Trade and Analysis Study for a Lunar Lander Habitable Module Configuration

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The paper demonstrates a method for a trade and analysis study of a configuration concept that derives from the Northrop Grumman 2008 Lunar Lander Development Study. It applies an algorithm for computing how many valid configuration combinations and arrangements may exist within the crew architecture of the Lunar Lander. It establishes a Crew Productivity Figure of Merit (FOM), which in addition to the Crew Safety FOM provides the metrics and rules with which to evaluate these configurations. The initial universe of allowable configuration permutations starts at 120. By applying the FOM-based rules to eliminate non-viable permutations, the analysis reduces the number of valid or "flyable" permutations to eight. Further refinement consolidates the number of fully acceptable configurations to five. This set of flyable and preferred solutions then becomes available for evaluation by allocating the functional requirements and applying the other criteria such as cost, mass, and mission success to the configuration.

Nomenclature

n:	the number of key elements that form the permutation
Offset:	the number of positions that the elements can occupy along the side of the linear chain.
P:	the number of possible permutations, based on the factorial of *n* elements
Polarity:	the degree to which the permutation chain is polar.
V:	logic symbol for Exclusive OR
!:	factorial

Acronyms and Terminology

AL: Airlock

Altair: NASA's name for the crewed Lunar Lander, 13 December 2007.

AM: Ascent Module

CEV: Crew Exploration Vehicle, Orion

CLL: Constellation Lunar Lander, 2006, also called the Lunar Lander Concept Requirements Description RFI.

Configuration 1 Suit: A space and flight suit attached to life support by an umbilical to the Orion or Lunar Lander life support system; also known as the Flight Operations (FO) suit or the Launch, Entry and Ascent (LEA) suit.

Configuration 2 Suit: A space suit arranged to carry its own life support system as a PLSS, but that can also plug into Lunar Lander life support via an umbilical; also known as the Lunar Surface Operations (LSO) suit.

Crew Productivity: How well the system supports the crew to perform the mission efficiently and safely.

DM: Descent Module

ECLSS: Environmental Control and Life Support System

EVA: Extravehicular Activity

FO: Flight Operations, refers to Configuration 1 or LEA suit.

HM: Habitation or Habitability Module

Hab: Habitat or Habitation Module

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Habitability: A measure of how well the living and working environment supports crew productivity and health (Yvonne Clearwater, NASA-Ames Research Center, personal conversations).

ISS: International Space Station

IVA: Intravehicular Activity.

JSC: NASA's Lyndon B. Johnson Space Center

LDAC: Lunar Development Analysis Cycle

LEO: Low Earth Orbit

LIDS: Low Impact Docking System, which incorporates the hatch between the Orion and the ISS, the Lunar Lander or other vehicle.

LLO: Low Lunar Orbit

LSO: Lunar Surface Operations refers to the Configuration 2 suit.

m^3: meters^3

NGC: Northrop Grumman Corporation

Orion: Crew Exploration Vehicle that carries the crew to LEO rendezvous with the Lunar Lander then travels with it to lunar orbit to serve as the earth return vehicle.

PLOC: Probability of loss of crew; a predictive measure of crew safety.

PLOM: Probability of loss of mission; a predictive measure of mission success.

PLSS: Portable Life Support System backpack for an EVA suit.

TAC-0: Northrop Grumman Aerospace Systems in-house study of the NASA Lunar Lander in 2009.

I. Introduction

In arranging habitable modules in Space Architecture to form a larger ensemble, many factors come into play. All too often, these factors are poorly understood, and the configuration of the modules arises somewhat arbitrarily, based upon convenient and simplistic criteria. This paper explores the deep structure and reasoning of configurations in Space Architecture. It begins with an appreciation of the 16th century architect Andrea Palladio's rigorous geometric compositions and shows how some of these principles may apply to Space Architecture. In so doing, it extracts the relevant properties of configuration in architecture: centrality, connections, geometry, rules, sets, and topology. The trade and analysis method correlates some of these properties to human factors and crew safety criteria. This correlation affords a verifiable approach to deciding which potential configurations meet the human factors and crew safety requirements.

