Concept for Lunar Surface Logistics and Infrastructure. Image credit: NASA.

A MULTIDISCIPLINARY WHITE PAPER

Estimating Lunar Construction

The Master Estimating Theory

System-Based Methods for Absolute Minimum Variance to the Predicted State

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This white paper represents an independent, unfunded, multidisciplinary collaborative effort spanning industry, aerospace, engineering, design, construction, and academia.

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IN THIS PUBLICATION

The Master Estimating Theory (MET) is presented through an Executive Summary followed by Professional Lens Papers examining the theory through estimating, design, construction, engineering, academia, and aerospace perspectives.

Executive Summary

1. Why a Master Estimating Theory?

The return to the Moon presents one of the most demanding estimating challenges ever undertaken. Yet even terrestrial megaprojects, supported by experienced teams, established technologies, mature supply chains, and extensive historical knowledge, continue to experience substantial cost and schedule uncertainties. Although the construction industry strives to improve the accuracy of the estimating process, megaprojects statistically continue to surpass their original estimate predictions. For example, McKinsey & Company reported that 98% of billion dollar plus megaprojects experience cost overruns greater than 30%, while 77% are at least 40% late [McKinsey & Company, 2015].

The industry has proven that early estimates of cost and time mega projects are challenging to maintain as the project design matures. In this context, lunar projects cannot rely on mature local supply chains, abundant historical data, readily available labor, established lunar production systems, or the ability to rapidly recover from engineering or construction errors. Every engineering decision can affect transportation, production, logistics, sequencing, energy, operations, risk, and ultimately mission success.

Every estimate attempts to describe a project that is not yet realized. At the moment an estimate is prepared, the project has not been completely designed, engineered, procured, constructed, or operated. Decisions affecting cost, schedule, resources, production, logistics, and risk cannot wait until that knowledge exists. The estimator must therefore make the best prediction possible from the information, experience, and professional judgment available at that time.

Consider a simple engineering exercise:

An apple is placed on a table. Before it is cut open, many of its characteristics can be predicted from direct observation, previous experience, and informed judgment. Its size, color, and external condition are objectively observable, while its internal condition remains an informed subjective prediction. Conceptually this is similar to the uncertainty illustrated by Schrödinger’s cat. However, unlike Schrödinger’s cat, the apple does not exist in a simple binary state because its condition is bounded by the system and function of the apple itself. The apple may be perfectly sound, contain seeds, overripe, or perhaps contain a worm. Once it is cut open, those plausible conditions give way to verified evidence. The apple itself has not changed; what has changed is our knowledge of its actual state. Before it was opened, we could predict with reasonable confidence that its core contained components and quantities based on system subjective knowledge. Once opened, those predictions can be objectively verified. Furthermore, if the examiner making the assessment of the internal state was an experienced apple farmer, that experience would likely increase the reliability of the detailed predicted state.

Projects develop in much the same way. Early in a project, much of the estimate is typically based on informed subjective prediction. As engineering and design develop, assumptions can progressively be tested against objective information.

The important relationship is between what was predicted and what is being realized. That relationship exists whether or not the estimate is keeping pace with it. An estimate may appear sound while design decisions, field conditions, production assumptions, or other cause and effect relationships have already moved away from what was predicted. Widely separated estimate revisions can allow that trajectory to be lost. Jennifer Taylor's work on Cycle Jumps provides a related professional perspective on discontinuities that can develop between cycles of information, decisions, and execution [Taylor, 2026].

Master Estimating Theory (MET) identifies the estimator's current understanding of the intended project as a Predictive State. The objective is not simply to replace one estimate with the next, but to preserve the relationship between what was originally predicted and what the project is becoming.

That requires structure. An estimate line has meaning because of the scope, unit, assumptions, and system relationships it represents, not simply its quantities and costs. More detail does not necessarily create a better prediction. Information without predictive relevance can instead become noise, a broader problem in professional judgment examined by Kahneman, Sibony, and Sunstein in *Noise: A Flaw in Human Judgment* [Kahneman et al., 2021].

Experienced estimators already use professional judgment, historical knowledge, specialized expertise, and increasingly sophisticated technologies to develop complex estimates. MET does not replace those practices or suggest that experienced estimators are incapable of this work. It addresses the fragmentation that can occur when estimating, design, engineering, construction, and operational information develop through separate processes and are periodically partially reconciled rather than continuously connected.

Terrestrial projects can partially absorb that information latency through historical precedent, mature supply chains, familiar production systems, and opportunities for corrective action. Lunar construction substantially reduces those buffers. Systems may be purpose designed, highly interconnected, and developed for conditions with little or no direct construction precedent.

The Master Estimating Theory provides a structure for maintaining the relationship between prediction and the project as it develops.

2. The Predictive State

Project information develops across multiple professional disciplines, yet no single discipline holds a complete representation of the project. Estimating brings these different streams together.

The Master Estimating Theory (MET) identifies the estimator's current representation of an intended project as the Predictive State. It begins with the best information, experience, and professional judgment available at that point. The challenge is not simply adding information as design develops, but structuring the estimate so that what was predicted earlier remains traceable as systems, components, quantities, and engineering decisions become better defined.

Consider again the apple. Early in the prediction, the apple may be represented as one aggregate unit. That does not mean its internal components do not exist. As additional information becomes available, the aggregate can be resolved into increasingly defined components without losing the relationship to the original apple. Even before design and engineering maturity, increased predictive detail can reduce ambiguity by exposing cost, time, system, logistical, and causal relationships that are not apparent at the aggregate level. Complex projects develop in much the same way. An early system level prediction may later contain hundreds or thousands of defined components, but those components should remain traceable to the scope and assumptions from which they developed.

This becomes particularly important when different stakeholders require different information. A general contractor may carry an electrical system at an aggregate level while the electrical trade partner requires substantially greater detail to understand production, installation, interfaces, and risk. Information that is unnecessary to one stakeholder may be important to another. On complex projects, valuable estimating detail can therefore exist in separate estimates without remaining connected to the central prediction.

Lunar construction increases the importance of that connection. Many systems may be purpose designed, highly integrated, and without substantial construction precedent. A condition that appears to be new later in design may be the further development of something implicitly contained within an earlier system prediction. The Predictive State must provide enough structure to distinguish between the two.

More information does not automatically create a stronger Predictive State. Experienced estimators spend substantial effort understanding scope, determining units, identifying system relationships, and deciding how the estimate should be structured before cost is applied. Specialized knowledge matters. A trade estimator may understand system interactions that are not visible at the level carried by a general contractor, owner, designer, or another professional lens.

The same principle applies to uncertainty. A single allowance may financially recognize that uncertainty exists, but a lump sum can become a bucket with little information about the individual conditions or risks it contains. Greater articulation provides a starting point from which those conditions can later be followed, tested, and refined. Patrick Duke's Professional Lens Paper (2026) examines this relationship between estimating detail, risk, and the understanding carried within an estimate.

Time adds another dimension. Design and engineering may develop over long periods, while the physical project and the information describing it continue to change. The Predictive State provides continuity among what was previously predicted, what is currently known, and what is developing ahead. Information can then remain connected across those states rather than being isolated within separate estimate iterations.

For lunar construction, this continuity also creates the opportunity for the Master Estimate to interact with engineering and design models, digital twins, production simulations, and other system information.

3. Identity Continuity

As project information develops, the estimate must preserve the identity of what was originally predicted. Engineering solutions, intents, quantities, construction methods, and even defined scope may change, but those changes should remain connected to the prediction from which they developed.

Identity Continuity (IC) applies this principle at the estimating line, component, system, and aggregate level. An early line item may later be divided into multiple components, revised substantially, or removed entirely. Its history still matters. If a line is deleted without preserving why it was originally included and why it was later removed, part of the analytical history is lost.

This is particularly important where early predictions contain assumptions about systems that have not yet been fully designed. As engineering develops, some assumptions will prove correct, others will change, and some may become unnecessary. The objective is not to preserve an obsolete prediction as though it remained correct. It is to preserve its lineage so the estimator can understand how the current condition developed from what was originally anticipated.

Without that continuity, successive estimates can become disconnected. Estimate 2 may replace Estimate 1, and Estimate 3 may replace Estimate 2, while the reasoning behind individual changes becomes progressively harder to reconstruct. The project may retain the final number while losing part of the knowledge that produced it.

For lunar construction, that lost history has consequences beyond the current project. A component predicted early and later eliminated may still provide useful information about assumptions, design decisions, system interactions, or risks that should be considered on the next mission. What did not become part of the final project can remain valuable estimating knowledge.

Identity Continuity (IC) preserves that analytical journey. Verified results can be traced back to the assumptions and decisions that preceded them, while earlier predictive pathways remain available for future analysis.

4. Verification

Verification compares the Predictive State with project conditions as they are realized. This occurs throughout the project lifecycle as predicted conditions become observable and can be tested against what occurred.

An estimate can contain different states of knowledge. Early in design, much of the project lies ahead of what is objectively known and must therefore be predicted through available information, experience, and professional judgment. As design, engineering, procurement, and construction advance, that boundary moves. Conditions that were once subjective can become objectively known.

The movement of that boundary is important. More information does not automatically mean the prediction improved. What matters is whether the estimating process can compare what was predicted with what occurred, understand the difference, and retain that knowledge. Conditions that were predicted correctly matter, but so do conditions that were incorrectly predicted, incompletely understood, or not identified at all.

The MET extends Verification through Actual Reality (AR) and Awareness of Actual Reality (AAR). AR exists when the physical condition occurs. AAR depends upon that reality having occurred, but occurrence and awareness are not necessarily simultaneous.

A condition may be measured quickly while its cause, relationship to the Predictive State, system identity, or downstream consequence is understood later. This latency already exists in terrestrial construction. Work in place, for example, can physically exist before its complete status, resource use, cost, or effect is measured and reported through the project controls process. The physical reality does not wait for the report.

For lunar construction, the interval between AR and AAR can carry greater consequence. Systems are highly interconnected, and a condition that is not recognized quickly may affect production, logistics, power, robotics, sequencing, resources, cost, or mission operations before its full significance is understood. Verification therefore depends not only on eventually knowing what occurred, but on how efficiently that knowledge becomes available to the predictive process.

Once AAR establishes sufficient awareness of a realized condition, the associated verified information can be connected to its predictive history through the Master Estimate. Earlier assumptions can be examined, the current Predictive State refined, and the resulting knowledge used in subsequent prediction.

As uncertainty is resolved, plausible future conditions progressively give way to what is verified. MET describes this progression as Probability Collapse. The verified history remains valuable beyond the current project because it provides inherited predictive intelligence for future estimates.

Verification therefore provides more than a final comparison of estimated versus actual results. Its value comes from maintaining the relationship among what was predicted, what occurred, when it became known, and what was learned from the difference.

5. The Master Estimate

The Master Estimate is the structure through which the Predictive State is maintained throughout the project lifecycle. It is not another estimate or simply the final estimate prepared before construction. Individual estimates are points in the development of the prediction.

This matters because complex projects rarely have only one estimate. Owners, general contractors, trade partners, designers, manufacturers, and other stakeholders develop estimates at different levels of detail and for different purposes. A general contractor may carry an electrical system at a system or contractual level, while the electrical trade partner may carry thousands of details necessary to understand installation, production, interfaces, and risk.

Both representations can be valid. The problem occurs

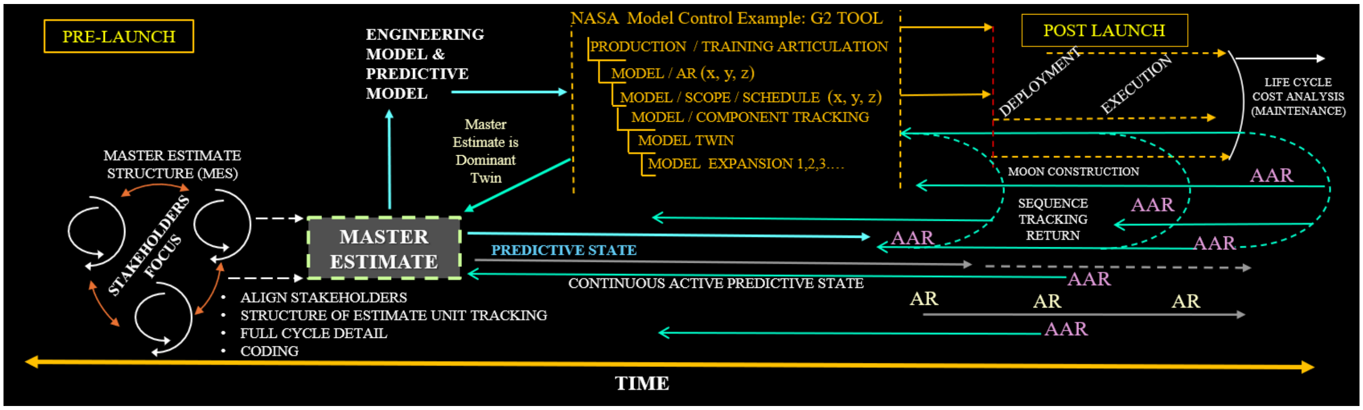

Figure 1. Simplified Master Estimating Theory (MET) flow architecture.

when valuable detail exists within one stakeholder's estimate but is lost when the scope is condensed into another. Information that appears unnecessary to the general contractor may be critical to the electrical contractor or to another system that depends upon it.

The Master Estimate serves as the central clearinghouse for these different representations. Relevant scope and detail remain connected through common identity, units, coding, and system relationships even when responsibility or risk moves between parties. Transferring contractual responsibility does not transfer or eliminate physical causality.

That distinction becomes particularly important in lunar construction. A condition within one system can affect power, production, robotics, logistics, sequencing, crew operations, resources, cost, and schedule. The Master Estimate must therefore preserve enough detail to understand both the individual condition and where its effects may travel.

Mueller's work on lunar base construction planning provides a related lunar construction perspective by organizing infrastructure needs, construction equipment, in situ resources, and construction activities within a coordinated planning framework [Mueller, 2022]. The work reinforces the importance of considering lunar construction as an interconnected system rather than as isolated construction activities.

The Master Estimate also supports Two Way Data Flow. Developing engineering and project information moves forward into subsequent prediction, while verified information can move back through the estimating structure to test what was previously assumed. Past information does not become irrelevant simply because the project has advanced, and future information can expose something important about an earlier prediction.

This requires continuity from the beginning. Objective information and informed assumptions need enough structure to remain associated with their scope, units, quantities, systems, and estimating logic as the project develops. Without that structure, later information may identify that something changed without preserving enough detail to understand why.

