Lunar Mega Project: Processes, Work Flow and Terminology of the Terrestrial Construction Industry versus the Space Industry

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ABSTRACT
Recent developments around the world show an increased interest and international activity toward developing a lunar surface human and robotic presence with a long term, sustainable vision. In Europe, the construction of a "Moon Village" has been proposed, and China has stated its intention to build a research station with a crew at the lunar South Pole. Russia stated it will land cosmonauts on the Moon in the 2030's. India has sent an orbiter, a robotic lander, and rover to the Moon. The USA intends to land the first woman and a man on the Moon by 2024 to initiate a sustained human lunar presence.

A lunar research station with associated commercial activities will require infrastructure to become a permanent capability. Landing and launch pads, propellant storage and distribution farms, spacecraft access and handling structures, cranes, blast protection berms or walls, roads, graded areas, dust stabilized areas, foundations, parking lots, radiation shelters, micro-meteorite protection hangars, habitats and other human shelters, greenhouse farms, utility trenches, power plants, industrial water and oxygen extraction plants, communications antenna towers, thermal protection, mining zones, crater access and sub-surface access will be required to create a safe and sustainable lunar operations capability. This infrastructure will require significant construction activities in an extreme environment, with risky and expensive operations. On Earth, there are similar large and expensive projects (>$1 Billion) in difficult locations that attract a lot of public attention. These are known as "Mega Projects" and examples include bridges, tunnels, highways, railways, airports, seaports, power plants, dams, wastewater projects, Special Economic Zones (SEZ), oil and natural gas extraction projects, public buildings, information technology systems, aerospace projects, and weapons systems. Large consortiums consisting of public and private entities typically implement these infrastructure Mega-Projects.

This paper compares the typical design process, project management process, and work flow in the terrestrial construction industry to the space industry in order to create a better understanding between the terrestrial construction industry and the space

industry, to further enable collaboration on a lunar Mega Project to build infrastructure on the Moon. In addition, a glossary of respective industry terminology with annotated linkages and definitions has been compiled. This information will enable contracts and business practices to be formulated for generating requests for proposals (RFP) by governments to consortiums consisting of construction and space industry companies that will bid on Lunar Infrastructure Projects that could lead to contracts to build the permanent capabilities.

INTRODUCTION

Mega Projects, sometimes referred to as “major programs”, are large-scale, complex ventures that typically take many years to develop and build, involve multiple public and private stakeholders, are transformational, and impact millions of people. As a rule of thumb, "mega projects" are measured in billions of dollars, "major projects" in hundreds of millions, and "projects" in millions and tens of millions. (Flyvbjerg, B., 2014).

NASA is no stranger to Mega Projects; The Apollo lunar program was its first large expensive project. The United States spent $28 billion to land men on the Moon between 1960 and 1973, or approximately $288 billion when adjusted for inflation. The International Space Station (ISS) has been described as the most expensive single item ever constructed. In 2010 the cost was estimated to be $150 billion. The latest NASA projects are also very expensive and can be classified as Mega Projects. The Space Launch System (SLS) rocket launcher has been estimated to have cost $17 billion so far, is three years behind schedule and has a projected cost of $2 billion per launch (nbcnews 2019). The Orion capsule for carrying human astronauts in to deep space has cost $16 billion to develop, and each additional capsule will cost $900 million, (Spaceflightnow.com 2019)

“During the last 15 years, the US Congress has authorized budgets totaling $46 billion for various NASA deep-space exploration plans. By late summer, 2020, that total is likely to exceed $50 billion, most of which has been spent on developing a heavy-lift rocket and deep-space capsule that may carry humans into deep space“, (Arstechnica 2019).

When projects of this size go wrong, whole companies and national economies suffer. (Flyvbjerg, B., 2014) In the era of a new proposed NASA lunar program named ”Artemis”, it is timely to examine the methods used to develop, implement and manage such large space-based projects in order to propose new ways to increase efficiencies in NASA’s space program.