This study attempts to determine the optimal arrangement of crew functions throughout the pressurized volumes of a Lunar Lander. This effort began with the Northrop Grumman Corporation's report to NASA for the 2008 Lunar Lander Development Study (Cohen, 2009, July, pp. 13-17) and continued through 2009 with the in-house Trade and Analysis Cycle Zero *(TAC-0)* study. This *TAC-0* study considers integration or separation of the primary modules or their functions: Ascent Module, Habitation, and EVA Airlock. It evaluates alternate combinations, separations, and permutations of connection sequences. The goal is to determine the best allocation of pressurized volume combination for the overall system primarily with respect to Crew Productivity. This Allocation of Functions appears in TABLE 1, which shows the most likely contents and activities in each module.
The key elements that comprise the Lunar Lander for the purpose of this model are:

AL = EVA Airlock

AM = Ascent Module

FP = Front Porch for EVA access via the AL

Hab = Habitation cabin, volume, or module

LIDS= Low Impact Docking System

Vert = The vertical connection between the pressurized modules on the Descent Module top deck and the lunar surface.

TABLE 1. Functional Allocation Matrix for Sorties Lunar Lander Pressurized Modules and Descent Module: Primary (P), Optional or Secondary (O), or Excluded (X)				
Function	**AM**	**Hab**	**AL**	**DM**
Architectural Circulation Volume	O	P	O	X
Avionics	P	X	X	O
Cargo Down, Pressurized Payload	X	P	O	X
Cargo Down, Unpressurized Payload	X	X	X	P
Cargo Up, Pressurized Payload	P	X	X	X
Clothing Stowage	X	P	O	X
Comm & Data Handling	P	O	O	O
Crew Restraints	P	O	X	X
Dust Exclusion, Control, Mitigation	O	O	P	O
ECLSS Consumables Stowage	P	P	O	O
ECLSS Hardware	P	P	P	O
EVA Config 1 Flight Suit Support (FO)	P	O	O	X
EVA Config 2 Surface Suit Support (LSO)	P/O	X	P	O
Flight Deck/Pilot Station	P	X	X	X
Food Stowage	P/O	P	O	X
Galley and Food System	O	P	X	X
Health Care, Medical	O	P	X	X
Housekeeping and Maintenance	O	O	P	X
LIDS Hatch	P	O	O	X
Operational Supplies	P	O	O	X
Personal Hygiene	O	P	O	X
Photography & Video	P	O	O	O
Radiation Shielding	O	P	O	X
Recreation	O	P	X	X
Sleep Stations	O	P	X	X
Surface Science Support, EVA	X	X	P	O
Surface Science Support, IVA	X	P	O	X
Thermal Radiators	P	X	X	P
Trash Handling and Stowage	O	P	O	X
Waste Collection System	O	P	O	X
Waste Stowage	X	O	O	P
Water, Drinking	P	P	O	X

FIGURE 1 maps these functions onto a generic module configuration of the Lunar Lander. These generic modules are the AL, AM, DM, and Hab. FIGURE 1 does not show the FP or Vert elements, as they are encapsulated spaces in themselves that are not domains to accommodate these types of functions or subsystems.