For lunar construction, the Master Estimate also can provide the estimating connection to engineering models, design models, digital twins, production simulations, and other developing sources of system information.

Not every additional line, revision, or piece of information improves the prediction. Some information materially changes what needs to be understood, while other information primarily adds detail. The Master Estimate may also consider value generated beyond the direct cost and function of the constructed asset.

Capturing the Unseen Value: Economic Returns from Lunar R&D

Lunar Construction efforts will generate additional Intellectual Property (IP) value from the associated Research and Development (R&D) investments and the resulting new innovations, technologies and capabilities. The aggregated IP portfolio value may be roughly estimated by applying the expected value formula,

$$E[V] = \sum_{i=1}^{n} p_i V_i$$

or by using the risk-adjusted probable return estimated from historic average returns. Managers will need to use best judgement when applying general results to specific projects and should adjust based on criteria such as terrestrial commercialization potential, team performance, application timelines, and the investment decision timeframe.

General studies have found private investments in R&D typically average 12-20% annual gross-returns, with greater average annual gross-returns of 25% from in-house R&D efforts. Public investment decisions should consider additional broader societal benefits, including both direct and indirect spinoffs, spillovers, inspired innovation, and productivity gains from use, which has been estimated as 390%-1230%. Private investors may also consider broader social and strategic benefit value including the publicity and prestige of involvement in such endeavors as lunar construction.

The very nature of lunar construction is likely to stimulate high levels of innovation and higher than average IP value returns, but we do not yet have sufficient data to recommend specific adjustments to return estimates.

5A. Multidimensional Coding and Classification Architecture

The Master Estimate is not an isolated estimate. Information developed through engineering, design, construction, finance, operations, and different professional disciplines must be able to coexist while remaining connected to the same project scope. A single coding hierarchy cannot carry every relationship needed for that purpose.

NASA work by Figueroa and colleagues using the G2 environment for Integrated System Health Management provides a relevant aerospace precedent for integrating data, analytical functions, and system context within a common architecture [Figueroa et al., 2010]. MET applies a related integration principle to estimating and predictive continuity.

MET does not replace NASA's established seven category Work Breakdown Structure [NASA, 2025]. This would be problematic and could result in the loss of important empirical data developed over many decades. Although MET expands with additional sections from Section 8 and on, each section is separated by numerical sequencing. As an example, when considering all the complexities of engineering model interfaces, as well as UniFormat, MasterFormat, OmniClass, and other relevant classification systems, these could expand to more than 20 sections. These structures were developed for valid purposes and should remain. The MET distinction is that different classifications can coexist around the same predictive object rather than requiring one classification to replace another.

This becomes more important as lunar projects move beyond mission equipment and deployment into construction, production, and operations. The same component may need to retain its WBS identity while also being related to Unit Articulation, cost, risk, professional lens, system interaction, spatial position, temporal position, and verification history. X, Y, and Z placement may matter to one analysis while production sequence or system dependency matters to another.

These are not additional WBS levels. They are different dimensions of the same predictive object. Their value comes from maintaining the relationships among them.

The temporal dimension is particularly important assumptions, revisions, Actual Reality (AR), Awareness of Actual Reality (AAR), and verification history develop through time. Spatial and system relationships add another layer where the physical location or interaction of one component can affect other systems.

This structure allows the Master Estimate to interact with engineering models, design models, digital twins, and production simulations. Information developed within those systems can remain connected to the estimating identity rather than being periodically translated into an isolated cost record.

Multidimensional coding provides the infrastructure for Two Way Data Flow. When verified information becomes available, common identity and coding allow it to be traced to the assumptions, units, quantities, systems, risks, and professional lenses associated with the earlier prediction.

6. Units of Line Item Measurement, their Character and Defining Criteria

Professional estimators recognize that not all information is equal. Some information changes the understanding of scope, production, risk, or system interaction, while some does not. Additional detail during design maturity does not necessarily mean a change in the prediction. MET considers this through the Criteria and Character of an item, component, assembly, or system construct. As described in Section 5.A, the MET coding construct also considers the relationships among these items.

Criteria define the boundaries and relevance of a line item within the estimate. Criteria establish the construct of the line item and its objective scope. Although each line item has a description, that description is often not sufficient to carry all relevant information about what the line represents within its unit of measure. Every line item in an estimate has specific Criteria, represented by multilayered Work Breakdown Structure (WBS) and coding described in Section 5.A.

Lines can be combined for strategic reasons, during analysis or design maturity, but their definition must be combined as well. This maintains lineage and carries the attributes and Character of the lines into the combined condition. Character considers how a line item interacts within its system and with other peripheral systems, including temporal relationships and implications of risk. Some of these relationships are obvious and others are not. Estimators refer to these interactions as peripheral cause and effect, where one item affects other components or system line items. Criteria and Character may be established prior to one another, or in some cases simultaneously.

Consider a simple glass of water. If the criteria require that the water is boiling, that changes what needs to be considered. Will the glass break? Will you need a mitten to handle the glass? The water temperature can affect many downstream and upstream conditions.

A concrete wall, for example, may have a specific thickness, concrete type, complexity, function, finishes, etc. These are defined by Criteria established for each line item. Their interconnectivity and the implications of that association establish the Character. Depending on what needs to be analyzed, the wall might be measured by linear foot, square foot, cubic yard, or another appropriate unit based on the analysis need. The unit of measure may also need to shift to interact with other systems for comparable or required analysis.

This is the meaning of the measure. Quantity has little estimating meaning without knowing what the unit represents. As an example, 5 each of a defined door type means more than the number five. A square foot of wall also represents more than its area because the measure carries the Criteria and Character of what is included in that square foot.

The meaning of the measure can also apply to the level of detail. A unit may represent an individual line item or component, a defined group of detailed items, an assembly, or an aggregate system. At the detailed level, Criteria, WBS, and temporal coding identify what the item represents and where it resides in the estimate and project progression. When line items are aggregated, their defining Criteria and Character carry into the larger group. This maintains the lineage between the detailed items and what the aggregate represents.

Looking at the same scope through different estimating or professional lenses may require a different unit of measure. A line item, component, assembly, or system may therefore be translated between unit types based on the analysis need. The meaning of the measure remains consistent through the unit transition. Otherwise, the calculation may still produce a number while no longer representing the same condition.

This becomes important as system complexity increases. Lunar construction magnifies this because a change in one condition most likely affects several connected systems, altering the trajectory of the prediction.

Experienced estimators have always made judgments of this kind. MET carries the Criteria, Character, lineage, and meaning of the measure as the estimate is viewed through different lenses.

7. Law of Diminishing Returns

A persistent challenge in estimating and engineering analysis is knowing when enough is enough. Most experienced estimators recognize some version of "pencils down." More analysis is always possible, but at some point the effort may stop materially improving the prediction.

Estimators sometimes express this more practically as, "Don't count the screws." In terrestrial construction, the number of screws in a defined wall assembly may already be sufficiently predicted through the wall type, specification, spacing, quantity, and production system. Counting every screw may add detail without changing anything important in the estimate.

Lunar construction can change that judgment. A single fastener may have predictive significance because of its mass, location, function, installation time, required rotations or torque, environmental exposure, tolerances, inspection requirements, or relationship to other systems. Under those conditions, knowing the number of fasteners may not be enough. How they are installed and verified may also matter.

There is no universal point where additional detail stops providing value. That judgment depends on experience, the cause-and-effect relationships being examined, and the professional lens requiring the information. An architect may not need a particular level of estimating detail while the entity responsible for installation may consider the same information essential.

Most experienced practitioners remember spending considerable time investigating a problem only to find that much of the additional detail had little effect on the final analysis. Experience helps identify where deeper investigation is justified and where it is not.

MET applies the Law of Diminishing Returns to this decision. A line item or collection of lines is not inherently too detailed or insufficiently detailed. Its value depends on whether the additional analysis materially strengthens the prediction for the system, conditions, and lens being considered.

The objective is always to maintain a relevant estimating structure detail necessary to achieve a minimum variance for the intended application.

8. General Mathematical Framework

Experienced estimators already manage highly complex projects, particularly at the megaproject level. Lunar construction does not diminish that professional capability. It changes the conditions and the level of integration required from the estimating process. Time, resources, system interaction, and risk can carry consequences that require estimating to remain closely connected to the engineering and operational systems producing them.

Consider astronaut time as one example. Using ISS program cost as an order of magnitude reference, escalation from 2021 dollars and a conservative adjustment for lunar operations can produce a planning value approaching $2 million per astronaut day [NASA OIG, 2021]. This is a derived estimating value, not a NASA published astronaut day rate.

The distinction becomes more important when an astronaut leaves a conditioned habitat. Time is still time, but the conditions of that time have changed. Life support, equipment, energy, logistics, crew exposure, production, and mission risk may now interact with the same unit of time. A relatively small change in construction sequence or production performance can have consequences well beyond a conventional labor or schedule calculation.

The following provides a brief exploration of the analytical logic used within MET.

MET Mathematical and Analytical Key

- PS = Predictive State
- CR = Criteria, the broader structure of defined predictive criteria
- CC = Cost Criteria, one defined criterion within CR
- C = Cost value within a defined Cost Criteria
- U = Unit Articulation, the defined estimating unit and the scope represented by that unit
- Q = Quantity expressed relative to the defined Unit Articulation
- M, L, E = Material, Labor, and Equipment
- VP = Verification Probability
- AR = Actual Reality
- AAR = Awareness of Actual Reality
- Δ = Change or variance between compatible predicted and verified conditions
- $Z_i(t)$ = Z Spin state set containing simultaneously valid Predictive States for estimating unit i at time t
- n = Total number of estimating items or units included in the summation
- z = Number of simultaneously valid Predictive States within $Z_i(t)$
- i = Estimating item or unit index
- T = Project time used to locate AR and AAR events
- t = Temporal position of the PS within the progression of project information

These variables perform different functions within Master Estimating Theory (MET) and so are represented through related mathematical relationships rather than combined into a single equation.

Integrated Mathematical Flow

At a high level, the principal estimating elements are considered in an analytical sequence. The sequence represents the progression of estimating analysis and does not imply that one variable uniquely determines the next:

$$\text{Unit Articulation } (U_i) \longrightarrow \text{Quantity } (Q_i) \longrightarrow \text{Criteria Criteria} \longrightarrow \text{Predictive State } (PS_i(t))$$

Unit Articulation establishes the estimating representation through which quantity, Criteria, and associated values are considered within the Predictive State. These relationships interact as project information develops rather than operating as a simple linear mathematical chain.

For estimating item i, the Predictive State at temporal position t may be represented generally as:

$$PS_i(t)$$

Multiple professional lenses and other unresolved assumptions, methods, sequences, or constraints may produce multiple simultaneously valid representations of the same estimating item prior to verification. These states are preserved within the Z Spin structure described later in this section.

The detailed weighting and synthesis operation among Z Spin states and the working Predictive State is developed in Dr. Vishesh Singh's Professional Lens Paper (Singh 2026).

Actual Reality occurs independently of the prediction. Awareness of that reality enters the predictive architecture when sufficient information about the realized condition becomes available. These relationships ultimately converge through Verification, where compatible predicted and realized conditions are brought into analytical relationship.

Verified information can then propagate through the Master Estimate to test earlier assumptions, refine the current Predictive State, and strengthen downstream predictions through Two Way Data Flow.

Cost and Unit Articulation

Traditional estimating commonly develops cost through the familiar relationship:

$$C_i = q_i c_i$$

where C_i is the cost associated with estimating item i, q_i is its numerical quantity, and c_i is its unit cost.

For multiple estimating items:

$$C = \sum_{i=1}^{n} q_i c_i$$

where n is the number of estimating items included in the summation.

Within MET, quantity is established relative to Unit Articulation. Unit Articulation defines the estimating representation and scope associated with the measure, while the associated physical unit provides the dimensional basis used in calculation.

For estimating item i:

$$U_i = \text{Unit Articulation}$$

and:

$$u_i = \text{physical unit of measure associated with } U_i$$

The two are related but are not mathematically equivalent. A physical unit such as square foot (SF), cubic yard (CY), each (EA), kilogram (kg), or hour (hr) establishes the dimensional basis of measurement. Unit Articulation preserves the broader estimating meaning of that measure, including the applicable Criteria, Character, identity, and scope of the estimating item.

Quantity may therefore be represented as:

$$Q_i = q_i u_i$$

where q_i is the numerical magnitude and u_i is the associated physical unit of measure.

Unit cost is dimensionally expressed as:

$$[c_i] = \frac{[C_i]}{[u_i]}$$

For example, where:

$$u_i = SF$$

then:

$$[c_i] = \$/SF$$

Unit Articulation (U_i) is therefore not treated as an algebraic denominator. Instead, U_i preserves the estimating meaning and establishes the compatibility of the quantities and unit values used in the calculation.

Once Unit Articulation is established, its meaning must remain consistent throughout the formula chain. If the physical unit of measure changes, the corresponding numerical quantity and associated unit values must be transformed consistently.

For two compatible representations:

$$q_i^{(a)} u_i^{(a)} \equiv q_i^{(b)} u_i^{(b)}$$

only where both representations preserve the same underlying estimating scope represented by U_i.

A mathematically valid unit conversion does not by itself establish MET equivalence. The applicable Criteria, Character, identity, and scope represented through Unit Articulation must also remain compatible.

MET Adds the Temporal Relationship

A conventional estimate generally represents conditions at a particular estimating point. MET retains the underlying estimating relationships but places them within a Predictive State that develops as project information changes.

For estimating item i:

$$PS_i(t)$$

where t identifies the temporal position of the Predictive State within the progression of project information.

As the Predictive State develops, quantity and cost may also vary with temporal position:

$$Q_i(t) = q_i(t) u_i(t)$$

and:

$$C_i(t) = q_i(t) c_i(t)$$

with:

$$[c_i(t)] = \frac{[C_i(t)]}{[u_i(t)]}$$

The same dimensional requirement applies at every temporal position. The numerical quantity, physical unit, and associated unit values must remain compatible with the Unit Articulation represented at that position.

Changes in $q_i(t)$, $u_i(t)$, or $c_i(t)$ do not by themselves establish a new estimating identity. Whether the underlying prediction has changed depends upon the applicable Criteria, Character, identity, and scope preserved through U_i.

Cost Criteria is one criterion within the broader

Criteria structure. Other criteria may represent schedule, resources, production, logistics, performance, risk, or other defined project conditions. Each criterion maintains the dimensions and Unit Articulation appropriate to that criterion.