The global construction market was valued at nearly $17 trillion in 2017 (marketwatch.com 2017), and there are many examples of Mega Projects that have been successfully completed on Earth. NASA’s policy under the Artemis program is to develop and operate a sustainable lunar base with human occupancy. To be truly sustainable in technical, political, financial and societal terms, it is envisioned that the infrastructure will be constructed on the lunar surface to ensure the health and safety of the human crew that will be visiting. This paper hypothesizes that by collaborating with the construction industry, NASA can leverage from existing methods and business networks to achieve its goals in a cost effective and sustainable way. The first step in this collaboration is to improve communication between NASA and the industry practitioners by comparing their respective work flows and terminologies. It is hoped that better communication will lead to a better mutual understanding of needs and possibilities.

SPACE INDUSTRY: NASA WORK FLOW AND TERMINOLOGY

NASA brings new aerospace concepts to operational reality by following a rigorous systems engineering process. Systems engineering is an interdisciplinary field of engineering involving engineering management that focuses on how to design and manage complex systems over their life cycles. Issues such as requirements definition, interfaces, reliability, logistics, coordination of different teams and perhaps separate systems, testing and evaluation, maintainability and other disciplines necessary for successful holistic design, development, integration, implementation, and final decommissioning become more difficult when dealing with large and complex projects.

NASA has developed a systems engineering process for dealing with large complex projects that has been stressed tremendously without failure to bring about complex space programs such as Apollo and the on-orbit assembly and continued safe operations of the International Space Station. That same process will be adopted for the Artemis Program.

NASA's systems engineering process uses a host of tools that include modeling and simulation, risk management, functional decompositions, requirements analysis and scheduling to manage complexity to ensure that all likely aspects of a project or a system are considered and integrated into a whole system. The systems engineering process begins by discovering the highest priority problems that need to be resolved and identifying the most probable or highest impact failures that can occur and then determining solutions for them. Once the project is up and running, work-process models, optimization methods, and risk management tools are used to manage the project. The systems engineering process is a discovery process that exists throughout the entire life cycle and overlaps technical and human-centered disciplines beyond just aerospace engineering, such as industrial engineering, civil engineering, process systems and controls engineering, organizational studies, and project management, to accomplish its goals.

NASA has found that a phased approach, with intermittent reviews and go/no-go decision points, is most effective in bringing into existence a complex system that is operationally viable, can be managed effectively, as well as decommissioned at the end of life with the least amount of stranded assets. NASA Systems Engineering Handbook, NASA SP-2016-6105 Rev2, describes the various phases and their intent. This handbook should be used as a companion for implementing NASA Procedural Requirements (NPR) document: NPR 7123.1, Systems Engineering Processes and Requirements, as well as the Center-specific handbooks and directives developed for implementing systems engineering at NASA. It provides a companion reference book for the various systems engineering-related training being offered under NASA's auspices. NASA accomplishes its strategic goals through human and robotic missions, which are conducted through programs and projects. In 2006, NASA undertook a major reordering of the management structure for its program and project life cycles. The result was codified in NASA Procedural Requirements (NPR) 7120.5E, NASA Space Flight Program and Project Management Requirements. With the establishment of significantly revised Agency policy and requirements for program and project management, a handbook to aid practitioners in the implementation and practice of policy was provided. This handbook is called the NASA Space Flight Program and Project Management Handbook: NASA/SP-2014-3705. This handbook provides implementation guidance for NPR 7120.5E, NASA Space Flight Program and Project Management Requirements, which changed and streamlined key procedural requirements across the Agency for space flight program and project management. The goal of the NPR requirements is to ensure programs and projects are developed and successfully executed in the most cost-effective and efficient manner possible. This handbook provides context, rationale, and explanation to facilitate the application of requirements so that they make sense and to pass on some of the hard-won best practices and lessons learned.

The Agency-level requirements in the policy documents provide the basis of practice across the Agency. However, the scope of NASA programs and projects - from research into new ways to extend our vision into space, to designing a new crew vehicle, or exploring the outer reaches of our solar system - is vast. This handbook takes a more detailed look at the principles of how to implement those high-level requirements. The goal of this paper is to start a discussion on how to correlate the NASA methods with existing construction industry Mega Project methods to achieve a mutually acceptable management structure and project implementation plan.

