions introduce alternative dominant LMP requirements.

performance options. For example, simple, inefficient amorphous silicon photocells will probably be manufacturable *in situ* on the Moon earlier than "better" cells. Their increased installation size, deployment and maintenance costs, and consequent infrastructure requirements may be worthwhile.

For the research phase -- where LMP is now -- *priority* is the driver. This is the time when the range of possibilities is widest, when selection among them is most difficult, and when changing direction is least expensive but most leveraging. Many LMP candidates have been proposed so far. Most appear workable in some way, and several have been proved empirically at small scale or by terrestrial process analogy. The relative importance of the various options remains unknown, however. Each has dedicated professional advocates, and program funding and development time are both severely limited.

Establishing research priorities over the coming decade is essential to make real progress despite resource limitations. Serial implementation of lunar materials processes in a well-structured program requires careful development sequencing. The government-funded SEI cannot afford to dissipate its resources across all LMP candidates; some will win and most will not. One way or another, priorities will be set and followed. Given proof of feasibility, the primary filter will be practicality, and system integration engineering will provide the analyses to enable informed prioritization. Thus SI is essential to the incorporation of LMP into SEI.

Context

The role of LMP in the evolution of lunar basing will depend critically on the purpose of the basing activities. *Figure 2* consolidates the potential applications of LMP according to three candidate objectives: (1) enhancing the operations of a primarily scientific lunar effort by increasing performance and reducing cost; (2) providing the material needs for lunar surface development, settlement and population growth; and (3) industrializing the Moon for export purposes. All proposed purposes of lunar exploration are covered by these three options. The figure characterizes each, describes its salient seeds, and outlines the focus of LMP activities most essential to support it. This distillation begins to clarify a likely evolution among LMP options. Regolith-moving for construction, and LLOX production, will precede the recovery of significant quantities of adsorbed volatiles and the large-scale conversion of regolith into agricultural soil. These in turn will probably precede the industrialization of exotic products like $_3$He and high technology components.

At all stages on this evolutionary path, it is the flow of critical resources (*Figure 3*) that defines the interaction among base elements. Each element -- a habitat, a mobile crane, a process plant -- is a system "user" competing for these resources with other users, but also producing resources they need. Importation of resources energy, equipment, crew, and so forth is rate-constrained and therefore governs the system productivity. Key measures of overall system efficiency are how closely user needs are matched to resource supply, and how thoroughly each import unit is utilized before being discarded.

One SI responsibility is to determine where surpluses of some resources can productively be used to compensate for insufficiency in others. For example, configuring the system to provide an energy-rich operating environment may enable the use of process plants which are more energy-wasteful but simpler, more-reliable, lighter, and easier to deliver and maintain. Along with everything else, materials processing activities must sacrifice self-centered optimization in favor of the overall optimization of the entire base they support. The constraints which emerge from folding individual element operation into base operation then become key design drivers for the elements. *Figure 4*

• **Delivered Mass**	• **Maintenance Activity**
• **Energy Supply**	• **Environmental Conditioning**
• **Material Supply**	• **Energy Disposal**
• **Time to Function**	• **Spare Parts**
• **Space to Occupy**	• **Communication Bandwidth & Duty Factor**
• **Transportation Service**	• **Computation Capacity**

Figure 3 The interactions among base elements are defined by the flow of these critical resources among them.