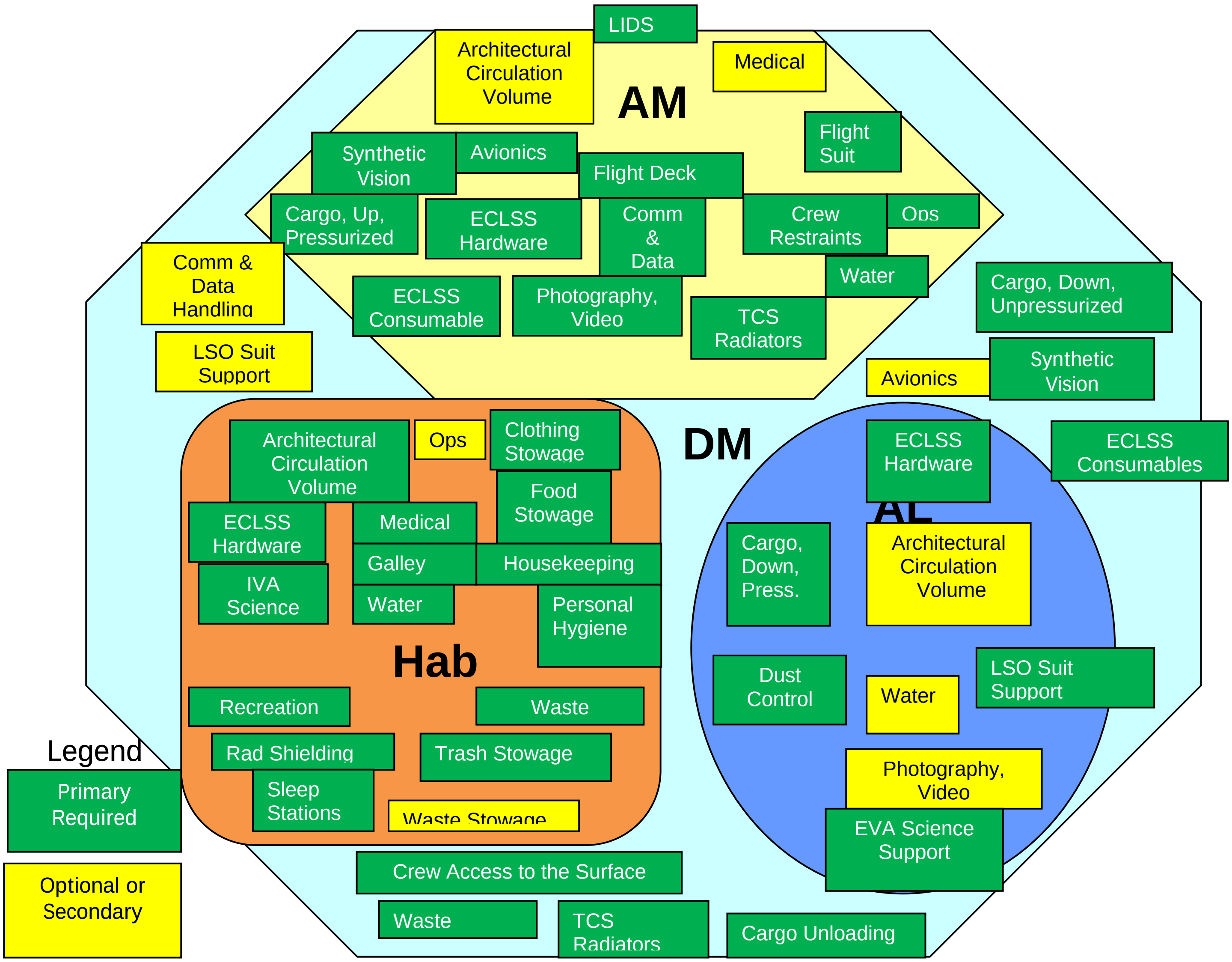

FIGURE 1. Allocation of Human Systems Functions to Specific Modules.

The study applies a rule-based design methodology to permutations of possible configurations of these modules. This approach treats the configuration of modules as a topology on a surface that is a non-vectorial geometry. The modules can connect horizontally, vertically, over the edge of the surface and around a corner. In this way, it is the connection between the key elements that is important, rather than their location in physical, three-dimensional space.

II. Approach

These five elements attach to one another on the Lunar Lander Descent Module (DM). The approach this analysis takes is to examine the allowable sequences of these key elements, and the allowable connections between them.

The algorithm describes the number of possible permutations among elements, and the rules circumscribe and reduce the valid connections among them.

The alternative solutions derive from the possible combinations and permutations of the elements shown in Figure 2, plus the Vertical Connection to the lunar surface and the EVA front porch, Descent Module. No solutions are ruled in or ruled out *a priori*; all potential solutions will be subjected to scrutiny and rigorous analysis. One theme that runs throughout this trade and analysis study concerns the allocation of pressurized volume to the modules: where to allocate it, how much, and ultimately in what geometry. This theme means to organize the volume in the way that is most advantageous for crew activity and operations by accommodating the functions in TABLE 1 within their respective modules.

FIGURE 2 shows the key elements of the Lunar Lander pressurized modules. Defining and analyzing ways to configure these functions, individually and collectively, constitute this design trade space. These Alternatives derive from the possible permutations of the Key Elements, plus the Descent Module. No solutions are ruled in or ruled out a priori; all potential solutions are subject to scrutiny and rigorous analysis. Among these six key elements, all except the LIDS proved to have a formative role in generating the configurations for analysis.