Accordingly, the complete Predictive State is not treated mathematically as though it were merely a cost value.

Z Spin State Set

Different professional lenses, assumptions, methods, sequences, or constraints may produce multiple simultaneously relevant representations of the same estimating item before verification.

For estimating item i, MET preserves these representations within the Z Spin state vector:

$$Z_i(t) = \left(PS_i^{(1)}(t), PS_i^{(2)}(t), \ldots, PS_i^{(z)}(t)\right)$$

where z is the number of simultaneously valid Predictive States retained for estimating item i at temporal position t.

The superscript k, where:

$$k = 1, \ldots, z$$

identifies an individual state within the Z Spin vector.

The states contained in $Z_i(t)$ remain associated with the same estimating identity i. Their differences therefore represent different currently plausible representations of that estimating object rather than unrelated estimating objects.

The General Mathematical Framework establishes the Z Spin state structure without reproducing its detailed weighting and synthesis functions. Weighting, synthesis, Cross Lens Validation, and recursive updating are developed in Dr. Vishesh Singh's Professional Lens Paper (Singh 2026).

Actual Reality, Awareness of Actual Reality, and Verification

Actual Reality (AR) represents the realized physical condition and its relevant system relationships whether or not those conditions are immediately observed or completely understood.

Awareness of Actual Reality (AAR) represents the predictive architecture's awareness of that realized condition.

Both occur on the same project time basis T.

For estimating item i:

$$T_{AR,i}$$

represents the project time at which the relevant physical condition occurs, and:

$$T_{AAR,i}$$

represents the project time at which sufficient awareness of that condition is established.

Because awareness of a realized condition cannot precede the occurrence of that condition:

$$T_{AAR,i} \geq T_{AR,i}$$

Equality represents the condition in which awareness is effectively contemporaneous with occurrence. Where awareness is delayed:

$$T_{AAR,i} > T_{AR,i}$$

The interval:

$$T_{AAR,i} - T_{AR,i}$$

represents the temporal separation between occurrence and sufficient awareness of the realized condition.

A component, for example, may be installed and appear complete while an unknown substrate or peripheral condition already exists and affects its performance. The Actual Reality exists even though awareness of the relevant condition may develop later.

This distinction preserves the MET proposition that physical reality does not depend upon the estimate or upon the observer's immediate awareness of it.

Compatible Verification

Once AAR provides sufficient awareness of a realized condition, that information can be compared with the corresponding predicted condition.

This comparison must occur between compatible criteria expressed on the same dimensional and Unit Articulation basis.

Let r identify a defined criterion within estimating item i. The corresponding variance is represented as:

$$\Delta_{i,r}(t) = AAR_{i,r}(t) - PS_{i,r}(t)$$

provided that $AAR_{i,r}(t)$ and $PS_{i,r}(t)$ represent the same criterion, estimating identity, dimensional basis, and compatible Unit Articulation.

For example, a cost criterion is compared with its compatible verified cost condition; quantity is compared with compatible verified quantity; production is compared with compatible verified production.

The complete multidimensional Predictive State, Actual Reality, and Awareness of Actual Reality are not directly added or subtracted as though they were dimensionally equivalent scalar quantities.

This allows variance to be evaluated within individual compatible criteria while preserving the broader relationships among criteria within the Predictive State.

Verified information can then propagate through the Master Estimate to test earlier assumptions, refine the current Predictive State, support root cause analysis, and strengthen downstream predictions through Two Way Data Flow.

Verification Probability and Probability Collapse

Verification Probability (VP) is associated with a predictive condition and its progression toward verification.

Prior to verification, more than one condition may remain plausible. As objective information develops and conditions become verified, the range or number of plausible states can narrow toward the realized condition.

MET describes this progression as Probability Collapse.

Within the Z Spin representation, verification may therefore reduce the number or relevance of simultaneously plausible Predictive States as evidence becomes sufficient to distinguish among them.

Probability Collapse does not cause Actual Reality. Actual Reality exists independently of the prediction. Probability Collapse describes the change in the predictive representation as uncertainty is resolved through verification.

Mathematical Boundary of the General Framework

The relationships presented in this section establish the high level mathematical architecture of MET. They identify the principal relationships among Unit Articulation, physical units of measure, quantity, cost, time, Predictive State, Z Spin, Actual Reality, Awareness of Actual Reality, Verification, and variance.

They are not intended to collapse the complete multidimensional Predictive State into a single scalar equation.

The detailed mathematical development of Predictive State continuity, Unit Articulation, dimensional consistency, temporal development, Verification and AAR, Criteria Units, Verification Probability, Probability Collapse, and Z Spin remains a separate analytical development.

The detailed Z Spin formulation, including cross lens state generation, weighting, synthesis, and recursive updating, is developed in Dr. Vishesh Singh's Professional Lens Paper (Singh 2026).

9. Conclusion

MET establishes a unified framework for developing, verifying, and improving prediction throughout the project lifecycle. It does not replace established estimating methods; it connects and expands on them through the Master Estimate.

The Professional Lens Papers extend this framework through independent professional perspectives and practical, empirical, applications. They show how different disciplines may examine the same predictive architecture through different responsibilities. The MET considers the wholistic Design and engineering process as it develops into verified engineering relevant effective knowledge, that remains connected to the original detailed prediction.

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[*Manuscript Citation Note: Each Professional Lens Paper follows the citation convention standard to its author's discipline (e.g., APA in construction- and management-oriented papers, IEEE numbered style in aerospace- and engineering-oriented papers), reflecting the multidisciplinary authorship of this white paper.*]

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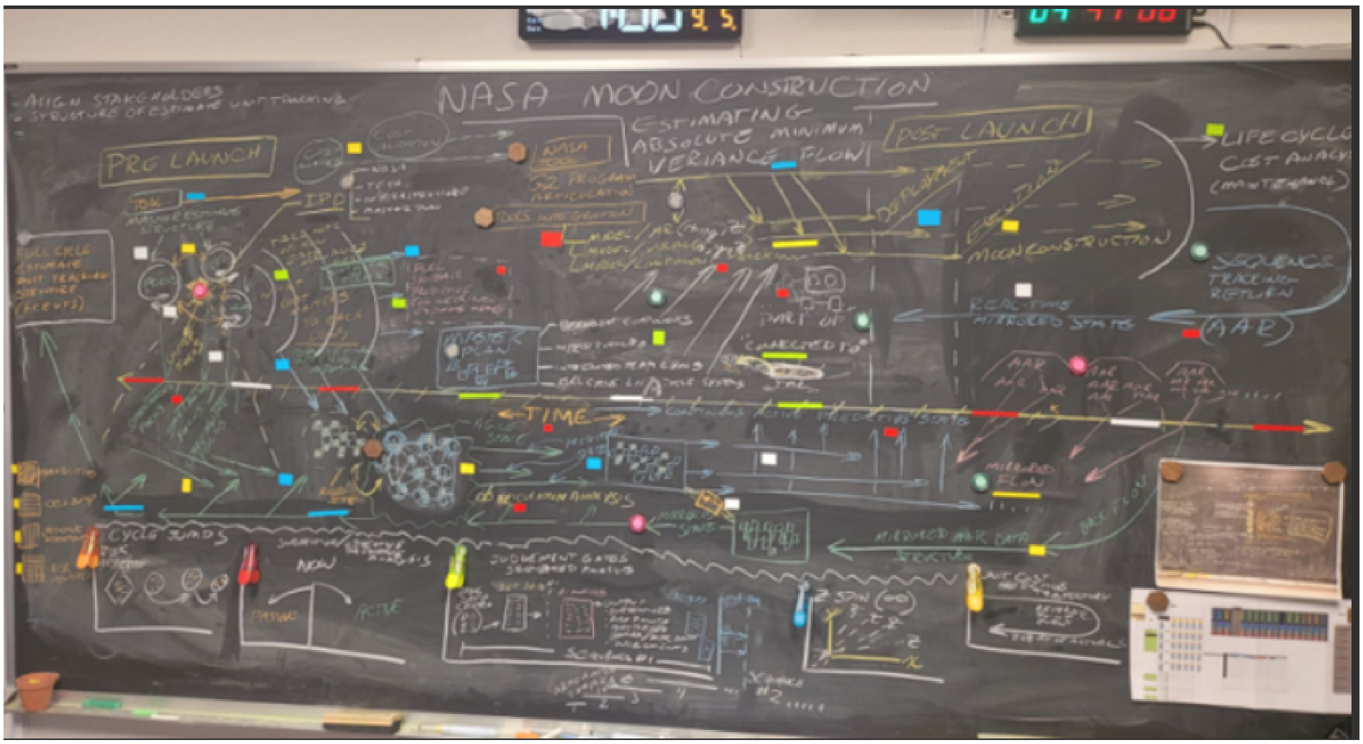

MET Development Discussion Board

Working discussion board illustrating the complexity of system interactions considered during development of the Master Estimating Theory.

THE PROFESSIONAL LENS PAPERS

Professional Lens Papers

Nine professional perspectives examining the Master Estimating Theory through estimating, design, construction, engineering, academia, and aerospace lenses.

Cycle Jumps in Complex Projects

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A cycle jump is *a discontinuous shift in project sequencing or system behavior caused by technological insertion, mission delay, or phase change that requires the estimate to re-anchor its logic across a new predictive structure.* Estimates at all stages of development are ideally structured to include both known and unknown factors to capture the total cost of a project at any given time. However, as a project matures from concept through construction, the shift from subjective to objective inputs is rarely smooth and continuous. Cycle jumps occur at the points where developing reality diverges from the predictive structure.

Cycle jumps often result in unexpected changes at a transition or "jump" point in the estimate. This transition can trigger re-estimation, value engineering, redesign, and delay. Discontinuities can occur with a transition from one estimator to another, from one system or software to another, as design strategies mature, and at progressive phases of a project. These discontinuities form barriers where knowledge is lost, differing methods produce unpredictable results, or market conditions change.

In earth-based estimating, cycle jumps are common and typically occur at major design milestones until the completion of construction or the AAR (awareness of actual reality) as defined in the Master Estimating Theory (MET). Often gross square foot unit costs are used in conceptual and early design stages for rough order of magnitude (ROM) estimating. At this stage unit costs are based on historical data manipulated for location, escalation, and other factors, often based on professional judgement, but with little transparency. As the design progresses and more detail is defined, those aggregate unit costs are replaced with square foot unit costs for systems and quantities which may have developed differently than anticipated in the initial pricing. Eventually, as specialist trades are brought in, they replace the estimators' unit costs with their own material and labor unit costs and experience, adding granularity. Each discontinuous shift introduces risk from the hard break from prior system conditions and estimates rather than a continuous flow from subjective to objective information. Without sufficient detail in the estimate structure, changing estimators or systems risk loss of knowledge of what the prior estimate actually assumed. These discontinuous shifts are too frequently treated as inevitable and value engineering is often anticipated in the design schedule introducing cycles of redesign, scope uncertainty, and delay.

Lunar construction is new and there are few precedents to base an estimate on. It is also vastly more complicated than terrestrial construction. Human labor alone, as discussed in section 8 of the MET, will require calculating multiple factors to determine cost and productivity. Engineering strategies and systems will be developed, tested, and adjusted. Cycle jumps therefore will be more frequent and emerge in new areas. The MET would reduce the risk and costs of cycle jumps by eliminating phases and the discontinuities typical of terrestrial/traditional estimating by creating a living structure that treats future, present, and past states with equal priority resulting in continuity across the lifecycle.

The quality of the temporal and contingent logic of the initial Master Estimate will affect the overall risk of cycle jumps later in development, preparation for future cycle jumps, and the costs and opportunities they bring. If the Master Estimate is established with enough useful micro-detail at the beginning, it will have the predictive logic to sustain through the mission lifecycle.

While the MET proposes to eliminate traditional phases, lunar construction will take into account the full life cycle of construction on the Moon including Pre and Post-Launch phases, lifecycle costs, maintenance, replacement (system decay), and decommissioning. The success of the MET will rely in part on how well the model transitions between these phases and captures the unknowns as subjective data with enough accuracy to prevent having to re-anchor the logic across a new predictive structure.

Managing Risk as Central to the Lunar Estimate

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Risk in lunar construction cannot be treated as a percentage carried at the bottom of an estimate. That practice assumes comparable history, mature supply chains, familiar productivity, and a practical ability to recover from field error. Lunar construction reverses those assumptions. The environment is extreme and low-precedent, logistics are mission-constrained, and a missed dependency can propagate across launch, surface operations, power, communications, crew support, and schedule. The estimating problem is therefore not simply to add contingency. It is to determine what can be calculated, what can only be bounded, what remains deeply uncertain, and what must be hedged through design, logistics, or operational strategy.

Traditional cost-risk methods remain necessary, but they function as a control layer rather than a complete solution. Work breakdown structures, sensitivity analysis, risk registers, Monte Carlo simulation, confidence levels, and independent review provide auditability and discipline. NASA's Joint Cost and Schedule Confidence Level process integrates cost, schedule, risk, and uncertainty [1], while GAO guidance establishes minimum disciplines for assumptions, sensitivity, documentation, and updating [7]. Their limitation in lunar construction is the instability of the underlying cost relationships where directly comparable history does not exist.

Risk as a Property of the Estimating Unit

The Master Estimate must treat risk as a central property of each estimating unit. In addition to quantity, cost, and time, each unit carries its assumption basis, maturity, Risk Variability (RV), Variable Probability (VP), dependencies, verification condition, and Variance Field (Delta) over time. The governing questions become: What remains subjective? What evidence would make it objective? What other systems move if the assumption changes? What event would create a Cycle Jump? What condition establishes Awareness of Actual Reality (AAR)? A Cycle Jump is therefore not merely a cost change; it is a break in predictive continuity that requires the estimate to re-anchor its logic while preserving the prior basis.

Three Analytical Approaches to Risk and Uncertainty

Master Estimating Theory (MET) should distinguish among three analytical postures, which may coexist within one unit and change as evidence matures. Bayesian or maximum-entropy methods can represent sparse evidence probabilistically; deep-uncertainty workflows provide a complementary way to identify vulnerabilities, robust actions, and decision triggers when agreement on probabilities or the governing model is weak [2, 3].