A typical NASA externally contracted project begins with a Request for Information (RFI) or a Broad Agency Announcement (BAA) which is used to gauge interest by potential bidders and to seek input from them prior to issuing a Request for Proposals (RFP). The RFP initiates a rigorous and legally binding contract competition process that is subject to the Federal Acquisition Regulations (FAR). These regulations are included in the Code of Federal Regulations ("CFR"), the omnibus listing of Government regulations, as Title 48. Chapter 1 of Title 48 is commonly called the FAR. In general, there are two main types of contracts – fixed price and cost reimbursement and at NASA there are various commonly used specific contracting mechanisms such as Firm Fixed Price, Cost-Plus, Small Business Innovative Research (SBIR), Space Act Agreement, etc. The selection of the type of contracting mechanism is dependent on the understanding of the risk posture in each case. The selected bidder will be awarded an appropriate contract with a related funding plan which is usually based on progress payments that are linked to the completion of selective milestones that gauge progress accomplished as related to a schedule. Once the contractor is engaged with NASA, they are expected to follow NASA systems engineering and project management guidelines as explained above, or at a minimum, equivalent reporting is required to inform the Contracting Officer (CO) and the Contracting Officer Representative (COR) of project progress and accomplishments. The operations phase begins with new project management methods and typically the operations team is a different group of professionals than the design team. NASA contracts about 80% of its work to private industry and universities, and NASA in-house work is mostly responsible for low Technology Readiness Level (TRL) technology development, technical oversight/insight, and project management of the contracts that have been awarded. All NASA projects are subject to NASA documented processes, as appropriate, with Chief Engineer Office and management reviews to ensure compliance. The operations phase is closely monitored by NASA and typically NASA makes all the major missions decisions.

The life cycle phases are grouped according to the system's level of maturity. (See Figure 1) While the system remains on paper, prior to fabrication, those phases are termed Formulation. Implementation phases begin when some level of system fabrication starts. Formulation Phases include Pre-Phase A Concept Studies, Phase A Concept & Technology Development, and Phase B Preliminary Design & Technology Completion. Pre-Phase A is often referred to as Pre-Formulation. (See Table 1). Implementation Phases include Phase C Final Design & Fabrication, Phase D System Assembly, Integration & Test including Launch, Phase E Operations & Sustainment, and Phase F Closeout. These are further described in Table 2. Formal programmatic approval and authority to proceed are required to move from the Formulation Phases to the Implementation Phases. Key Decision Points (KDPs) and major project reviews are tied to each phase. (See Figures 1 & 2)

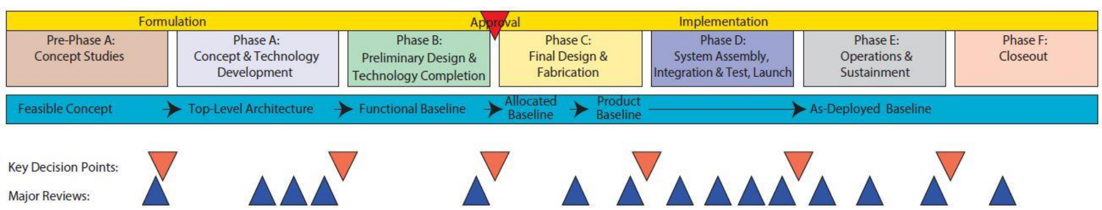

Figure 1: NASA Project Life Cycle Process Flow for Flight and Ground Systems [NASA SP-2016-6105 Rev2]

The life cycle costs of a program or project tend to get "locked in" early in design and development. The cost curves clearly show that late identification of and fixes to problems cost considerably more later in the life cycle. Conversely, descopes taken later versus earlier in the project life cycle result in reduced cost savings. This figure, obtained from the Defense Acquisition University, is an example of how these costs are determined by the early concepts and designs. The numbers will vary from project to project, but the general shape of the curves and the message they send will be similar. For example, the figure shows that during design, only about 15% of the costs might be expended, but the design itself will commit about 75% of the life cycle costs. This is because the way the system is designed will determine how expensive it will be to test, manufacture, integrate, operate, and sustain. If these factors have not been considered during design, they pose significant cost risks later in the life cycle. Also note that the cost to change the design increases as you get later in the life cycle. If the project waits until verification to do any type of test or analysis, any problems found will have a significant cost impact to redesign and re-verify.