Base Functions	Imposed *by* LMP	Imposed *on* LMP
Science	• Necessity of schedule adherence • Capability to mobilize serendipitous investigations	• Production-scale operations paced by *in situ* exp'ts • Environmental contamination management • Possible excavation slowdowns to allow investigation
Space Transportation	• Delivery of relatively large, heavy, complex plant components	• Fixed, limiting delivery capacity and rate • Package volume premium • Rough ETO ride, erosive LEO environment
Surface Transportation	• Sessile plant requires feedstock supplied • Efficiency & reliability favor plant assembly of few, large sections • Volatiles collection requires processing relatively vast quantities of regolith	• Raw material conveyance rate & periodicity • Equipment positioning accuracy
Energy Production & Disposal	• Lots of energy to decompose rocks • Consistency & reliability favor continuous operation	• Nighttime power premium • Exclusively radiative thermal rejection: *380K daytime environment*
Resupply	• Reliable resupply of critical materials: *reagents; replacement parts & catalysts*	• Periodic (rather than continuous) delivery • Good foreknowledge of stock needs • Downtime contingency planning • Commonality: *plant design for cannibalization* • LMP recycling of refuse desirable
Robot Capabilities	• Heavy work, fine work • Continual monitoring & inspection • Sophisticated sensors/telemetry	• Design-for-maintenance: *modularity, non-cascading access, in-line mounting, maneuvering room* • Machine limits: *strength, range, dexterity, intelligence* • Available time
Crew Capabilities	• Special skills onsite • Break-in period, time to resolve bugs	• EVA limitations: *stamina, dexterity, strength, reach* • Operations & maintenance procedure safety • Available time
Life Support	*(Not a driver to first order, since LS requirements are relatively independent)*	• LS priority for all services: *power, transp., etc.* • GCR shielding uses lots of regolith • Guaranteed supply if ISMU for consumables *(for large scale settlement)*

Figure 4 LMP is just one of many base functions all of which constrain, and are constrained by, each other.

identifies some of the integration constraints imposed both by and on LMP in the context of a complete lunar base, broken down into functional categories derived from the list of critical resources in *Figure 3*. This summary hints at the range and complexity of tradeoffs which must be performed to achieve a practical, balanced system design.

Calibration

The LMP roles outlined in *Figure 2* can only evolve as project resources permit; for the foreseeable future, those resources consist of public money and governmental projects. Inescapably, the sequence and pace of development is largely independent of the stridency with which particular LMP options might be advocated. A realistic assessment of the likely extrinsic program constraints is essential to effective LMP system integration efforts.

All projects can be characterized according to the three programmatic dimensions of scope, scale and timing. *Scope* is what the program consists of how much it includes. For the present purpose, that means the types of LMP it needs. It is useful to employ a taxonomy of six LMP types, ordered by their intrinsic difficulty and energy cost: (1) siteworks (like paving, radiation shielding, ejecta barriers, and thermal buffers) require only physical material handling like excavation, fractionating, transportation and deposition; (2) recovery of adsorbed volatiles (for fuel, atmosphere and biogenic resources) requires relatively simple physical and thermal processing, and gas handling, albeit at large scales for effective utilization; (3) extraction of iron (for simple structural elements) requires magnetic separation, probably beneficiation, and at least primitive forging to be useful; (4) manufacture of ceramic-based objects requires beneficiation, physical preparation and application of high energy densities; (5) production of large amounts of oxygen (for propellant oxidizer and life-support makeup) requires chemically and/or thermally mediated reduction of lunar minerals and subsequent cryogenic management; and (6) advanced extraction of refined Si, Al, Mg, Ca, Ti and other less abundant elements (leading to complex fabrication of useful products) requires sophisticated, multi-step, energy-intensive infrastructure. It is interesting to note in passing that oxygen production in most commonly discussed product for early implementation falls toward the more challenging end of this spectrum. The LMP program scope is set by how many of these processing types are invoked.

Scale is how much of the program there is -- its size or, in this case, the extent of LMP, independent of which LMP types it uses. Thus, for an early, small lunar exploration and development project, LMP might be just a scientific phenomenon (an opportunity to learn). Or, it could be a practical enhancer (for example, producing oxygen to offload the Earth-to-orbit lift capacity required to maintain a certain level of base operations). Beyond that, it might be utilized as a growth enabler, by providing a significant fraction of the material mass required to increase the planetary "toehold". Ultimately, LMP might become the driving activity (for instance, by supplying built resources vital to the large-scale, space-based industrialization of terrestrial energy supply). The scale at which LMP will be implemented partly controls the selection of appropriate processes and infrastructure.