Operationalizing Risk Within MET

Risk must be modeled where the estimate is built: at the estimating-unit level and within the dependency network connecting units. A separate risk register can record concerns, but it cannot substitute for traceable unit records. At minimum, each unit should include its baseline and owner; evidence and assumption basis; uncertainty representation; correlations, dependencies, and Cycle Jump pathways; maturity and AAR criterion; trigger and recalibration rule; priced hedge or fallback; and Two-Way Data Flow from observed performance.

This structure changes the role of contingency. A probabilistic reserve is appropriate where a distribution is defensible; a bounded allowance where physical or empirical limits are known; and a design or operational hedge where the essential decision is how to preserve a viable path if the assumed architecture fails. Modularity, standardized interfaces, redundancy, spares, alternate sequences, operational buffers, and import fallbacks create real mass, energy demand, fabrication, testing, launch burden, storage, maintenance, and time. They must be estimated as scope rather than described as general management intent.

Propagation, Verification, and Recalibration

Risk becomes consequential when uncertainty propagates. A launch slip can idle surface labor, extend habitat support, consume spares, and delay verification of downstream units; a lower-than-assumed excavation rate can change energy demand, equipment utilization, crew or teleoperation time, and the sequence of shielding or foundation work. The Master Estimate must therefore model dependencies and correlation explicitly rather than assume that separately listed risks are independent. GAO's 2026 NASA assessment, in which a small number of projects accounted for most reported cost growth, reinforces the importance of concentration and tail

Approach	Evidence condition	Primary treatment	Decision output / lunar example
Calculated / probabilistic risk	Outcomes and dependencies are known and evidence supports a probability model.	Frequentist or Bayesian distributions; correlation; Monte Carlo or joint cost-schedule analysis.	Confidence levels, tail exposure, and reserve; tested-component failure or launch reliability.
Bounded uncertainty	Credible upper and lower limits exist, but a defensible probability density does not.	Physics-based ranges; prototype testing; expert elicitation; sensitivity and break-even analysis.	Ranges, thresholds, and next evidence; regolith productivity, energy demand, or dust-driven maintenance.
Deep uncertainty	The model, probability structure, technology maturity, or operating architecture is unstable or disputed.	Scenario discovery; robust decision making; adaptive pathways; stress testing across plausible futures.	Vulnerabilities, hedges, and triggers; ISRU fallback, human-robot allocation, or logistics architecture.

Table 1. Comparative approaches for organizing analysis of lunar risk and uncertainty.

exposure rather than reliance on a stable symmetric average [4].

When a prototype failure, new regolith characterization, launch-capacity change, revised crew allocation, spares constraint, or verification result invalidates the prior model, MET should preserve the superseded basis, identify the originating unit, propagate the change through dependent units, recalculate cost, time, RV, VP, and Delta, reprice hedges, and document the evidence required for AAR. The surrounding lens papers supply the conditions this architecture must carry - Cycle Jumps, excavation, human-robot systems, mission architecture, lifecycle performance, cross-lens validation, and Construction Intelligence - while the risk lens defines how those conditions remain visible, connected, and recalibrated within the Master Estimate.

AI and digital twins can support missing-scope detection, scenario generation, inconsistency checks, and Two-Way Data Flow. Future quantum methods may eventually accelerate selected simulation and optimization problems. Both should support, not govern, the Master Estimate; material changes must pass through transparent evidence and accountable human judgment gates [5, 6].

Conclusion

The purpose of lunar risk analysis is not to eliminate uncertainty. It is to prevent uncertainty from hiding and to preserve predictive continuity as evidence, designs, technologies, and operating plans change. Conventional methods remain necessary controls, but risk must be embedded in each estimating unit and connected across the system. In that sense, risk is not an appendix to the Master Estimate; it is one of the primary reasons the Master Estimate must exist.

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Estimating the Cost of Excavation on the Moon: A Protocol-Based Approach

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Summary

This paper explores key considerations in developing a structured methodology for estimating excavation costs on the lunar surface. While grounded in proven Earth-based estimating principles, the paper highlights unique technical and cost-related challenges under lunar conditions. As lunar infrastructure development becomes increasingly viable, the need for estimating practices that are disciplined, repeatable, and above all transparent is critical.

This document identifies key parallels between terrestrial and lunar excavation while highlighting fundamental differences that affect cost. These differences include variable regolith behavior, terrain unpredictability, limited equipment availability, differential gravity, and spoil management in a uniquely challenging vacuum and low-gravity environment.

Core cost drivers include excavation depth, production rates, material expansion and compression, terrain variability, safety and stability, utility bedding requirements, and the viability of in situ resource utilization (ISRU). Each domain is analyzed through a cost-estimating lens, focusing on assumptions, contingencies, and how known data integrates with reasonable projections.

This paper is intended for use by estimators, engineers, and mission planners seeking to build defensible cost models for lunar surface operations. It serves as a foundational guide that can be adapted and refined as mission data, technology, and field experience evolve. This document does not attempt to produce a complete model. Rather, it proposes a structured way to think about estimating in a domain where so much remains uncertain.

Keywords:

Lunar Excavation Cost Estimating, Lunar Excavation, Projecting Lunar Excavation Costs

Table of Contents

1. Defining Scope

A reliable estimate begins with a clearly defined scope of work. On the Moon, where many environmental and technical variables remain uncertain, the starting point is to draw parallels to Earth-based excavation practices and identify key differences. These differences drive the adjustments needed to account for lunar conditions across geotechnical, logistical, and operational domains.

Lunar gravity is approximately one-sixth that of Earth. This fundamental difference underpins nearly every deviation from terrestrial excavation norms. It affects equipment behavior, soil mechanics, spoil trajectories, slope stability, hauling logistics, and energy consumption. Throughout this document, differential gravity should be understood as a universal modifier that shapes both the physical mechanics and cost implications of lunar excavation.

When Apollo 16 Lunar Module Pilot Charles M. Duke, Jr. was asked by Paul Thies in an interview how it felt to have less gravity on the moon he responded:

“Well, it was a good deal. Let me put it that way. When I put on my spacesuit, backpack, life support system, and all the equipment, down here on Earth, I weighed . . . I think it was 363 pounds. Well, up there that turns into 60 pounds. And so you had this lightness as you ran across the Moon or you hopped across the Moon. But the suit is stiff and you couldn't bend at the waist. . . . It took a lot of work to move the spacesuit . . . In the undulating, lunar surface, you fell down a lot. You tripped over a rock or you stumbled . . . It was three pushups to get up. And so you were always working" (Jacobs, 2022, p. 4).

His account reinforces the central principle that estimating must follow the logic of the environment. Reduced gravity introduces both efficiencies and complications, not inherently good or bad, but materially different. While weight is reduced, effort might not be. Tasks that seem easier may be offset by other constraints. A defensible estimate must reflect these tradeoffs, quantifying conditions as they are, not as we assume or hope them to be.

Excavation is not a standalone task. It inherently generates spoils, and cost implications are incomplete without a full lifecycle analysis of how those spoils are handled. Hauling, processing, storing, stabilizing, and resolving the final disposition of material are all essential contributors to total cost that must be incorporated into the estimating protocol from the outset.

These variables, especially those with no Earth-based precedent, underscore why estimating on the Moon demands a careful and deliberate protocol. "Allocating cost to units involves a complex process. When an estimator 'puts a number' on a unit, identifying it as cost, there must be a logic behind it that the estimator understands fully, one involving a comprehensive methodology, formulated specifically to the entity that will rely on it" (Malik, 2019, p. 25).

2. Excavation Depth and Production Rates

Lunar regolith characteristics change with depth, and excavation production rates will likely decrease as denser layers are encountered. Heiken, Vaniman, and French (1991) observed that the in situ relative density of lunar soil, a measure of compaction state ranging from loosest to densest possible condition, increases significantly with depth, from approximately 65% near the surface to over 90% beyond 30 cm, suggesting higher resistance and reduced excavation efficiency as depth increases (p. 495).

Just as major Earth-based excavation projects rely on project-specific geotechnical studies to inform production assumptions and guide equipment selection, lunar projects will require a comparable understanding of subsurface variability to produce reliable cost estimates.

Cost implications arise from changes in:

- Equipment type and capability required to excavate denser material
- Production efficiency across variable strata
- Energy demands as excavation difficulty increases
- Equipment maintenance and downtime as mechanical stress increases with material density
- In situ resource utilization (ISRU) potential based on material type

Reliable estimates must account for how variable subsurface conditions affect productivity and cost across the excavation scope. Ongoing trials with NASA's RASSOR (Regolith Advanced Surface Systems Operations Robot), a lightweight lunar excavator prototype, are expected to provide data on excavation performance in low-gravity, regolith environments. As testing advances, estimators will be better equipped to align production rates and cost assumptions with equipment capabilities suited to lunar site conditions (NASA, n.d.-b).

3. Excavation Safety and Slope Stability

On Earth, excavation safety and slope stability are not just engineering concerns; they are direct cost drivers that influence equipment selection, production rates, and choice of techniques such as benching or sloping. Estimators routinely account for the cost of shoring systems and protective measures based on soil conditions, excavation depth, and regulatory requirements. Failures of natural slopes, deep excavations, or unsupported trench walls can result in delays, rework, equipment damage, or even loss of life, each carrying measurable cost implications. Terrestrial estimating benefits from a robust body of geotechnical data, standardized safety protocols, and well-characterized soil behavior.

According to Mitchell, Houston, Carrier, and Costes (1974), soil mechanics was one of the few areas studied across all Apollo missions, and the resulting continuity and interaction with other parts of the program proved valuable (p. 2). However, much remains unknown. From a costing perspective, excavation safety on the Moon should be approached as a high-risk, design-critical factor, requiring conservative estimates of excavation and slope stability and appropriate risk buffers to account for unknowns in soil behavior until more precise performance data becomes available.

Lunar Regolith Properties: Shear strength, which results from a combination of soil cohesion and internal friction angle, is a key factor governing the stability of lunar regolith. As Connolly and Carrier (2023) explain, "the cohesion and the frictional shear strength of the lunar regolith allowed the astronauts to dig trenches in the lunar surface with smooth, nearly vertical walls. Because of the low lunar gravity, trenches with vertical walls can be excavated to a depth of approximately 3 m, and drill core holes will remain open and stable to that same depth" (Connolly & Carrier, 2023, p. 4).

However, they further caution that "Apollo missions probed no more than a few meters into the lunar surface, and as depth below the lunar surface increases,

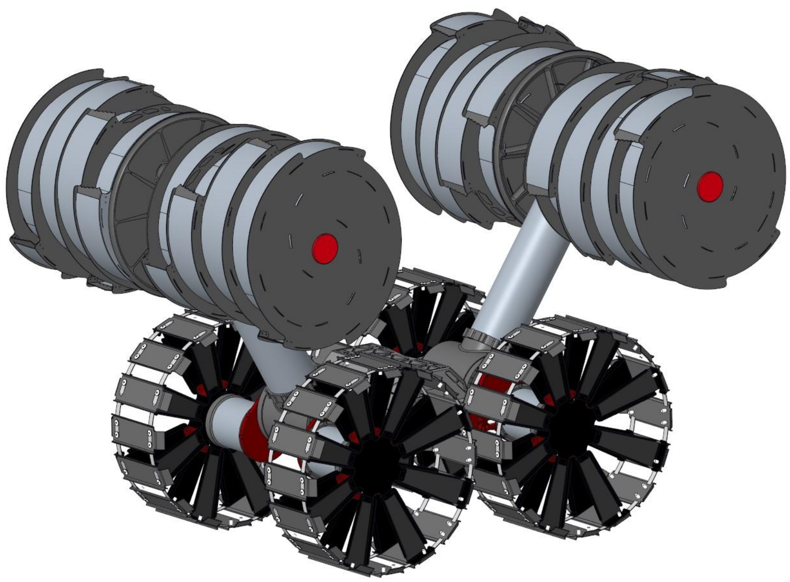

Figure 1
Note. RASSOR (Regolith Advanced Surface Systems Operations Robot) is a lightweight lunar excavator concept designed for efficient regolith collection and transport in low-gravity environments.
Image credit: NASA. Source: https://nasa3d.arc.nasa.gov/detail/RASSOR

the understanding of geotechnical properties transition from known, measured values towards best engineering estimates and models. One geotechnical truth is that lunar surface properties change with depth, and an understanding of density, cohesion, shear strength, and porosity of the lunar regolith, as these properties increase with depth, is essential to an understanding of the lunar surface" (Connolly & Carrier, 2023, p. 7).

Commander Alan B. Shepard Jr., of the Apollo 14 crew, described the challenge of trench excavation on the moon. "You know what's happening in this trench; It's the surface fines are so loose that they're just falling down covering the layering that we want to get. I'll tell you, we're not going to get a classic vertical wall here, Houston, In this trench" (Bailey & Ulrich, 1975a, p. 118). Addressing depth and slope conditions, he added "Well, actually, the first cut I took was down to about 6 inches and there was some caving at that time. The side walls were standing probably about 70 to 80 degrees. The next cut I took made the walls a little more steep, closer to the vertical perhaps 80, 85; and, at that point, they started coming down. Fine-grain regolith, at the top of the cut, just a couple down into the trench" (Bailey & Ulrich, 1975a, pp. 136-137).

Safety Protocols: With no equivalent to the Occupational Safety and Health Administration (OSHA) on the Moon, safety standards must be engineered based on material behavior, excavation requirements, and mission-specific risk tolerance. These engineered standards will directly influence production rates and the protective measures incorporated into the estimate.

4. Material Expansion and Compression

On Earth, project estimates account for expansion and compression factors when soil is being excavated or compacted. These volumetric changes impact haul quantities, stockpile sizing, backfill requirements, final placement volumes, and equipment cycles. The same considerations are expected to apply to the lunar regolith. According to Heiken, Vaniman, and French (1991), "the in situ lunar soil is very dense, with a greater density than could be produced with mechanical compaction equipment. The processes of handling and manipulating the lunar soil would loosen it considerably, and it would not then be possible to compact the soil back to its original, undisturbed density" (p. 521). Estimates should be guided by the best available data, with uncertainty in regolith performance addressed through carefully considered variability ranges and built-in cost contingencies.

Expansion and compression ratios should be reflected in quantity takeoffs, equipment selection, and cycle time calculations. These adjustments influence hauling demands, storage capacity, and the quantity of material available for ISRU, making them essential cost drivers in lunar excavation estimates.

5. Spoils Management

On Earth, poor spoil management leads to excessive handling, site congestion, and costly rework. The same concerns presumably apply on the Moon, though influenced by different environmental factors. Spoil handling should be evaluated as a continuous cost center, not a one-time operation. Differential gravity on the lunar surface affects the shape and dispersal pattern of spoil piles. These factors directly influence site layout, equipment access, and rehandling risk. Estimating protocols should consider the following:

Placement: The proximity of stockpiles to the excavation site, terrain, and stabilization practices required will impact cost.