Table 1: Project Life Cycle Phases Pre-Formulation and Formulation Phases [NASA SP-206-6105 Rev 2]

Phase		Purpose	Typical Outcomes
Pre-Formulation	**Pre-Phase A** Concept Studies	To produce a broad spectrum of ideas and alternatives for missions from which new programs/projects can be selected. Determine feasibility of desired system, develop mission concepts, draft system-level requirements, assess performance, cost, and schedule feasibility; identify potential technology needs, and scope.	Feasible system concepts in the form of simulations, analysis, study reports, models, and mock-ups
Formulation	**Phase A** Concept and Technology Development	To determine the feasibility and desirability of a suggested new system and establish an initial baseline compatibility with NASA's strategic plans. Develop final mission concept, system-level requirements, needed system technology developments, and program/project technical management plans.	System concept definition in the form of simulations, analysis, engineering models and mock-ups, and trade study definition
	Phase B Preliminary Design and Technology Completion	To define the project in enough detail to establish an initial baseline capable of meeting mission needs. Develop system structure end product (and enabling product) requirements and generate a preliminary design for each system structure end product.	End products in the form of mock-ups, trade study results, specification and interface documents, and prototypes

Table 1: Project Life Cycle Phases, Implementation Phases, following Pre-Formulation and Formulation Phases [NASA SP-2016-6105 Rev2]

Implementation	**Phase C** Final Design and Fabrication	To complete the detailed design of the system (and its associated subsystems, including its operations systems), fabricate hardware, and code software. Generate final designs for each system structure end product.	End product detailed designs, end product component fabrication, and software development
	Phase D System Assembly, Integration and Test, Launch	To assemble and integrate the system (hardware, software, and humans), meanwhile developing confidence that it is able to meet the system requirements. Launch and prepare for operations. Perform system end product implementation, assembly, integration and test, and transition to use.	Operations-ready system end product with supporting related enabling products
	Phase E Operations and Sustainment	To conduct the mission and meet the initially identified need and maintain support for that need. Implement the mission operations plan.	Desired system
	Phase F Closeout	To implement the systems decommissioning/disposal plan developed in Phase E and perform analyses of the returned data and any returned samples.	Product closeout