Timing is how fast the project happens -- here, how soon a particular LMP option comes on line (even a large-scale program can happen gradually over time). At one extreme is the "go as you pay" SEI prescription, in which the timing of project milestones is a variable dependent on program funding rate. The opposite alternative is deadline-driven, in which the milestone timing is the independent variable (the classic example of this is Project Apollo). In any case, fixing the timing of basing milestones sets the corresponding demand schedule for appropriate LMP capabilities. An LMP program scoped for siteworks and experiments, and scaled for science and modest enhancement, matches the reconnaissance/outpost phase. Later on, including production of structural elements, at a scale capable of enabling basing growth, matches a true consolidation/utilization phase. An eventual industrialization phase would be matched by advanced, complex processes implemented at high-yield scale. Identifying when these very different phases are likely to occur enables prudent LMP planning by avoiding premature, unaffordable development.

Figure 5 shows a strawman timeline based on one projection of government-funded lunar development. Outright prediction of the future is of course perilous. Each detail of the strawman schedule is thus individually arguable, however the integrated result appears valid based on the history of spaceflight programs and the evolution of the role of space exploration in world events. A few points are noteworthy. First, the first decade matches current planning by NASA's Exploration Programs Office. Second, beginning about the year 2015, a zero-sum choice may occur between focusing limited resources on the human exploration of Mars or on the expansion of lunar development. Third, if lunar development proceeds, it is difficult to come up with a viable lunar scenario that does not lead one way or another to settlement by large numbers of people, supporting large-scale, export-based industrialization.

Lunar surface operations are ten years away. Another decade appears required for LLOX to enhance operations routinely; yet a third decade is likely to pass before LLOX leverages real operations growth. In the meantime, the current generation of LMP professionals will be at least retired. The sobering point of the schedule exercise is that many of the fascinating processes which the LMP community could pursue now have little to do with collapsing this schedule. They will not likely become important for another quarter century because of the inevitable *timing* of the *scale* required for their practical implementation. An important "wild-card", though, is the potential for private investment. The entire 1992 NASA budget is about $15 B, whereas the commercial airplane industry -- which really came into existence only two generations ago -- is a $50 B/yr enterprise. Development of lunar-based commercial markets could dramatically foreshorten the schedule.

SI helps planners maintain perspective by verifying that the efforts expended match the results obtained. For a simple illustration, consider the problem of resupplying nitrogen to an early lunar outpost. A typical habitat module designed to support a crew of four for several months holds about 400 m^3 of atmospheres. At 10.2 psi, 70% of that is nitrogen. One repressurization's worth is 220 kg, about the same amount lost to leakage over a year's time. At issue, then, is how to resupply 220 kg/yr of nitrogen per module. Supplying it from Earth ready-to-use would cost about $1.3 M, given an ETO cost of $1 k/kg and a 6x multiplier for transportation cost to the lunar surface from LEO. Alternatively, the nitrogen could come from solar-wind volatiles adsorbed in lunar regolith. At an average abundance of 80 ppm and recovery efficiency of 80%, we would have to process 3500 t of regolith. So the issue reduces to one of identifying the LMP production rate at which the required infrastructure could cost less (emplaced) than $6000 per kilogram of nitrogen recovered. Clearly that rate is far greater than the 200 kg/yr level. Which decreases faster the cost of emplaced LMP infrastructure or the delivery transportation cost? Can the cost of LMP-supplied nitrogen ever be competitive? This simple example illustrates the kind of caution that must be applied when considering LMP scenarios.

Input-Output Modeling

System integrators use a variety of methods to analyze system behavior. The three primary tools are feasibility/practicality checks, parametric models, and integrated point-design analysis. Feasibility/practicality checks are used to determine if an idea is worth pursuing. They provide a rough-order-of-magnitude (ROM) sense of how a system will behave, or a confirming "sanity check" to see if a system concept is at all practical. Typical approaches include using existing analogs for comparison, and performing ROM calculations based on simplifying assumptions (like the nitrogen example of the last section).