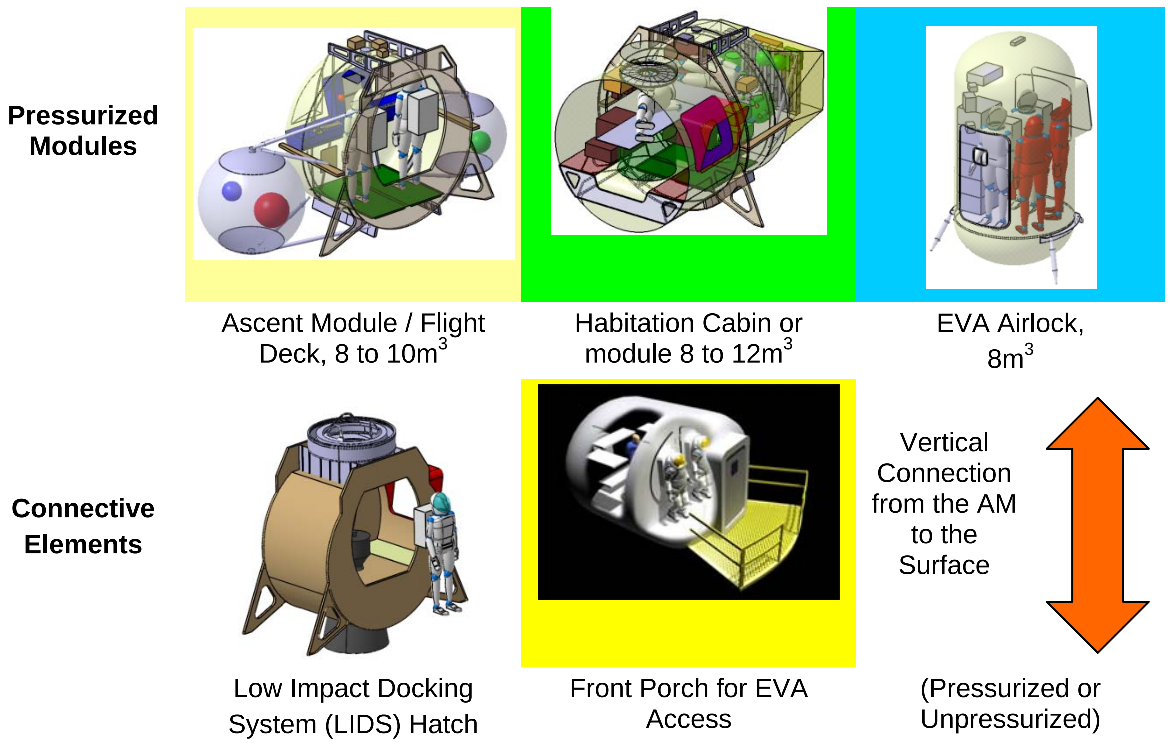

FIGURE 2. Elements of the Lunar Lander Pressurized Modules. Credit Abid Ali Khan except the Front Porch which is by Juan Bautista, 3D Cinematix.

A. Design Parameters to be Analyzed

The trade and analysis study started with a broad approach to looking at what design parameters may inform the configuration. The challenge was to narrow and focus this approach to distill the factors that have a dispositive effect.

- Definition of pressurized modules, including size, number, functionality,
- Layout of the living and working environment on the Lunar Lander,
- Layout of the flight deck/piloting station, including windows, view angle, and eye position,
- Equipment selection, arrangement, and geometry for the airlock.

- Height of the various modules above the lunar surface, and safe access to the surface,
- Size, role, and layout of the EVA Front Porch (FP),
- Design of the pressure vessels to accommodate these functions,
- Position of the LIDS hatch on axis with the CG or offset or doubled on a second module, and
- How to combine or separate functions among the modules to best advantage.

The constraints upon these design parameters begin from the guidelines and assumptions about suitable volume allocations as shaped by anthropometric and ergonomic envelopes and as a function of mission duration. What is more important, the constraints imply that the modules on the Lunar Lander must be connected to produce a functional arrangement that supports the crew and their mission.

B. Architectural Design Methodology

This section on design methodology uses methodology in its original meaning: the study of method. The methodology for this analysis combines classic and academic architecturally theory with Space Human Factors and Space Architecture into a simple matrix of spatial and arithmetic logic. These sources converge to create a method of analysis that can reduce the vast design problem space to a manageable handful of valid and viable configurations for the Lunar Lander modules and their connective parts. The topics for this discussion of methodology include representation, topology, sets, rules, configuration, and centrality. The discussion opens with representation, a common property of these topics.