Hauling: Equipment selection and productivity depend on gravity, traction, terrain, and regolith behavior. Equipment options should be evaluated for feasibility and operational efficiency under lunar conditions.

Stabilization: On Earth, spoil piles are often stabilized to prevent erosion or collapse. On the Moon, dust migration and material displacement pose unique risks. Stabilization methods, whether mechanical, chemical, or structural, should be costed based on their feasibility and application.

In Situ Resource Utilization (ISRU): Estimates should account for processing regolith into usable forms. This includes evaluating the percentage of extractable material, processing cost, and handling of residual waste.

Long-Term Impact: Earth-based estimates account for future site access and construction phasing when planning spoil placement. While lunar conditions differ, it is reasonable to assume that poor placement could result in rehandling, restricted access, or operational delays. Estimates should prioritize single-handling where possible, while also incorporating allowances for cases where optimal placement cannot be achieved due to mission constraints or site evolution.

6. Terrain Variability

Lunar terrain presents significant variability and unpredictability, with direct implications for construction planning, estimating accuracy, and operational logistics. Firsthand accounts from Apollo missions underscore the extent to which lunar topography can deviate from prior assumptions.

Surface Topography: Lunar elevations and subsurface conditions are more complex than satellite-based maps suggest. Upon landing, Commander Alan Shepard of the Apollo 14 mission remarked, "as I sweep from one horizon to the other, we find that the terrain is a little rougher than I suspected" (Bailey & Ulrich, 1975a, p. 11). Lunar Module Pilot Edgar D. Mitchell added, "Let me suffice it to say that I think there is more terrain, more relief here, than we anticipated from looking at the maps" (Bailey & Ulrich, 1975a, p. 13).

Echoing this experience on a later mission, Apollo 17 Commander Eugene A. Cernan observed, "I guess the thing that probably surprised me the most about the site, as far as landing is concerned, is the fact that there were these – I hesitate to say they're outcrops but certainly they're buried massive pieces of rock. ...And we're talking about anywhere from 1 to 2 meters down to – oh, 2 or 3 feet, which, when they're sticking out and on the sides of some of these subtle craters look pretty menacing" (Bailey & Ulrich, 1975b, p. 13).

Uneven terrain will impact equipment mobility and production rates. Estimating protocols should incorporate adjustment factors for terrain difficulty.

Boulders and Obstructions: Astronauts encountered both visible and partially buried boulders of significant size. "But there certainly are boulders on it. From here, it looks as though they are at least 20 feet in diameter perhaps," Commander Shepard observed (Bailey & Ulrich, 1975a, p. 24). Pilot Mitchell noted, "the area here is in an area of considerably more boulders, a larger boulder field, more numerous boulders than we've seen in the past." (Bailey & Ulrich, 1975a, p. 84). Importantly, many were not fully visible: "There's a lot of them buried, half buried, a few of the smaller ones sitting on the surface" (Bailey & Ulrich, 1975a, p. 84). These observations were reinforced during Apollo 17 by Lunar Module Pilot Harrison H. Schmitt, who remarked "There aren't very many rocks that just sit on the surface. All of them seem to be slightly buried to moderately buried" (Bailey & Ulrich, 1975b, p.145). Such variability demands flexibility in estimating assumptions. Large boulders may necessitate rerouting, alternative strategies for trench and mass excavation, and allowances for potential equipment damage, each with implications for schedule and cost.

Craters and Navigational Impact: Numerous craters posed both obstacles and surprises. "I think you'll have to go around this crater, here, to the left... Good heavens, that's a deep hole," Commander Alan B. Shepard Jr. warned (Bailey & Ulrich, 1975a, p. 38). He also noted, "It's a very uneven landing area here. And, of course, like all of the sections of the Moon, it's pockmarked by a - enormous amount of craters." (Bailey & Ulrich, 1975a, p. 23). These features affect mobility, safety planning, and equipment performance that should be considered in the cost estimate.

Predictive Modeling: The Apollo missions revealed ground-level challenges that continue to inform how we approach estimating for lunar construction. "Nothing like being up to your armpits in lunar dust," remarked

Commander Shepard, highlighting surface conditions that directly affect mobility, equipment performance, and labor productivity (Bailey & Ulrich, 1975a, p. 39). These are not abstract observations; they reflect the real obstacles construction teams will face and must be reflected in any cost or schedule model. As astronaut Mitchell later reflected, “There are so many things we'd like to have done; so many things to do, so many interesting things to look at here, and we didn't even have the chance to scratch the surface” (Bailey & Ulrich, 1975a, p. 141). While lunar exploration has advanced since these missions, the underlying truth remains that much of the Moon’s terrain and behavior is still unknown. These firsthand insights reinforce the need for predictive modeling that incorporates probabilistic inputs and wide tolerances. Parametric estimating, where cost drivers adjust with excavation depth, equipment limitations, and environmental variables like gravity, provides a defensible approach when empirical data is limited. Estimating protocols must allow for uncertainty in surface conditions, subsurface variability, and terrain interactions, particularly in environments where real-time adjustments are limited and costly.

7. Utility Bedding and Foundation Support

Earth-based infrastructure relies on bedding materials to support conduits, footings, and other subsurface elements. Even in favorable soils, select bedding and backfill are used to ensure long-term performance and avoid pipe, cable, or foundation failure.

On the Moon, cost estimators need to evaluate:

- Whether appropriate bedding can be sourced or manufactured in situ
- How much effort and energy are required to screen or process native regolith
- The cost of transporting bedding materials from Earth where ISRU solutions are not viable

These elements affect the feasibility and cost of constructing utility systems and supporting structural foundations. Although their functions differ, both utilities and foundations rely on bedding and/or structural fill to achieve uniform load distribution and prevent settlement. On Earth, the risk of differential settlement is often mitigated by overblasting into rock and rebuilding the zone with compacted structural fill, particularly when subsurface conditions vary across the foundation footprint. On the Moon, these practices may require adapted methods, depending on the availability and behavior of local material.

As lunar development progresses, cost estimators will likely face a three-way decision when preparing the subsurface to support structures: (a) bore into solid layers to directly bear loads on competent material, (b) excavate across the footprint to a uniform depth, potentially extending into denser layers or rock in some areas, and replace the zone with structural fill to equalize bearing conditions and mitigate differential settlement, or (c) modify the native regolith until a satisfactory base is achieved. Each option introduces distinct operational demands, costs, time implications, and long-term performance risks. Incorporating this decision logic into early estimating protocols will improve defensibility and may serve as a foundation for developing a Lang Factor specific to lunar surface construction.

8. Material Sourcing and In Situ Resource Utilization Integration

On Earth, estimates are shaped by the balance between sourcing materials on site and importing them from external suppliers. The same cost-based evaluation applies on the Moon, with the added complexity of extreme transport costs and limited in situ processing infrastructure.

Project estimates must assess the feasibility and cost implications of in situ resource utilization (ISRU) compared to transporting materials from Earth. This includes evaluating the technical readiness, energy requirements, and equipment needs associated with ISRU processes such as:

- Screening regolith or crushing rocks for use as structural fill or base material
- Sintering or melting for fabrication of various materials
- Extracting volatiles for life support, fuel, or industrial use

Each ISRU pathway carries distinct capital and operational costs that should be estimated based on current research, prototype performance, and Earth analogs where available. Where ISRU is not viable or proven, estimators must include transport costs for imported material, factoring in mass, packaging, and launch logistics.

Reliable estimates should reflect both the preferred ISRU approach and fallback options requiring imported material. Value analysis is recommended to compare cost exposure for different sourcing scenarios, especially in early-stage designs where mission architecture is still evolving and continues to shape logistics, infrastructure layout, and operational planning.

Figure 2
Note. Apollo 17 image AS17-140-21494, taken on December 13, 1972, at the Taurus-Littrow landing site.
Image credit: NASA (1972).

9. Closing Summary

Estimating the cost of excavation on the Moon requires a structured approach grounded in sound estimating principles. Drawing on Earth-based methodologies provides a practical foundation. However, it is paramount to identify and recognize the fundamental differences introduced by the lunar environment. Project estimates must carefully identify where those parallels hold and where assumptions must be adapted.

The estimating protocols outlined here emphasize the importance of defining scope, understanding regolith behavior, accounting for spoil management, evaluating terrain and excavation and slope stability, and assessing sourcing strategies for materials and bedding. In each case, cost implications must be derived not from speculative scenarios but from a disciplined analysis of what is known, what can reasonably be assumed, and where contingencies are necessary.

As lunar missions progress and data improves, estimating protocols will evolve. Until then, cost models must remain flexible and defensible, anchored in experience, adjusted for lunar conditions, and ready to inform critical decisions in mission planning and infrastructure development. Estimating lunar excavation is about structuring uncertainty in a way that supports credible decision-making.

This document is not a finalized model but a foundational framework to guide estimation in an untested domain. As mission planning advances and lunar construction concepts move from conceptual design into feasibility and procurement, this work can serve as a foundation for developing a formal estimating protocol. Future iterations should incorporate evolving mission architectures, equipment-specific performance data, and validated subsurface modeling. Collaboration between lunar scientists, civil engineers, and cost professionals will be essential to refine assumptions and establish a credible basis of estimate for lunar surface operations. As these concepts move toward development and execution, disciplined cost estimating will be central to project viability, investment decisions, and the responsible allocation of resources in an emerging and capital-intensive domain.

Glossary of Terms and Acronyms

Bench / Benching
A step-like excavation technique used to reduce slope failure risk and improve stability in deep cuts.

Cohesion
The component of soil shear strength resulting from electrostatic or chemical bonding between particles.

Compression Factor
The ratio describing the reduction in soil volume when it is compacted from a loose to a dense state.

Contingency Allowance
An added cost factor to account for uncertainty, risk, or incomplete information in early-stage estimates.

Cycle Time
The total time required for one complete operation cycle of excavation equipment (e.g., dig, load, haul, return).

Density (In Situ)
The mass per unit volume of undisturbed soil or regolith in its natural state.

ISRU (In Situ Resource Utilization)
The use of local materials (e.g., lunar regolith) for construction, life support, or fuel production, reducing dependence on Earth-supplied resources.

Lunar Regolith
The layer of loose, fragmented, and unconsolidated rock material covering solid bedrock on the Moon, created by meteoroid impacts and lacking organic content.

Shear Strength
The resistance of a material to sliding failure along a plane, governed by cohesion and internal friction.

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Human-Robotic Teaming in Construction Systems: Implications for Lunar Estimating

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Summary

Terrestrial construction estimating is founded on the assumption that labor can be represented as a scalable production resource. This assumption does not hold for sustained lunar construction, where productivity emerges from the interaction of astronauts, robotic systems, autonomy, communications, logistics, and operational support. Here we introduce the concept of the Lunar Labor Unit, arguing that the fundamental estimating unit is no longer the individual worker but the integrated human-robot construction system. The implications of this shift are examined through human performance limitations, EVA constraints, human-robot teaming, and the treatment of degraded and recovery modes. It is argued that explicitly modeling these interactions improves the estimate's ability to represent operational capability, preserve predictive continuity, and reduce the variance between predicted and realized construction performance within the framework of the Master Theory.

Human labor has historically been one of the principal drivers of construction cost, schedule, and productivity, and consequently forms a central component of conventional estimating methodologies. However, many of the assumptions underlying terrestrial labor models no longer hold in the lunar environment. Planetary surface construction must contend with finite crew availability, extravehicular activity (EVA) constraints, human physiological limitations, communications architectures, robotic systems, and varying levels of autonomy. These factors fundamentally alter the relationship between labor input and construction output. Whereas existing approaches typically treat astronaut and robotic labor as separate estimating resources, this section argues that future lunar construction should instead estimate the performance of the integrated human-robot construction system.

1 – The Lunar Labor Unit

Terrestrial construction estimating generally represents labor requirements through labor productivity norms, defined as the work-hours required to complete a specified construction activity under clearly defined reference conditions. These labor norms form the basis of project estimates, schedules, resource management, and risk management, with project-specific conditions accounted for through productivity adjustment factors. Consequently, when realized productivity differs from plan, schedule recovery can often be achieved through changes in crew composition, shift patterns, equipment allocation, or subcontracting, while retaining the same fundamental representation of labor as a scalable production resource [1]. The Lunar construction environment represents a radically different paradigm. Human labor can no longer be modeled as an independent production resource whose capacity may be increased through additional crews or longer shifts. Instead, each labor-hour is embedded within a tightly coupled operational system comprising astronauts, robotic assets, life-support infrastructure, communications networks, transportation systems, mission operations, and logistics. Consequently, the productivity of a lunar construction activity cannot be estimated by considering labor alone; it emerges from the performance of the integrated human-robot system [2], [3], [4], [5].

Each astronaut-hour is the operational output of an integrated mission architecture that includes transportation systems, extravehicular mobility units, life-support consumables, communications networks, intravehicular (IVA) crew support, mission control, medical oversight, logistics, and contingency capabilities. Each EVA therefore requires substantial planning, vehicle preparation, suit servicing, operational coordination, and post-EVA maintenance before productive construction activities can begin. The direct execution of a construction task represents only one component of a much larger expenditure of mission resources. Consequently, estimators must distinguish between productive construction time and total mission resource consumption, recognizing that the effective cost and availability of astronaut labor are governed by the supporting operational architecture rather than by the duration of the EVA alone. This distinction becomes increasingly important when comparing alternative construction concepts, evaluating logistics architectures, or assessing the operational and economic benefits of increased robotic autonomy. Accordingly, EVA capacity should be modeled as a finite operational resource rather than as an expandable labor pool.

2 – Human Performance as an Estimating Variable

If astronaut labor is viewed as an operational capability rather than a conventional production resource, then human performance limits become a critical estimating variable rather than simply a productivity adjustment factor. EVA imposes a unique set of operational limitations that have no direct terrestrial analogue. Pressurized suits reduce mobility and dexterity [6], increase metabolic workload [7], and require careful thermal regulation [8]. Crew performance is further affected by dust contamination [9], communications requirements, translation between work sites [10], and task setup and closeout activities. With the duration of an EVA already constrained by consumable limitations and the requirement to minimize risk of decompression sickness [11], these factors reduce the proportion of EVA time available for productive construction work. Consequently, the duration of a construction task cannot be estimated independently of the operational environment in which it is performed. Furthermore, these constraints affect not only expected productivity but also the uncertainty associated with that productivity, increasing the variance between predicted and realized construction performance.