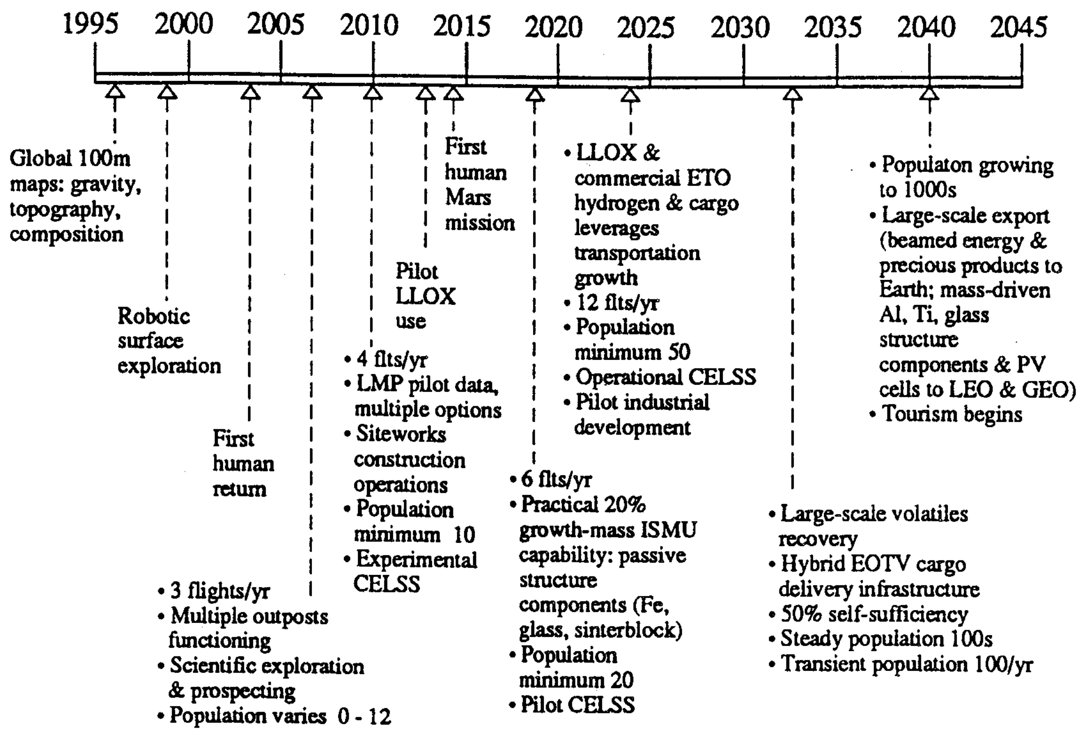

Figure 5 A strawman lunar timeline helps ascertain when LMP products might become essential to further growth.

Inputs: Common	Inputs: Particular	System Element	Outputs
• Delivery/ transportation service • Deployment/ construction activity • Power consumed • Parts/ consumables • Maintenance time, skills & tools	• Propellants consumed • Prepared surface area	**Lander**	• Mass delivery and return
	• Prepared surface area • Equipment upgrades • Gas makeup	**Habitat**	• Controlled environment • Low-grade heat
	• Controlled environment • Oxygen, water, food	**Crew**	• Operations time/skill • Data, interpretation • Low-grade heat • CO2, water, solid wastes
	• Crew operations time	**Robots**	• Operations time/skill • Data
	• Prepared surface • Access to sunlight • Reactants, or fissile fuel	**Power Plant**	• Power produced • Heat • Water
	• Feedstock consumed • Reagent makeup	**Materials Plant**	• Value-added regolith • Elemental products (oxygen) • Structural components • High-tech products
	• Crew operation/ supervision time	**Miner-Transporter**	• Carrying service • Operations time

Figure 6 The first I-O modeling step is to identify the system elements of interest, and the resources they consume and produce.

Parametric modeling is a more sophisticated and flexible approach used to understand multivariate relationships among system elements and functions. Just as an algebraic equation enables deeper insight than an arithmetic solution, parametric methods allow the generalization of system performance estimates. Requiring convergence in such a model establishes values -- or ranges of values -- for the driving quantities which are mutually consistent. Parametric modeling can also explore the effects of varying system drivers throughout their valid range. By experimenting with a numerical system model, comparing its behavior as key quantities are changed, the analyst can determine which parameters the system is most sensitive to. Such sensitivity analysis leads to an understanding of system robustness and operating margins. (Input-output models, the type of parametric models used for high-order multivariate systems, are discussed in detail below.)

The third kind of tool is full-blown, integrated point-design analysis. This uses a broad suite of specialized engineering design and analysis capabilities to drive out potentially crucial details of the system's dependencies. Because it is a step closer to the hardware phase of a project, its results are more reliable than the other methods. However, this greater detail sacrifices generality and adaptability, and obtaining it is slower and more expensive. Consequently this kind of analysis is usually reserved until parametric modeling has identified the proper design "neighborhood".