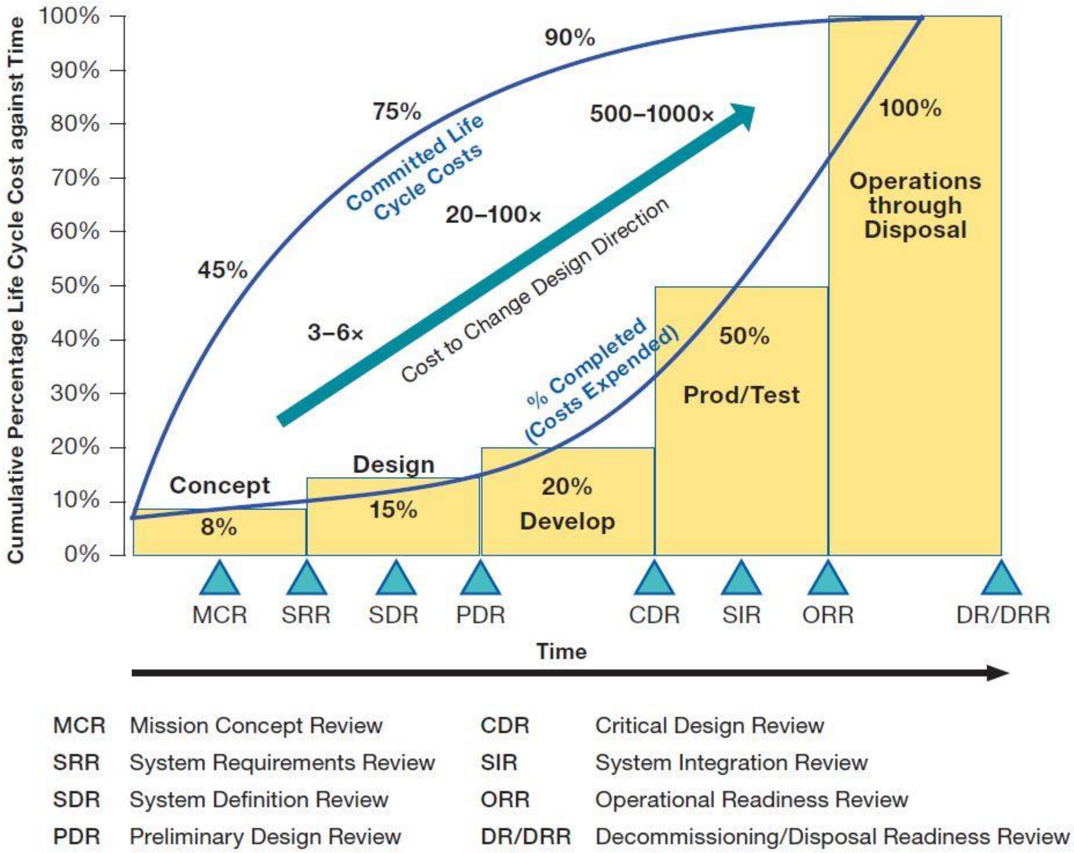

Figure 2: Life-Cycle Cost Impacts from Early Phase Decision-Making Including the Various Programmatic Reviews (Source: Defense Acquisition University, United States Department of Defense)

TERRESTRIAL CONSTRUCTION INDUSTRY: WORK FLOW AND TERMINOLOGY

Multi-billion-dollar projects are common in aerospace, defense, energy, green field cities, spaceflight and transportation. Mega Projects particularly aligned with the needs of development of a permanent Moon base include terrestrial power plants, oil and gas facilities, mining operations, and chemical projects Examples of privately financed projects costing tens of billions of dollars are provided in Table 3 below.

Table 3: Examples of Terrestrial Mega Projects

PROJECT	LOCATION	TYPE	OWNERS	COST*
Kashagan	Kazakhstan	Oil & Gas	Shell, Exxon, ConocoPhillips …	$116B[(a)]
Gorgon	Australia	Natural Gas	Chevron, Exxon, Shell	$57B[(a)]
Curtis Island LNG	Australia	Natural Gas	BG Group	$34B[(a)]
Kearl	Canada	Oil	Imperial Oil, Exxon	$33B[(a)]
Gladstone LNG	Australia	Natural Gas	Santos, Petronas, Total, Kogas	$30B[(a)]
Sadara Chemical	Saudi Arabia	Chemical	Saudi Aramco, Dow Chemical	$20B[(b)]
Serra Sul S11D	Brazil	Mining	Vale	$14B[(c)]

(a) *http://money.cnn.com/gallery/news/economy/2012/08/27/expensive-energy-projects/10.html*
(b) *http://www.chemicals-technology.com/projects/sadara-complex/*
(c) *https://www.ft.com/content/aebec85c-c547-11e6-8f29-9445cac8966f*
**$B= $ Billions*

Due to the protracted timeframe as well as technical and human complexity of Mega Projects, enormous planning and change management is required. Successful project delivery is realized by using a phased approach, focused on development of client expectations, technical requirements and cost estimates. In industry, the phases of project development include: Concept (Initial Studies), Pre-Feasibility (Evaluate), Front End Engineering and Design FEED (Feasibility), Execute (Engineering, Procurement, Construction, Commissioning), Operate, and Closure. In the NASA systems engineering process this is equivalent to Concept (Pre-Phase A), Pre-Feasibility (Phase A), Front End Engineering and Design FEED (Phase B), Execute (Phase C-D), Operate (Phase E), and Closure (Phase F) as summarized in Table 4.