Experience from the Apollo program illustrates this distinction. Although lunar gravity substantially reduced body weight, astronauts consistently reported that suit stiffness, limited mobility, challenging terrain, and operational procedures significantly increased physical effort and reduced task efficiency [12]. Activities that appeared straightforward in terrestrial planning frequently proved more demanding when executed in the lunar environment [13]. As sustained surface operations expand under the Artemis program, these relationships will become increasingly well characterized; however, current estimators should not assume that terrestrial productivity models can be transferred directly to planetary construction without explicitly accounting for human performance limitations.

3 – Human-Robot Teaming

The operational constraints imposed on astronaut performance have important implications for the architecture of future lunar construction systems. Since crew time represents a finite critical operational capability, robotic systems become a necessity to augment human performance, reduce EVA demand, and improve construction productivity [14], [15]. Unlike terrestrial construction, where schedule recovery frequently relies on changes to crew composition or workforce allocation [16], lunar construction is constrained by a fixed crew complement and finite EVA capacity. However, an additional astronaut may instead increase construction productivity by increasing the number of robotic assets that can be supervised, coordinated, or recovered following off-nominal events. For example, a crew member may spend an EVA supervising multiple autonomous excavation or construction systems rather than performing the physical construction activity directly [17]. Similarly, human intervention to diagnose a robotic fault, recover a disabled asset, or perform a precision alignment task may restore the productivity of several robotic systems simultaneously. The effective output of a construction team therefore depends not only on the number of astronauts available, but also on the number of robotic systems they can supervise, the maturity of their autonomous capabilities, and the efficiency with which work is allocated between humans and machines [18].

These characteristics fundamentally alter the structure of the estimate. Rather than assigning labor hours to individual construction activities, the estimator must model the interactions between human operators, robotic assets, autonomy, and supporting operational systems that collectively determine construction performance. The objective is no longer simply to estimate labor requirements, but to estimate the behavior of the integrated construction system. By explicitly representing these dependencies, the estimate is better able to preserve predictive continuity as operational conditions evolve, thereby reducing the variance between predicted and realized project states.

4 – Estimating Recovery and Degraded Modes

Unlike terrestrial projects, where productivity losses can often be absorbed through additional labor, local procurement, or schedule slippage, lunar construction occurs in an environment where recovery options are limited, delayed, and expensive [15], [16]. A nominal estimate may define the planned sequence of work, but it does not by itself represent the operational reality of a surface campaign in which dust contamination, robotic faults, communications interruptions, power shortfalls, mobility restrictions, crew health issues, or regolith variability may interrupt the planned flow of work. The estimating implication is that every lunar activity must be evaluated not only for its planned duration and resource demand, but also for the consequences of disruption and recovery. If a construction sequence depends on a single robotic asset, a single EVA window, a single communications link, or a single supply pathway, then the estimate must reflect the cost of interruption and the time required to restore productive capability. Thus, recovery pathways, fallback modes, redundant capabilities, spare parts, alternative task sequencing, and operational buffers therefore become intrinsic components of the estimate. These recovery pathways represent a major source of uncertainty within the estimating process. The uncertainty arises not only from whether an off-nominal event will occur, but also from how the integrated human-robot construction system responds once it does. Estimators must therefore account for uncertainty in both event occurrence and recovery performance, as each contributes to the variance between predicted and realized construction states.

This is where the concept of cycle jumps becomes especially relevant. In addition to adding incremental cost, off-nominal events may force the construction system to re-anchor its logic around a new operational state. Examples include a robotic failure shifting the work from autonomous execution to crew-assisted recovery [18]; a communications outage requiring a change from direct teleoperation to delayed supervisory control [14]; or dust-related degradation requiring cleaning, replacement, or rescheduling of dependent activities [9]. In each case, the estimate must accommodate not just the direct cost of the event, but the discontinuity it creates in the planned construction process. The ability to model these discontinuities, and to quantify the associated recovery architecture costs explicitly, is essential if the estimate is to preserve predictive continuity as operations evolve.

Accordingly, off-nominal operations must be understood as a core estimating problem. Lunar construction estimates must represent failure states, degraded modes, and recovery pathways with the same seriousness as planned production. This is especially important in a surface environment where productivity is tightly coupled to crew time, autonomy, logistics, and system availability. The estimate must remain valid not only when the system performs as intended, but also when it is forced to adapt.

5 – Conclusion: Implications for the Master Theory

The Master Theory proposes that the objective of estimating is to minimize the variance between the predicted and realized state of the construction system. Achieving this objective requires the estimate to represent the fundamental drivers of construction performance rather than relying on traditional labor and equipment models. As lunar construction transitions toward integrated human-robot operations, the assumptions underlying terrestrial labor productivity norms become increasingly inadequate.

This section has argued that the fundamental estimating unit is no longer the individual worker or crew, but the integrated human-robot construction system. Construction productivity emerges from the interaction of astronaut performance, robotic capability, autonomy, communications architecture, operational support, logistics, and mission constraints. Consequently, changes in any of these subsystems have the potential to propagate throughout the construction process, influencing schedule, resource utilization, cost, and ultimately the realized project state. Within this framework, astronaut labor should be treated as a critical operational capability whose value lies not only in direct task execution but also in supervising autonomous systems, recovering from off-nominal conditions, and enabling the productivity of the broader construction architecture. Therefore, the estimator should model the operational capability of the integrated human-robot construction system rather than assigning productivity independently to astronauts and robotic assets.

As lunar infrastructure evolves from short-duration exploration missions to sustained construction campaigns, increasing levels of autonomy and human-robot collaboration are likely to further separate construction productivity from traditional measures of labor input. Estimating methodologies that explicitly represent these interactions will be better positioned to preserve predictive continuity throughout the project lifecycle, reducing the divergence between predicted and realized construction outcomes.

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Addressing the Verification Interval Gap Through Human-Machine Interfaces

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One of the driving innovations of Master Estimating Theory (MET) is its ability to support Two Way Data Flow. As discussed by Singh (2024) in his thesis "Data-Driven Production Planning and Control using Work Density for On-Site Building Construction," working backward from site and project data allows for the development of context-aware production databases, and in turn transitions construction towards a supervised learning problem. MET builds on this by extending verification through Actual Reality (AR) and Awareness of Actual Reality (AAR), which provide critical reality data that can confirm predictive representation, identify causality risks, and inform historical data for future predictions tied to specific criteria (Section 4 of the MET Executive Summary).

Thanks to their situational awareness and ability to act under unexpected conditions, humans will continue to play a critical role in the verification process, even alongside technological improvements. For this reason, successful implementation of MET for lunar construction is in part dependent on developing strategies focused on Human-Machine Interface (HMI) technology as a direct way to enable safe, reliable, and timely verification.

Perhaps one critical aspect of Two Way Data Flow is its temporal nature. Increasing the frequency of verification while reducing the interval gap between AR and AAR can improve variance trajectories and risk identification and mitigation, in addition to enriching articulated historical data (Section 4 of the MET Executive Summary). Lunar construction has the potential to make this especially challenging. As estimated in Section 8 of the MET Summary, the cost of an astronaut per day starts at $2 million, and that figure increases once the astronaut steps outside the habitat. These costs demand that astronauts be extremely efficient with their time, including the time they spend interfacing with technology.

Aware of this, scientists and engineers have begun working on methods of mitigation. One primary approach aims to shift dependency from humans toward automation and robotic teaming, as previously discussed by Whittle (2026). The work done by these systems remains vital to human oversight; the core challenge lies in designing how that information is shared.

Furthermore, despite extensive training, astronauts will likely encounter challenges outside their domain of expertise. As such, astronauts must be able to lean on technology and the collective expertise of mission control, equipped with tools that allow them to communicate their observations clearly and with minimal delay.

These challenges can be addressed by the explicit development of HMIs between astronauts and their robotic and AI counterparts. This involves two information pathways: human-to-robot and robot-to-human. As Hyatt (2026) highlights in his lens, computers possess specialized capabilities to store, manage, and organize large amounts of data, whereas humans remain particularly well-suited to making context-informed decisions and acting under uncertainty. Therefore, HMI is best suited to enhancing human capabilities, treating them as an augmentation strategy for preexisting project management techniques (Mokrane and Boch, 2026).

Terrestrial construction has already begun developing platforms for enhanced construction monitoring. Augmented and mixed reality tools have been field-tested (Wang et al., 2021; Mitterberger et al., 2020), alongside field-overview monitoring systems (Liu et al., 2026). The application of such technologies has not only improved the quality of construction output, but has also reduced the frequency of required manual intervention (Liu et al., 2026). Furthermore, these technologies have proven effective in assisting inspections both during construction and after project completion (Mitterberger et al., 2020; Pan and Isnaeni, 2024).

For these technologies to be effective in lunar construction settings, they must not impede astronauts' ability to perform their duties. Ideally, astronauts can interact with their environment naturally, wherein their body language, gestures, and surroundings are processed to generate context-aware reports. Such sensing technologies have been developed in the context of emotion and body language recognition (Palash and Bhargava, 2024; Mittal et al., 2020) and have been applied in the context of construction (Wang et al., 2024). Recently, researchers have begun exploring how technologies like Segment-Anything Models and Vision-Language Models with eye-tracking could be integrated into Extravehicular Activity (EVA) suits, offloading critical telemetry data to computer systems so astronauts can perform complex tasks relatively efficiently (He et al., 2025).

By combining all these techniques and technologies, we can imagine a mixed-reality system where the astronaut can inspect a structure by overlaying a digital twin. If an anomaly is observed during inspection, rather than relying solely on the astronaut describing what they see over a camera feed, the astronaut can highlight and interact with the digital twin using intuitive gestures and voice and vision AI tools to generate a detailed log. The primary innovation here is to enable the astronaut to contextually triangulate an observation with a necessary context to achieve continuous verification, ultimately facilitating MET.

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Lunar Mission Architecture and Resource Demand

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1. Lunar Construction Mission Example

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As stated, the Master Estimating Theory intends to mitigate problems from traditional estimation assumptions that projects progress linearly. To communicate the complexity of functional interdependencies and the implications of resource demands, this section outlines an example of a mission architecture outlining the delivery and commissioning of a lunar in-situ resource utilization (ISRU) system for oxygen generation to the lunar south pole, using data from a previous analysis performed by Brown et al. (2025) [1].

Consider the following mission architecture based on future lunar mission operations (Fig. 1) [1] [2]. The successful delivery and commissioning of a lunar ISRU system depends highly on architectural decisions and transformation logistics among available technological elements such as launch vehicles and lunar landers. The design of this architecture can be iterated on for various logistical decisions to identify a feasible mission architecture trade space and sensitivities (Table 1).

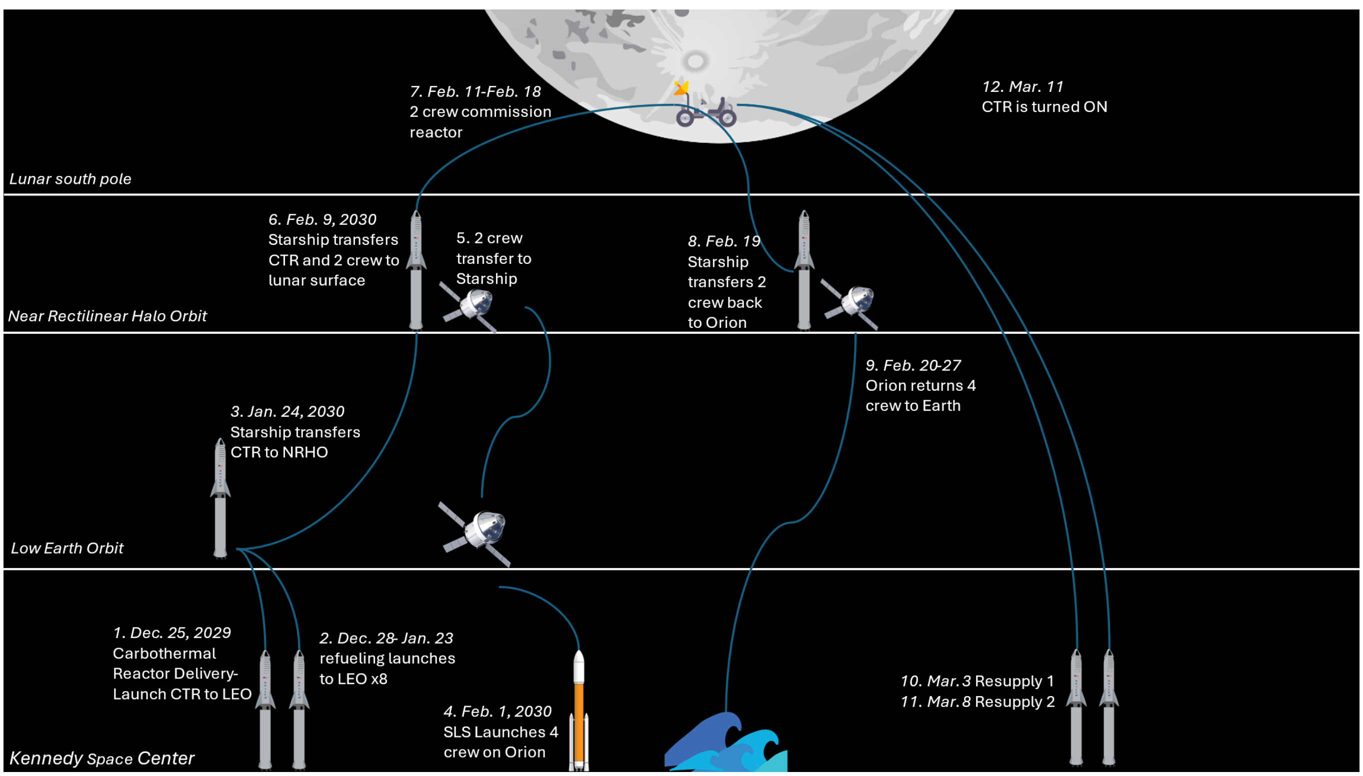

Fig. 1. Concept of operations for the delivery and commissioning of a lunar surface oxygen generation system using Starship as the lunar lander.

Table 1. Design vector for the three feasible logistics architectures supporting a lunar ISRU LOX.