Input-output (I-O) modeling is a cost-effective way to find the right neighborhood, and to grasp and manipulate parametrically the performance of an entire system. It integrates the needs and products of key system elements, reconciling them with each other. In so doing, it validates the mutual compatibility of the various elements' design capabilities. I-O modeling facilitates system-wide sensitivity analyses, and can determine the break-point regions for important driving parameters -- those regions of their range which result in step-function-like behavior elsewhere in the system. The understanding gained helps build confidence in the validity of system sizing and scaling factors useful to designers. Finally, because numerical modeling is cheaper than experimenting with real systems, I-O modeling allows SI to compare different system designs quickly. I-O models can be as simple as desired or as complex as needed, depending on their purpose. Simple ones can be solved on programmable calculators or PC spreadsheets. Large ones with thousands of parameters are best implemented on mainframe computers. In the remainder of this section, a simple, linear I-O model illustrates the power of this tool.

The linear procedure follows seven steps: (1) list the critical system elements and resources; (2) qualify the pair-wise mutual resource dependencies among the elements using an N^2 format; (3) quantify each dependency algebraically using scaling quotients specific to the paired elements; (4) formulate the resulting matrix equation system; (5) select the output drivers of interest; (6) iterate the system parameters to achieve first a consistent, and then a desirable, integrated solution set; and (7) vary the parameters systematically to perform sensitivity analyses.

Figure 6 lists the kinds of top-level resource inputs and outputs pertinent for system elements typical of a lunar base which includes LMP. Note that all elements require delivery, power, parts, and attention in the form of setup and maintenance activity. Note also that some output (like delivery capability, maintenance time, power or material product) are desirable, whereas some (like waste heat, waste products, or broken parts) are undesirable losses to the system which must nonetheless be accommodated by the integration model. Advanced basing scenarios can capture some of these waste streams, for example by recycling value-added or scarce materials. However, waste heat is always eventually rejected, just as energy is ultimately imported.

Figure 7 illustrates a quantified N^2 dependency matrix. This format provides a framework for capturing all key, pairwise interactions among the selected elements. The example models just six base functions: habitation, crew presence, power production, thermal rejection capacity, surface transportation capacity, and resupply capacity. Setting up even such a simple model already forces attention to fundamental but often-overlooked aspects. For instance, how much equipment can one person maintain continuously? What is the annualized transportation requirement to keep different kinds of equipment supplied with replacement parts? How much habitat, and how much power, are required to support one person on the Moon indefinitely? Implicit relationships are embedded in the matrix: one example is the requirement for a 2 kW of thermal rejection for each 1 kW of power used, which captures the ~50% conversion inefficiency incurred by using regenerable fuel cells for nighttime power storage.

Figure 8 shows how to develop a system equation set using the N^2 relationships. Examining the second row, for instance, shows each term to define the crew required by a particular base function. The units are all quotients because each coefficient is a unit-specific value, not an absolute number. Multiplying the habitat-specific term by the total tonnage of habitat in the base, the power-specific term by the total kilowattage of power in the base, and so on, and then summing these products yields the total number of crew required to run the base. Similarly, the other rows describe the other system parameters as implicit sums. The problem, of course, is to find the consistent set of all these required totals simultaneously. The problem can be written algebraically as follows.

Let **A** be a square matrix with off-diagonal numerical coefficients taken from the N^2 matrix. Let each diagonal entry be -1 (with the same units as the units numerator common to all other entries in the row). Let **x** be the column vector consisting of the (unknown) total quantities of each system element (tonnes of habitat, number of total crew, kilowatts of power provided, etc.) required to "make the system work." That is, these are element values which define an overall system consistent with the multivariate relationships expressed in **A**. The equation $\mathbf{Ax} = \mathbf{0}$ then models the system, and can be solved to find the element vector **x**. If no solution exists, it means that no combination of element values satisfies the system behavior embodied by the N^2 relationships. Iterating matrix coefficients until convergence occurs leads to a permissible system description.