A typical project in the terrestrial construction industry begins at the Concept phase, where the customer requirements and objectives are defined, a preliminary budget is established, and the location of the project is identified. Next, at Pre-Feasibility phase, the scope is further defined in preparation for completion of a feasibility study. During this timeframe, potential industry partners are identified, a preliminary estimate is produced, and the regional codes and standards to be utilized are identified. This leads to the Feasibility phase. Front End Engineering and Design (FEED) where the technical requirements as well as rough investment cost for the project is developed. This phase also includes the overall the project layout, system definitions, preliminary material quantities, and a high-level project schedule. Once the FEED is complete, the Execution phase begins. It is comprised of three major components: Engineering, Procurement, and Construction (EPC), Start-up and Commissioning, and Operations. During the EPC portion the design is finalized, construction materials are procured and delivered to the jobsite, and construction is completed. Following EPC, Start-up and Commissioning performs the final testing of systems and measures overall performance of the project facilities. During operations the performance of the facility is monitored, maintenance is performed, and any necessary upgrades are completed. Once the project has completed its intended mission, the Closure phase occurs. This phase includes the controlled shutdown of facilities, decommissioning of systems, and demolition of the project.

Because of the importance of each of these phases a consortium may be a valuable way to pool resources and distribute risk across various entities. Consortiums can take many forms and may include the owner, contractors, and outside stakeholders. Regardless of the form, the consortium is a formal contract between all parties that defines the roles and responsibilities of each entity as well as the negotiated terms and conditions that ultimately establish the risk each party is willing to accept. A consortium between contractors, whether as a joint venture or primary/subcontractor relationship, is valuable to combine varying skill sets and levels of experience and apply them to the execution of the EPC phase of the project. A consortium which involves the owner operator and construction contractor is also beneficial as it aids in the integration of operability during the design and construction phases.

INDUSTRY COMPARISON AND "SCHEMA CROSS WALK"

Table 4: Schema Crosswalk showing Work Flow with a corresponding NASA and Industry Terminology Dictionary for Collaborative Efforts

NASA	Notes	Construction Industry	Notes
Pre-Phase A	Concept Studies	**Concept**	Initial studies
KDP A	Key Decision Point A		
Phase A	Concept & Technology Development	**Pre-Feasibility**	Evaluate
MCR	Mission Concept Review	PESP	Project Execution Strategy Plan
SRR	System Requirements Review	FEP	FEED Execution Plan
KDP B	Key Decision Point B		
Phase B	Preliminary Design & Technology Completion	**Feasibility**	FEED
SDR	System Definition Review	EEP	Engineering Execution Plan
PDR	Preliminary Design Review	PEP	Project Execution Plan
KDP C	Key Decision Point C		
Phase C	Final Design and Fabrication	**Execute**	Engineering and Procurement
CDR	Critical Design Review	CEP	Construction Execution Plan
SIR	System Integration Review	SEP	Start-up Execution Plan
KDP D	Key Decision Point D		
Phase D	System Assembly, Integration & Test, Launch	**Execute**	Construction and Start-up
ORR	Operational Readiness Review	C&Q	Commission and Qualify
KDP E	Key Decision Point E		
Phase E	Operations & Sustainment	O&M	Operate & Maintain
KDP F	Key Decision Point F		
Phase F	Closeout	**Closure**	Mission complete
DR/DRR	Decommissioning Review / Disposal Readiness Review	D&D	Decommissioning and Demolition

HYPOTHETICAL CASE STUDY: A LUNAR LANDING AND LAUNCH COMPLEX (LLLC)

A short hypothetical case study is examined below where the construction industry work flow is applied to a Lunar Landing and Launch Complex Mega Project. The first step in creating a lunar base will be to have safe and reliable landings and launches.

After the Landing and launch pad complex has been built, subsequently propellant storage and distribution farms, spacecraft access and handling structures, cranes, blast protection berms or walls, roads, graded areas, dust stabilized areas, foundations, parking lots, radiation shelters, micro-meteorite protection hangars, habitats and other human shelters, greenhouse farms, utility trenches, power plants, industrial water and oxygen extraction plants, communications antenna towers, thermal protection, mining zones, crater access and sub-surface access will be required to create a safe and sustainable lunar operations capability.