1. Representation

Representation is a common property of all the topics of design methodology. The application of this methodology to representing the configuration of Lunar Lander key elements derives from architectural theory. It turns on two fulcrums, the use of the grid to represent the division of an architectural plan and the concept of centrality in design. The historical background is that the 16th century Italian architect Andreas Palladio perfected the formal plan based upon geometric proportional sections to generate the rooms.

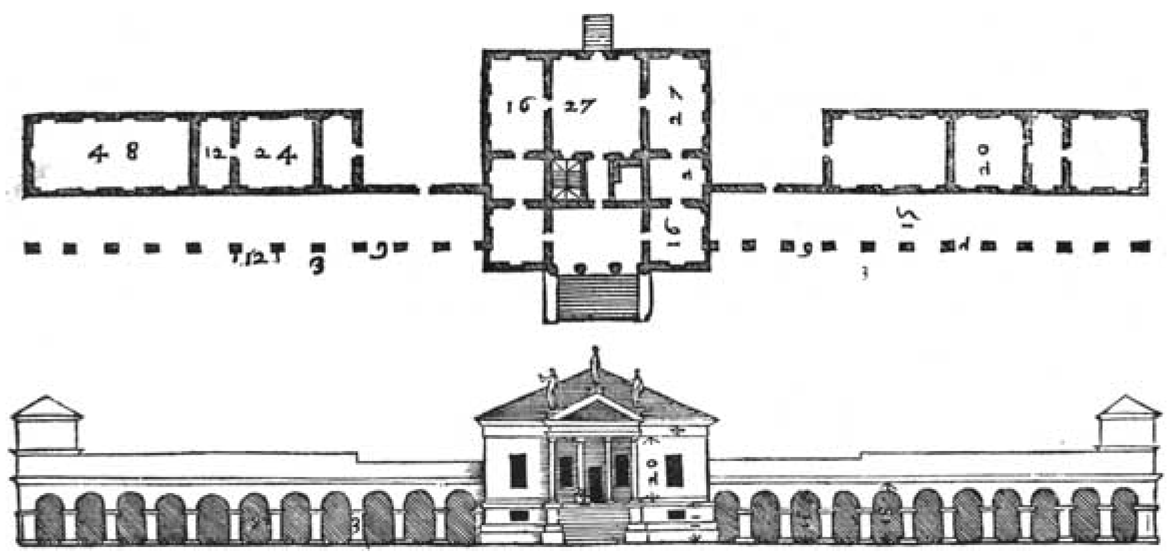

FIGURE 3. Plan and front elevation for the Villa Emo, Fanzolo di Vedelago, Italy, designed 1559 by Andrea Palladio. Original Woodcut 1570, Public domain.

FIGURE 3 shows the plan of the Villa Emo, for which Palladio designed the center square section in 1559. This center plan shows the allocation of the vertical circulation core to the cells in the grid. The numbers indicate the principal dimension of the room in the direction the number is inscribed. These numbers could also suggest an allocation of function to the rooms, perhaps even tied to the size and shape of the room. The barn, stable, and storerooms that comprise the agricultural wings illustrate this assignability of functions within the strict bilateral symmetry.

2. Topology

The core methodology for this analysis is to describe the relationships among the key elements in terms of a topological surface, delineated as a square grid. (Wolfram Mathworld http://mathworld.wolfram.com/Topology.html, retrieved 2009, October 5) defines topology as:

> (1) The mathematical study of the properties that are preserved through deformations, twisting, and stretchings of space.
>
> (2) A set along with a collection of subsets that satisfy several defining properties . . . and knowledge of objects is independent of how they are "represented" or "embedded" in space.

In this study, the analytical method involves representing the configuration of the five key elements on one surface, regardless of whether these elements may be arranged vertically, horizontally, or otherwise. *The properties are preserved* despite deformation, so it is possible to represent the relationships (properties) among these elements on a common topological surface.