Such a homogeneous equation is fine if the purpose is simply to find out how much of each function it takes to enable all the other functions. This situation would apply to a fully modeled system -- one in which a functional "free body diagram" drawn around the modeled system has no net inputs or outputs. More useful is the formulation of the inhomogeneous equation $\mathbf{Ax} = \mathbf{b}$, where $\mathbf{b} \neq \mathbf{0}$. This now represents a system which yields net product, appearing as an excess of the system elements on the right hand side. Algebraically, the column vector **b**, with the same units as **x**, consists of the opposites of the desired system outputs. Extracting one equation from the set and rearranging it shows simply that the sum of the requirements levied on that particular element by the other system functions, plus any desired excess of that element, equals the total amount of that element required to make the system consistent.

The inhomogeneous formulation allows partial system modeling. For example, the simple model illustrated here has no expression for crew to perform scientific duties, only crew to maintain the base function. However, specifying $\mathbf{b}^T = \{0, -6, 0, 0, 0, 0\}$ requires the model to "produce" a net "output" of six excess crew, who could perform science. Solving the system then leads to $\mathbf{x} = \{104$ t habitat, 10 total crew, 80 kWe power, 162 kWt thermal control, 10 t surface transportation, 32 t/yr resupply$\}$.

Linear I-O models can be used for many systems if the parameter coefficients are kept within well-controlled ranges. Within those ranges the solution vector is scalable (doubling all the element values still yields a consistent system). The advantage of linear models is that linear algebra can be used to solve them; matrix inverters are available on pocket calculators. More advanced methods

How much of these... ↓ | **...does it take to enable these?** →

	Habitat	Crew	Power	Thermal Control	Surface Transport	Resupply
Habitat		10t of habitat to support 1 crew	—	—	—	—
Crew	1 person to maintain 100t of habitat		1 person maintains 100t of power system	1 person maintains 100t of thermal mg't system	1 person maintains 33t of transporters	1 person performs 50t/yr of the resupply function
Power	—	6kW power for activities and LS for 1 person		1kW power runs 20kW-worth of thermal mg't system (e.g. pumps)	1kW power recharges 1t of transporters	—
Thermal Control	—	150W thermal rejection for each person	2kW thermal rejection for use of 1kW power		—	—
Surface Transport	5t pressurized transportation per person	1t transportation constructs 20t of habitat	1t transportation deploys 100t of power system	1t transportation deploys 100t of thermal system		(Resupply function uses transporters already required by other functions)
Resupply	5%/yr replacement, upgrade parts	2t/yr provisions per person	5%/yr replacement parts	1%/yr replacement parts	1%/yr replacement parts	

Figure 7 Simplified example shows how the quantified N^2 format can capture selected pairwise element dependencies.

Relationships from N^2 matrix | **System Totals**

	10 t/crew					==>	**Habitat** t
0.01 crew/t		+ 0.01 crew/t	+ 0/01 crew/t	+ 0.03 crew/t	+ 0.02 crew/t-yr	==>	**Crew** number
	6 kWe/crew		+ 0.05 kWe/kWth	+ 1 kWe/th		==>	**Power** kWe
	0.15 kWth/crew	+ 2 kWth/kWe				==>	**Thermal Control** kWth
0.05 t/t	+ 0.2 t/crew	+ 0.01 t/t	+ 0.01 t/t			==>	**Surface Transp.** t
0.05 t/yr-t	+ 2 t/crew-yr	+ 0.05 t/t	+ 0.01 t/yr-t	+ 0.01 t/yr-t		==>	**Resupply** t/yr

Figure 8 The dependency coefficients allow a simultaneous accounting of all the elements in the model.

are useful, though. The linear example above models base resupply as a system byproduct. The exponential rock equation could be used to include the space transportation delivery system behavior in the model as well. Doing so would preclude a linear algebraic solution, however. Computer-based iteration techniques work well to solve nonlinear models, or very large models with thousands of parameters.