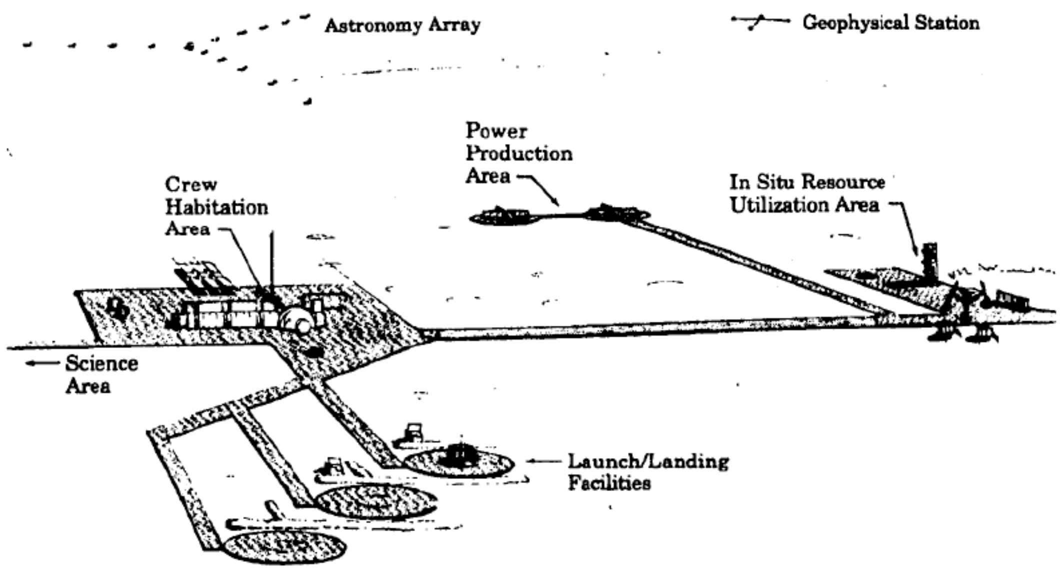

Figure 3: A NASA concept for a LLLC produced during the 1989 "90 Day Study"

A Lunar Landing and Launch Complex (LLLC), undoubtedly located at the South Pole, will be the first extraterrestrial space port constructed by humans, and easily meets the definition of a Mega Project. Among the many benefits of an LLLC are 1) the deployment of fully reusable lunar landers, 2) a focused location for developing a lunar city and, 3) an important component for supporting missions beyond the Moon.

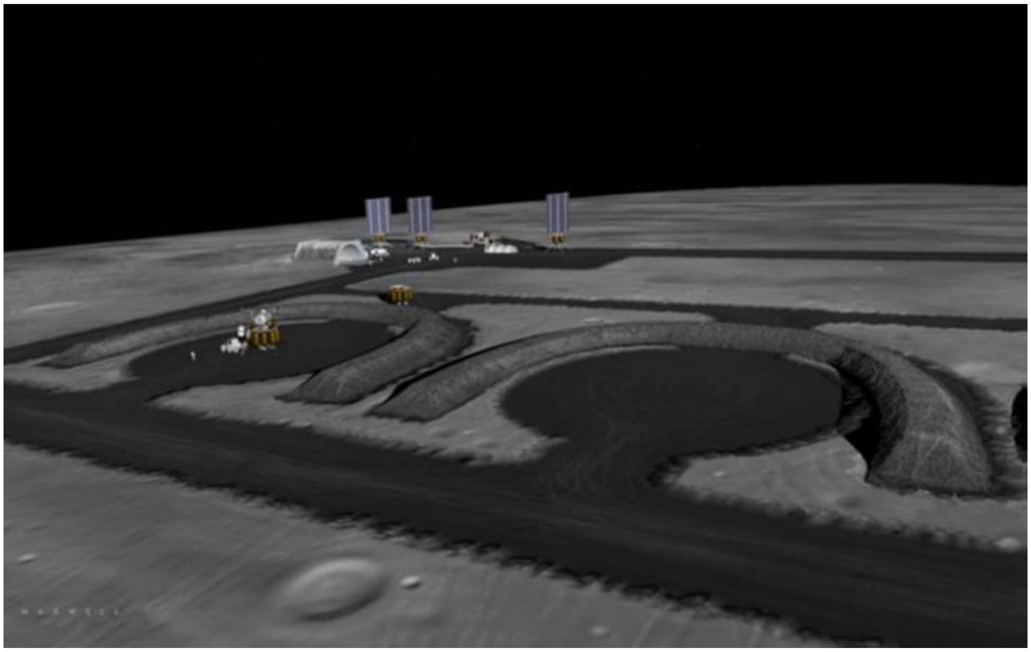

Figure 4. An artistic illustration of a typical LLLC master plan (Source: NASA)

During all phases of project planning, the potential growth of the LLLC as space commerce develops needs to be carefully considered. A terrestrial comparison, using Heathrow airport as an example, provides an example of potential growth of such facilities.