Decision Variable	**Scenario 1**	**Scenario 2**	**Scenario 3**
1: Initial stockpile of resources at LSP	No	Yes	Yes
2: Closed loop vs. open loop ISRU system and sparing model	Partially Closed (methane consumption rate by 90%), 25% mass spares per year	Open, 10%	Partially Closed (methane consumption rate by 90%), 25% mass spares per year
3: Flight vehicle	Starship	Starship	Starship
4: Container Specifications	Pressurized	Pressurized	Unpressurized
5: Reduction agent	Hydrogen	Methane	Hydrogen

The SpaceNet java application is a discrete event and mission simulator that evaluates the logistical feasibility of a mission design [3]. Elements are input as models of resource consumers with consumption rates simulated over specified mission events occurring in chronological order to express their associated resource and labor demands (Table 2-4). For example, astronauts will require oxygen, food, and water during the traverse to the lunar surface, as well as while they are on the surface and the traverse back to orbit. The availability and success of these elements are examples of probabilistic operational risk; launch and transportation vehicles have payload limitations; the maximum duration that landers can support humans on the lunar surface is a logistical constraint.

Table 2. Element specifications as modelled in SpaceNet.

Name	**Element Type**	**Mass [kg]**	**Crew Capacity**	**Cargo Mass Capacity [kg]**	**Cargo Volume Capacity [m^3]**
Starship	Carrier	-	100	100,000	1,000
Space Launch System	Carrier	-	-	95,000	14.6
Orion	Carrier	26,520	4	1,100	9
Crew Member	Human Agent	100	-	-	-
ISRU System	Element	1,000	-	-	-

Table 3. Crew demand rates as modelled in SpaceNet.

Resource	**Demand Rate** [kg/crew member-day]
Oxygen	0.900
Water	3.60
Food	2.15
Hygiene Kit	0.2778
Clothing	2.3
Trash Bags	0.05
Waste Containers	0.05

Table 4. Demand models for oxygen production from carbothermal reduction of ilmenite regolith using methane gas.

Commodity	Rate
Gaseous Oxygen Production Rate [kg/day]	70.10
Regolith Processing Rate [kg/day]	4800
Methane Consumption Rate [kg/day]	13.30

Based on consumption rates of the crew and ISRU system, the mission duration (and duration in transport between locations), and element and resource specifications, feasible mission architectures can be identified as well as their total resource and labor needs (Table 5).

Table 5. SpaceNet simulation accrued demands for three feasible mission architectures.

	Scenario 1	Scenario 2	Scenario 3
Number of Crewed Flights	1	1	1
Number of Crew per Crewed Flight	4	4	4
Number of Cargo Flights for Delivery	2	2	2
Number of Cargo Flights for Resupply	1	1	1
Number of LEO Refueling Launches	8	8	8
Fuel Mass per Refueling Launch [kg]	120,000	120,000	120,000
Total Cargo Mass (Sum of all flights) [kg]	808	1,433	805

The resulting resource demand data can be used with their costs to understand the cost sensitivities to logistical decision variables, the cost of mission contingencies and cycle jumps, and overall mission complexity.

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Bringing Iterative Learning and Future Asset Management Into Master Estimating Theory

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The life cycle of the Moon Base beyond initial deployment is open-ended in the scoping documents (1) calling for operations for living and working on the moon to go from “2032 and beyond”. This paper summarizes thinking about how the Master Estimating Theory (MET) might consider three sources of uncertainty during decisions made in the design phase: 1. Constructability and construction variability of large-scale infrastructure, 2. Assumptions of required functionality and whether they consider the complete life cycle and end-of-life, and 3. The effects of component and system performance and their variability on the longer-term costs of the mission.

Constructability and Construction Variability Cost Considerations.

Construction turns a design into a physical reality. There are many decisions made in design which are changed due to constructability issues, which are most cost-effectively identified and remedied prior to beginning construction rather than during construction. NASA and the space industry pioneered technology readiness assessment and have robust technology development processes. This will certainly happen in preparation for Moon Base construction and will be a part of the iterative MET process. However, previous lunar and space work has been at a very small scale where hyper-attention has controlled variability and resulted in very high reliability (probability that something won’t fail). Moon Base infrastructure construction will be on a much larger scale, approaching small to medium size projects on earth for shelter and environmental protection, energy systems, waste management, transportation systems (landing pads, roads), and other infrastructure identified in previous studies (2), and that are in current planning (3). A question is whether the increase in scale will begin to introduce constructability issues and the types of variability in construction productivity and quality that occur on earth, how they will be considered in design and how they will be considered in the MET, and how the feedback loop to design, construction planning, and then in the MET will be used to reduce and account for those variabilities. Reduction of construction variability and after technology improvement is one of the most important drivers of cost reduction, as pioneered by Shewhart and Deming (4,5) and their plan, do, check, act (PDCA) approach and statistical quality control, implemented in the US construction industry starting in the 1990s (6).

As scale increases, lunar construction is expected to transition from pre-integrated modules with common interfaces to pre-fabricated parts can be brought from Earth and assembled or deployed to ISRU using in-situ resource utilization (ISRU), meaning manufacture on the moon using lunar materials. The application of In-Situ Resource Utilization (ISRU) to lunar infrastructure construction to reduce the need to bring resources to the moon (2) invites analogies to two types of terrestrial construction that can be considered in the MET:

- **Building of roads and launch pads.** This involves the use of moon surface materials (regolith) with an approach based on Earth construction (Cut / Fill Excavator, Bulldozer, Regolith Transporter (truck), Grader, Compactor, Paver [2]). This process has considerable variability on earth and variability of raw materials and compaction are the two drivers of pavement performance. Regolith has unique properties and relatively unknown spatial and vertical variability (7,8). Constructability for different conditions (particle gradation, surface texture) is a problem on Earth, and will be compounded by lunar effects such as surface charges. The development of technologies and advancement of technology readiness level (TRL) requires development under similar conditions (8). For a linear facility (roads, levees, dams) it only takes failure of a very small section to destroy the structure’s functionality. The ability to measure variability of materials and compaction to provide feedback during construction (When is compaction done? What is structural capacity? Is my surface sufficiently stable?) across the entire structure is a technology that is still being perfected. Development of construction techniques and quality control technologies that function with regolith, which has unique characteristics, will be critical to reducing the costs of rework.

- **Stabilization of geotechnical structures.** Inexpensive sand and gravel stabilized in concrete structures with hydraulic cement are the most fundamental ingredients of terrestrial civil infrastructure. Stabilized lunar geotechnical materials are being considered for many Moon Base structures (2), including roads, pads, foundations, and for making "bricks" for vertical construction. If water cannot be produced on the moon, these structures will require a stabilizer that does not require water and will need to be transported, likely a resin or epoxy of some type (9). Concrete has inherent variability due to raw materials, binder interaction, and fabrication processes.

Development of constructable approaches and assessment of quality variability, limits for needing rework, and then probabilities for needing rework will be important inputs to the MET. The two examples discussed above are taken from the experience of the California Department of Transportation (Caltrans) and their industry partners in their continuous quality improvement transitions since the mid-1990s from method specifications, to initial statistical quality control, to performance-based pay factors, addition of new materials and new quality parameters, and increasing automation and use of databases to provide feedback for design, construction, and asset management. The same considerations apply to nearly all construction that will not involve pre-fabricated assemblies, and to the assembly of pre-fabricated assemblies.

Complete Life Cycle and End-of-Life Cost Considerations

Life cycle durability considerations drive initial costs as well as life cycle costs. All materials and structures wear out and need eventual replacement, rehabilitation, or reconstruction. Part of determining functionality requirements for design is identifying how long the structure is expected to retain that functionality. The design life has cost implications for selection of architectural approach and materials. Preventative maintenance, meaning maintenance prior to development of any identifiable distresses, and reactive maintenance, once initial distresses are identifiable, are life cycle costs that are dependent on those design decisions and the extent and variability of environmental exposures (dust, radiation, temperatures, etc.) and operational loading. Rehabilitation is needed when functionality is lost but the entire structure does not need to be reconstructed or replaced. End-of-life is another potential life cycle cost if structures must be disposed of to maintain functionality, or if materials and structural components can be reused in reconstruction. Durable designs and appropriate maintenance may stave off rehabilitation, reconstruction, and end-of-life for much longer periods than if the design life and maintenance are not well thought out.

Inclusion of these design and life cycle decisions by means of life cycle costing should provide input to the MET, to provide a balance between initial costs and longer-term costs. That balance is a potentially important consideration in the MET.

Asset management is the tool used to manage maintenance, rehabilitation, replacement and end-of-life for terrestrial infrastructure systems, applied to infrastructure, vehicle fleets, buildings, power plants, and any other set of assets. A good asset management system includes an inventory with correct identification of each asset, probabilistic performance models for expected frequency of preventive maintenance and time to reach critical thresholds for maintenance and rehabilitation, decision trees or other means of considering likely actions and their consequences, and systems for updating the inventory after treatment preferably including information about construction quality to inform updating of the performance models.

Effective asset management systems have been proven to reduce long-term costs. They also deal with the initial relief at completing deployment (or as it slows down) that is often followed by chaos and panic as an organization transitions from initial deployment to longer-term operations and realizes that management, thinking, policies, procedures and funding are needed to keep the operation going cost-effectively and to maintain safety. US state highway agencies began the transition from deployment to operations in the late 1960s, in part based on the then nascent implementation of systems thinking (10-12) and early applications in the US military base infrastructure management (13) and state DOTs (14). This led to the first pavement management systems in 1978 and 1979 (Arizona, then California), expansion to bridges and then other transportation assets, and eventual mandatory implementation required by later federal legislation. China is going through the transition now, and India will need to do the same as they build out their road network in about 10 years. Global experience is that funding for asset management is much less interesting to political leaders and the public than deployment, until crisis levels of safety problems and lack of functionality are reached.

The costs of installing and operating an asset management system(s) should be a cost item in the MET. Extension of the MET approach to asset management would be a useful contribution.

Interactions of Component and System Performance on Costs

The first two areas of consideration for the MET discussed in this section have been based on attention to individual components of systems. Estimating changes in design assumptions and outcomes and their effects on cost that come from system vulnerabilities, from interactions of components in systems, and from system interactions with other systems, may be another area for consideration in the MET. As different elements of systems and systems of systems are moving through technology development stages, updating of designs based on these considerations may result in additional costs that are not considered when only individual components or systems are being costed. Similarly, increased understanding of interactions may result in identification of cost savings from identification of less need for robustness, durability, and/or functionality.

An analogy is the design of reinforced concrete and steel bridges, where some types of designs have sufficient redundancy to prevent catastrophic failure when one or two critical components fail, and other types where the risk of catastrophic failure is one or two component failures away. (15,16)

Consideration of these interactions can be mathematically included in the MET.

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Cross-Lens Validation (CLV) and Z-Spin

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Lunar infrastructure development requires coordination between mission planners, systems engineers, robotics specialists, transportation and launch logisticians, excavation and regolith operations personnel, survivability and shielding engineers, power distribution designers, materials scientists, operations and maintenance teams, and many more. Each discipline observes a different facet of the same estimating unit, and each must remain structurally synchronized within the Master Estimate rather than analytically isolated. Cross-Lens Validation (CLV) is the behavior through which synchronization is achieved. This sections specifies how it operates, expressed entirely in the terms the Master Estimating Theory (MET) already provides.

Z-Spin as Multiplicity Within the Predictive State

The Executive Summary of the MET [*Section 8*] establishes that the Predictive State is the estimator's current representation of the intended project, and that this representation is preserved across revision through Identity Continuity: the information describing a unit continually changes, but the unit remains the same analytical reference throughout. The MET also carries the symbol z, identified in Figure 2 as Z (Spin), among the terms governing the theory's mathematical relationship. CLV takes up this symbol directly and asks what z represents when several disciplines assess the same unit before that unit has been verified.

Identity Continuity guarantees that every lens is assessing the same unit. It does not guarantee that every lens assesses it identically. A robotics lens and a survivability lens evaluating the same shielding placement may agree on quantity and unit articulation and disagree entirely on verification probability, because each is reasoning from a different body of engineering precedent. Z-Spin is the condition in which this disagreement is retained rather than resolved prematurely: a unit may simultaneously carry z distinct Predictive States, one or more contributed by each lens, prior to verification. Where Identity Continuity keeps the unit stable across the disagreement, Z-Spin is the structure that keeps the disagreement itself visible instead of allowing it to be silently averaged away.

Lens-Generated Predictive States

Figure 2 of the MET expresses the Predictive State of a unit as the integration of quantity, unit articulation, cost, and the material, labor, equipment, and verification-probability components that compose it. CLV applies this same relationship independently for each Z-Spin state. For estimating unit i, a lens ℓ operating within its domain of competence submits a criteria vector

$$CR_i^{(k)}(t) = (Q_i^{(k)}(t), U_i^{(k)}(t), M_i^{(k)}(t), L_i^{(k)}(t), E_i^{(k)}(t), VP_i^{(k)}(t))$$

where k indexes the state and the ordering follows Figure 2. Substituting this vector into the Figure 2 relationship produces the lens-generated Predictive State

$$PS_i^{(k)}(t) = (M_i^{(k)}/U_i^{(k)})\ Q_i^{(k)}\ (C_i^{(k)}/U_i^{(k)}) + (L_i^{(k)}/U_i^{(k)})\ Q_i^{(k)}\ (C_i^{(k)}/U_i^{(k)}) + (E_i^{(k)}/U_i^{(k)})\ Q_i^{(k)}\ (C_i^{(k)}/U_i^{(k)}) + (VP_i^{(k)}/U_i^{(k)})\ Q_i^{(k)}\ (C_i^{(k)}/U_i^{(k)})$$

A lens does not submit an opinion about a unit. Under this formulation it submits a complete instance of the theory's own governing relationship, populated with the values implied by its professional judgment. This is what allows z simultaneously valid states to coexist without contradiction. They are not competing estimates of the same number. They are z separate applications of one relationship to z different criteria vectors, and the disagreement between them is located precisely in the terms where the vectors differ rather than absorbed into a single aggregate figure.

The complete Z-Spin state set for unit i is the ordered vector

$$Z_i(t) = (PS_i^{(1)}(t), PS_i^{(2)}(t), \ldots, PS_i^{(z)}(t))$$

indexed by ordered record of which lens produced which state, which allows a specific state to be traced back to the discipline that generated it.