For all I-O models, finding a consistent solution is really just the beginning of integration understanding. The true behavior of the system is revealed through sensitivity analyses. Observing the effect on the system element solution set as the matrix coefficients are varied around their nominal values indicates which parameters are principal drivers. Desirable values of the driving parameters then become technology development goals. Knowing how sensitive each is helps establish performance margin tolerances which can be used as design guidelines. For lunar base models, the maintenance-time requirement is typically an especially strong driver, because it leverages the total requirement for very expensive crew presence.

Next Steps

This paper's primary purpose in discussing SI methods is to clarify for the LMP technical community how the data they generate are used in system models to support the program decision-making process. The preceding section makes apparent the importance of quotient-based system metrics, especially early in the program. For an oxygen plant, parameters like oxygen produced per tonne of plant, or power consumed per tonne of product, and an understanding of their scale-dependence, are far more important than single-unit measures (like mass) of any given point design.

SEI will benefit by the LMP research community addressing the metrics that matter the most. To a specialist researcher working on a particular process, approaching the theoretical conversion efficiency may pose a scientifically challenging problem. However, to the system integrator, that research target may be moot if the process in question is half as practical as a competing one. For space systems in general, system elements involving crew presence (or analogous skills) are very important. Onsite astronaut attention is the most expensive kind for setup or maintenance, and genuinely capable robots -- if possible -- are expensive to develop. For lunar systems in particular, system elements with cascading mass-leverage are very important. LMP elements are consistently strong model drivers, because the space transportation cost of delivering an LMP plant is exacerbated by the derivative transportation cost of delivering the associated power system, surface transportation capacity, replacement parts and maintenance crews to make it work.

Useful modeling requires good metrics; on the validity of the parametric coefficients hinges the validity of any system model. Both a practical range and a preferred value within that range should be known for each parameter. Such knowledge evolves over time. Typically, first-generation models are built using parameter estimates based on terrestrial analogs or extrapolations. The next generation updates these by anchoring them with point data taken in laboratory experiments designed by approximate certain aspects of the proposed end-use. Third-generation refinement is enabled by integrated testing of developmental hardware systems as the program progresses. Finally, the validity of model parameters is confirmed through the accumulation of statistically meaningful quantities of empirical data from the real system operating in the field. This database then enables a new generation of analog-based modeling to begin for other applications.

LMP is currently in the transition from the first to the second generation. Knowledge confidence for many crucial metrics remains poor. *Figure 9* characterizes a few representative system parameters to indicate the types that can benefit most from laboratory data now. Reviewing even this short list highlights several important investigations: dusty thermal-vacuum prototyping of miner mechanisms;

contextual, end-to-end simulation of processes; quantitative assessments of practical system equipment candidates for substitution by LMP-derived components; and environmental breadboarding of robotic systems using specific LMP-relevant tasks.

Presently our concepts outstrip our supporting data. More data, particularly parametric datasets and experimental results, are needed. Specialist technology researchers are in the best position to provide such data. Thus the SI community needs help from the LMP research community in three ways. First, the LMP community needs to be aware that system metrics will be used to set priorities, given the zero-sum nature of limited governmental funding for SEI. Second, LMP researchers need to understand that process prioritization will consider effects both by and on other system elements and functions, and that many promising processes must nonetheless await later phases of lunar base development to be practical. Finally, the LMP community must work together, focusing on the nearest-term, most-likely process options, to pursue both improved accuracy and peer validation for the highest-leverage, worst-confidence metrics. Together the three measures outlined here can help produce a taut, lean, responsive and progressive LMP program for SEI. Such discipline will facilitate the earliest possible implementation of keystone processes, and hence ultimately of all viable process candidates.

Metric Confidence Classification	Fairly well-characterized	Changing with technology, experience	*Terra incognita*
Examples	• Habitat mass per person • Consumables mass per person • Pressurized rover mass per person • Lunar surface delivery mass ratio t/t-LEO	• Solar array kW/m^2 • ETO launch \$/kg • %/yr replacement for electro-mechanical systems in lunar environment • Feasible EVA hrs/wk	• Online duty factor for regolith mining equipment • Achievable recovery efficiencies for lunar materials processes • % infrastructure mass practical for ISMU substitution • Maintenance factors for LMP plants of all kinds • Reasonable ratio of robotic/crew maintenance activity

Figure 9 Current knowledge of important system metrics is uneven, and can benefit greatly from new, focused data.