Figure 5. The rather limited facilities of Great West Aerodrome (Heathrow) in 1931: a single hangar and grass landing ground. (Wikipedia)

Figure 6.   Heathrow Airport Master Plan in 2019. (Wikipedia)

The construction industry would likely approach a LLLC Mega Project as follows:

CONCEPT: During the concept phase of the LLLC the potential future-state of the proposed facility must be considered. The LLLC will grow to well beyond the initial construction project which might include a single stabilized pad with associated navigation and communication infrastructure. A concept that envisions many square kilometers needed for future development is imperative.

PRE-FEASIBILITY: The pre-feasibility study is critical to the success of delivering Phase 1 of the LLLC. Performance requirements (Concept for Operation - ConOps) for this phase of the LLLC are defined. What is the design basis vehicle, how many missions per year are anticipated, is refueling included, etc? A raw order of magnitude (ROM) cost estimate and initial project delivery program (Level 0 schedule) should be established.

FEASIBILITY: Given the performance requirements from the pre-feasibility study both technical and commercial challenges are established. What are the technical readiness levels (TRL) for all component of the Phase 1 LLLC? Equally important is the TRL for the major construction equipment and plan for In Situ Resource Utilization (ISRU) needed to deliver the project.

Commercial challenges are provided in a preliminary return on investment (ROI) study that considers; costs of developing equipment both for construction and as part of the permanent facility, construction cost, landing and launch fees, identifying potential investors and potential customers, etc. Procurement and project delivery strategies are formulated. What components will be purchased from a prequalified sole source vendor. What components will be competitively bid. The project organization is proposed; partnership, joint venture, etc. Engineering and construction contracting methods are reviewed; Design Build, Integrated Project Delivery, Cost Reimbursable, etc.

Front end engineering is performed on the Phase 1 LLLC to provide a conceptual design for critical structures systems and components (SSCs). An initial cost estimate and a Level 1 schedule, in addition to the preliminary engineering designs, are deliverable from the feasibility study.

ENGINEERING PROCUREMENT AND CONSTRUCTION (EPC): This is the portion of the project delivery process where all the “heavy lifting” takes place. Designs are finalized for the project, with the associated costs and schedules completed. Procurement strategies are executed. Construction means and methods are finalized and implemented. Start-up and commissioning of the LLLC takes place.

OPERATE: An operations plan for Phase 1 of the LLLC will probably need to be finalized during the start-up and commissioning portion of project delivery. Due to the long duration required to deliver a major infrastructure project such as this it is not unusual for project operations plans to evolve over time. Some form of spaceport authority is envisioned. This could be a private, semi-governmental or multi-national organization that is responsible for maintenance and operation as well as collecting fees and duties.

CLOSURE: The eventual closure of Phase 1 of the LLLC is not considered. However, assimilation of this initial facility into a growing and maturing lunar spaceport should be part of this project.

CONCLUSION

This paper has explained how NASA and the construction industry manage their projects in the context of a “Lunar Mega Project”. A Lunar Landing & Launch Complex (LLC) has been considered as a part of every major lunar master planning architectural study performed at NASA since at least 1989. By examining the NASA work flow in developing such a large and critical project and comparing it to the terrestrial construction industry typical work flow, an industry workflow comparison and schema crosswalk table has been generated which can serve as a guideline and terminology dictionary for joint ventures between NASA and the construction industry. More details on terrestrial Mega Project equivalent efforts will be provided in a future paper to inform potential collaborators on relevant practices.

It is highly likely that a future LLLC will be constructed and managed by a NASA / industry lunar consortium and this paper serves as a valuable tool and a first step in coordinating related activities and methods.

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