Synthesis Into a Working Predictive State

The Master Estimate cannot carry z unresolved states forward indefinitely; it requires a single working Predictive State at each point in time while preserving the ability to trace that value back to the states behind it. The z states are combined by

$$PS_i(t) = \Sigma_{k=1}{}^{z}\, w_k(t)\, PS_i{}^{(k)}(t)$$

where $w_k(t)$ is the weight carried by state k at time t. Two considerations govern this weight: the confidence the originating lens attaches to its own state, and the structural relevance of that lens to unit i. A robotics lens assessment of an autonomous assembly duration carries more relevance to that unit than a power distribution lens assessment of the same unit, and both the confidence and relevance components should be declared rather than applied informally. The precise functional form of $w_k(t)$ is left open in this paper, and remains open for future research.

Objective-Subjective Composition of the State Set

Because each state declares the evidentiary basis of its terms, the objective-subjective composition of unit i is computed directly as the share of total synthesis weight carried by states grounded in verified operational data and instrumented simulation, relative to total weight across all states. Early in mission formation it approaches zero for nearly every unit, since no lunar operational precedent exists and $Z_i(t)$ is populated entirely by judgment-derived states. As analog testing, regolith simulant trials, subscale robotic demonstrations, and eventually deployed mission telemetry accumulate, the ratio rises unit by unit. Its trajectory across the estimating structure becomes a direct measure of predictive maturity, reportable alongside cost and schedule. A unit whose working predicted state has remained stable while its objective-subjective ratio has risen is stabilizing correctly. A unit whose predicted state has remained stable only because its ratio has not moved is not stabilized, it is unexamined.

Verification, AAR, and the Contraction of Z-Spin

The MET describes Verification as continuous rather than episodic: prediction is compared against verified project reality on an ongoing basis, not at isolated milestones, and Awareness of Actual Reality is the continuous awareness of the relationship between the two. CLV applies this continuity at the level of the state set. As Actual Reality is observed and admitted as $AAR_i(t)$, it is compared against the working Predictive State through the variance already defined in the theory,

$$\Delta_i(t) = AAR_i(t) - PS_i(t)$$

but AAR is compared against every surviving member of $Z_i(t)$, not only against the synthesized value. A state whose criteria vector is inconsistent with what has been verified loses standing in the next synthesis; a state consistent with it gains standing. This is the same continuous strengthening and narrowing the MET describes for the Predictive State generally, applied here across z states rather than one.

Probability Collapse, as the Executive Summary defines it, is the progressive convergence of multiple possible outcomes toward one realized result. Within CLV this convergence is visible directly as the contraction of $Z_i(t)$: as verification accumulates, weight concentrates on fewer surviving states, the practical value of z for unit i falls, and the spread of remaining states about $PS_i(t)$ narrows. Collapse is complete when a single verified state remains and the unit's cost criteria are fixed, consistent with the CC term in Figure 2. CLV does not introduce a different mechanism for Probability Collapse; it gives the existing mechanism a population of z states to act upon instead of one.

Diagnostic Value of the State Set

Because every state in $Z_i(t)$ is attributable to the lens that produced it, the spread of states carries diagnostic information beyond its role in synthesis, even without a dedicated symbol for it. Disagreement concentrated within a single lens indicates that a discipline does not yet possess a stable internal model of the condition and is a signal to commission additional simulation or analog testing within that discipline. Disagreement concentrated between lenses, where each discipline is individually confident but the disciplines disagree with one another, indicates an unresolved interface condition or an undeclared assumption at a system boundary. This second pattern is an early indicator of what the section on Cycle Jumps addresses directly, and CLV is offered as the elicitation structure that surfaces such a condition before it propagates.

States that diverge sharply from $PS_i(t)$ are retained rather than discarded, on the same logic that governs the rest of the theory: a low-probability, high-consequence condition recognized by only one lens is exactly the kind of information Verification exists to test, not noise to be filtered before it has the chance to be verified. How such conditions should be weighed against the range of possible outcomes is developed further in the section on Risk and Uncertainty.

Directing Elicitation Through Criteria Units

Populating z states for every unit at every point in the project is neither necessary nor consistent with the Law of Diminishing Returns as the MET presents it. Criteria Units measure the predictive contribution of new information, not its volume, and the same measure applies to the decision of how many lens-generated states a given unit warrants. A unit whose criteria vector is already well constrained by verified precedent gains little from an additional Z-Spin state, however, a unit at the center of significant unresolved cross-lens disagreement gains a great deal. CLV is therefore directed by the same principle that governs the rest of the Master Estimate: elicitation effort is allocated toward the units where an additional Predictive State most improves predictive understanding, and tapered where it does not.

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Construction Intelligence as an Enabler of the Master Estimating Theory: Aligning Construction 5.0, Human-AI Collaboration, and Lunar Construction Estimating

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Lunar construction presents an estimating problem of unusual scale and complexity. A lunar project must account not only for cost, quantities, and production, but also for launch capacity, transportation architecture, power, communications, robotic systems, crew availability, life support, in-situ resource utilization (ISRU), environmental uncertainty, maintenance, and long verification delays. These conditions do not operate independently. A change in one system can alter the performance, timing, resource demand, and viability of many others.

Mueller's (2022) lunar-base planning framework illustrates these relationships across site planning, transportation, power, communications, excavation, robotic construction, survivability, and ISRU. It also shows that excavation, hauling, grading, and compaction recur across many infrastructure types, creating shared equipment and resource dependencies that extend beyond individual work packages.

The Master Estimating Theory (MET) responds to this problem by treating estimating as a continuously recalibrated predictive discipline rather than a periodic financial exercise. The Master Estimate is the living predictive structure through which MET is applied. It maintains cost, schedule, resource, operational, probabilistic, and verification logic while preserving the lineage of assumptions and decisions across the mission lifecycle.

MET establishes what the estimating system must accomplish. It does not, by itself, fully explain the human, technological, and organizational capability required to operate such a system. Construction Intelligence (CI) addresses that implementation requirement.

> **Central proposition:** Lunar construction is too complex, interdependent, uncertain, and verification-constrained for either human expertise or artificial intelligence to manage independently. Implementing the Master Estimating approach therefore requires Construction Intelligence: a human-centered socio-technical capability that integrates professional judgment, AI, digital systems, and verified operational evidence.

Construction 5.0 and the Changing Context of Construction

Construction 5.0 provides the broader paradigm within which CI and MET can be aligned. It extends the technology-centered orientation of Construction 4.0 by emphasizing human-centeredness, resilience, sustainability, and collaboration between people and advanced technologies. Yitmen et al. (2023) frame Construction 5.0 through the interconnected dimensions of Operator 5.0, Society 5.0, human-centricity, sustainability, and resilience. Marinelli (2023) similarly locates the transition from Construction 4.0 to Construction 5.0 in the movement toward closer human–technology collaboration, particularly human–robot collaboration. Automation remains important, but it is not the end state. The objective is a construction environment in which technology strengthens human judgment, organizational adaptability, and long-term value creation.

This distinction is particularly important for lunar construction. A lunar construction system cannot be evaluated only by the sophistication of its robots, models, or analytical platforms. It must also be evaluated by whether qualified people can understand the system, establish priorities, challenge assumptions, coordinate across disciplines, respond to failure, and remain accountable for decisions made under uncertainty.

Intelligent construction is the more established academic term for the technological and operational environment created by integrating AI, building information modeling, digital twins, sensors, connected equipment, robotics, simulation, automation, and data-driven management into construction processes. The literature shows that these technologies are transforming how projects are planned, designed, constructed, monitored, and operated (Abioye et al., 2021; Pan & Zhang, 2021).

However, an intelligent construction environment does not automatically produce intelligent decisions. A project may have extensive data, advanced models, and automated systems while still suffering from fragmented information, unclear authority, unverified assumptions, weak interoperability, or poor professional judgment. The existence of intelligent technology is therefore different from the capability to use it effectively.

Construction Intelligence

Construction Intelligence is presented here as an emerging concept synthesized from Construction 5.0, intelligent-construction research, construction AI competency studies, and evidence of changing human-technology relationships in the construction workforce.

> *Construction Intelligence is the human-centered socio-technical capability through which construction professionals, teams, and organizations integrate domain knowledge, professional judgment, project information, artificial intelligence, digital models, automated systems, and verified operational evidence to understand conditions, anticipate outcomes, coordinate action, support decisions, adapt to disruption, and learn across the construction lifecycle.*

This definition makes four distinctions.

First, CI is not equivalent to artificial intelligence. AI can recognize patterns, analyze large datasets, generate scenarios, detect anomalies, and support prediction. Humans remain responsible for defining objectives, determining relevance, interpreting evidence, challenging model outputs, authorizing decisions, and accepting accountability. This allocation of roles is consistent with Construction 5.0's human-centered orientation and emphasis on collaboration between people and advanced technologies (Marinelli, 2023; Yitmen et al., 2023), as well as emerging construction AI competency research (Hosseini et al., 2025; Tummalapudi et al., 2025).

Second, CI is not a software platform. BIM, digital twins, estimating systems, simulations, dashboards, sensors, telemetry, and robotic systems can contribute to CI, but no individual system constitutes the capability.

Third, CI is construction-specific. Intelligence competencies become meaningful only when applied to actual construction materials, methods, systems, constraints, workflows, stakeholders, and decisions. Research on intelligent-construction competencies consistently indicates that emerging data and AI capabilities must be integrated with—not substituted for—traditional engineering and construction knowledge (Hosseini et al., 2025; Liu et al., 2025; Tummalapudi et al., 2025).

Fourth, CI exists at multiple levels. Individuals interpret evidence and exercise judgment. Project and mission teams maintain shared understanding and coordinate action. Organizations provide governance, infrastructure, interoperability, leadership, workforce capability, and institutional learning. Effective CI depends on alignment among all three.

How Construction Intelligence Aligns With MET

MET and CI address different but complementary questions.

- **MET asks:** What must an estimating system do to preserve predictive continuity and minimize consequential variance?
- **CI asks:** What must people, technologies, teams, and organizations be capable of doing to operate that estimating system?

MET supplies the estimating logic. CI supplies the implementation capability. Table 1 outlines these relationships.

Table 1

MET requirement	CI enabling capability	Lunar-construction significance
Represent the construction system, not merely its price	Integrate domain experts, mission planners, engineers, estimators, operators, models, and project data	Reveals dependencies among transportation, power, communications, excavation, ISRU, robotics, crew support, and infrastructure
Maintain predictive continuity	Use AI, simulation, digital models, and professional judgment to evaluate evolving conditions and alternative futures	Preserves an actionable forecast despite technology maturation, mission changes, and limited precedent
Maintain Two-Way Data Flow	Connect estimates with test data, telemetry, reality capture, operational records, and human interpretation	Allows predictions to influence execution and verified performance to recalibrate future predictions
Preserve probabilistic conditions	Distinguish evidence, assumptions, uncertainty, model output, and expert judgment	Prevents immature or weakly supported inputs from being treated as verified facts
Establish Awareness of Actual Reality	Verify provenance, causality, field conditions, and operational performance through qualified review	Converts observations into defensible evidence before the Master Estimate changes
Detect and manage variance	Use analytical systems to identify deviations and humans to interpret significance and authorize action	Turns variance into a decision signal rather than a retrospective report
Anticipate cycle jumps	Combine conditional modeling, scenario analysis, system knowledge, and organizational adaptability	Supports planned and unplanned changes without losing prior logic or historical lineage
Learn across the lifecycle	Preserve verified outcomes, decisions, relationships, and lessons in reusable organizational knowledge	Builds a lunar-construction evidence base where little historical precedent currently exists

Human-AI Interaction in Lunar Construction Estimating

The central proposition does not assume that AI will replace the estimator. It assumes that lunar estimating will exceed the practical cognitive and computational capacity of any individual professional while also exceeding the contextual and ethical competence of AI operating independently.

Humans contribute:

- construction and mission-domain knowledge;
- understanding of purpose, context, and stakeholder priorities;
- interpretation of incomplete or conflicting evidence;
- causal reasoning and professional skepticism;
- ethical and risk judgment;
- decision authority and accountability; and
- the ability to act under novel or off-nominal conditions.

AI and advanced digital systems contribute:

- management of large and heterogeneous datasets;

- rapid scenario and sensitivity analysis;
- pattern, anomaly, and variance detection;
- probabilistic and predictive modeling;
- traceability across complex system relationships;
- continuous monitoring; and
- support for organizational memory and learning.

Neither contribution is sufficient alone. The required capability emerges from their interaction.

Organizational Conditions for CI-Enabled MET

CI-enabled implementation of MET requires more than capable individuals and advanced tools. It also requires organizational conditions that allow evidence and decisions to move across disciplinary and institutional boundaries.

Analytics maturity contributes data quality, governance, interoperability, infrastructure, leadership, common definitions, and evidence-based decision processes. These conditions enable CI, but they are not equivalent to it. An organization may possess advanced infrastructure and still produce weak intelligence if its systems are fragmented, outputs are not trusted, verification is absent, or decision authority is unclear.

For MET implementation, the organization must establish:

- common estimating and system definitions;
- clear ownership of data, assumptions, models, and decisions;
- interoperability among engineering, estimating, logistics, simulation, and operational systems;
- verification and change-control procedures;
- traceable human approval for material recalibration;
- workforce capability in construction, AI, data, and systems thinking; and
- processes for converting verified project experience into reusable knowledge.

These conditions allow the Master Estimate to function as a shared predictive environment rather than an isolated estimating product.

Conclusion

Construction 5.0 establishes the broader human-centered paradigm for a technologically advanced, resilient, and sustainable construction environment. Intelligent construction describes the digital and operational context created by AI, models, sensors, automation, and robotics. Construction Intelligence describes the capability of people, technologies, teams, and organizations to use that environment to understand conditions, anticipate outcomes, coordinate action, make accountable decisions, adapt, and learn.

MET requires precisely this capability. Its continuous predictive state, Two-Way Data Flow, verification logic, variance management, cycle-jump response, and lifecycle learning cannot be implemented through a static estimate, an isolated professional, or an autonomous AI system.

The Master Estimate provides the predictive structure. Construction Intelligence provides the socio-technical capability to operate it.

For lunar construction, their integration is not merely advantageous. The complexity, interdependence, uncertainty, and verification constraints of the mission make sustained human-AI collaboration a necessary condition for credible estimating and responsible decision-making.

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CONCEPT FOR SUSTAINED LUNAR SURFACE OPERATIONS

Sustained Lunar Surface Operations at the Moon Base

Artist's rendering depicting astronauts, habitats, rovers, power systems, and cargo operations supporting sustained human activities at the Moon Base near the lunar South Pole.

Image credit: NASA.