This topological analysis is different from the traditional geometric appreciation of Palladio, and so it is important to explicate the distinction. The Palladian villas engender a rich heritage of design analysis and speculation about the use of the grid as a framework for proportional systems of rectangular elements. Indeed, Palladio's oeuvre spawned not only its own geometric/baroque movement in architecture, but also a modern cottage industry of architecture books that seek to explain and exalt his accomplishments. March and Steadman (1971) published diagrams representing Palladio's division of space on the floor plan of the Villa Malcontenta, with rooms of simple whole-number proportions. What is most revealing in March and Steadman's approach is their assessment that there is no underlying grid plan, but rather that Palladio "divided the overall dimensions of the building" into "suitable ratios to determine the breakdown of a plan or elevation into its subsidiary parts" (1971, pp. 224-225). What this statement implies is that the shapes and proportions of the rooms can change without affecting the relationships among the functions that the rooms accommodate. This description allows us to view the Palladian plan as a topological surface

William Mitchell published the first systematic explication of Palladio's rule-based geometric subset generation. He took a series of rectangles and squares in a modularization that allowed them to program a computer to generate an exhaustive set of permutations, each comprising a different plan or pattern (1990 pp. 152-179). What this approach does not do is to assign specific functions to the rooms or spaces.

Hersey and Freedman (1992) published a more extensive exercise in computer-generation of Palladian schema, Possible Palladian Villas. They go to great lengths to document the mutability of individual cells and their collective plasticity that can change without altering the totality or *gestalt* of the larger building plan. With their *Facademaker* software, they demonstrate the importance of the relationship between plan and elevation. This mathematical relationship suggests that the set of proportions can translate from one plane to another – from the horizontal to the vertical, and even bend around corners.

None of these examples from March and Steadman, Mitchell, or Hersey and Freedman identify the relationships among the functions assigned to the rooms or spaces in plan. Thus, the exercises of ratios, proportions, and permutations do not imply sets or rules for *functions or modules* that may exclude certain results as unallowable. Therefore, the rules for the relationships among functions must derive from a separate source.

3. Sets and Rules

On beyond March and Steadman's exercise, Hershey and Freedman published a book, Possible Palladian Villas, devoted to generating floor plans and elevations by computer that conform to their reading of Palladio's rules and topology. Hershey and Freedman articulate this approach:

> We have said that Palladio is called the most influential architect who ever lived. One reason for this influence, we believe is that his villas can be replicated with set variations . . . from a single architect's having reasoned out a basic idea and then run it through a series of permutations. . . .
>
> Let us call this kind of architecture *paradigmatic*. Paradigmatic architecture generates buildings according to rules expressed by a model . . . . By articulating the rules, we newly define and clarify . . .
>
> In the end, we shall find that Palladio's rules, expressed and unexpressed, are as elegant as any geometric proof or algorithm (Hershey, Freedman; 1992; pp 7-12).

The key elements comprise a master set of objects. The relationships among these objects create subsets that represent configurations of the Lunar Lander habitable modules plus the front porch and the vertical connection. Where Palladio used rules to define the shape and adjacency of rooms, this analysis applies its rules to the allocation of functions (modules) to locations in the topology and the allowable conditions for connections among them.[2]

4. Configuration

Understanding the configuration of the Lunar Lander or any other complex crewed spacecraft is a major undertaking within the design process. The properties of configuration often may seem simple or obvious, but it is often very difficult to determine which design criteria affect the configuration, which aspects or parts of the configuration they affect, and how these factors interact with the configuration. Bill Hillier writes about architecture and spatial relationships:

First we must bring a little more formality into the definition of "configuration." Like the word "pattern" (which we do not use because it implies more regularity than we will find in most spatial arrangements), configurations seems to be a concept addressed to the whole of a complex rather than to its parts. Intuitively, it seems to mean a set of relationships among things all of which interdepend in an overall structure of some kind. There is a way of formalizing this idea that is as simple as it is necessary. If we define spatial relations as existing when there is any type of link – say adjacency or permeability – between two spaces, then configuration exists when relations between two spaces are changed according to how we relate one or other, to at least one other space. (Hillier, 1996, pp. 23-24).

Substitute "module" or "volume" for Hillier's "one other space," and the definition accords with the design challenges of the Lunar Lander configuration. This definition of configuration is particularly on-point for the notions of topology described above. In this light, the idea is to describe the key relationships between the modules or functions as a configuration mapped onto a topological surface.

5. Centrality

Centrality can be both static and dynamic; even when it appears static, centrality may act as a dynamic element or process. Centrality plays a role both in architecture and in the design of aerospace vehicles. In architecture, the essence of centrality is the center room or rotunda. Often, symmetry about a center axis enhances and reinforces the centrality of this main functional or ceremonial space, as in the role of the "wings" of the Villa Emo, shown in FIGURE 3. Palladio's archetype of centrality is his Villa Rotonda. FIGURE 4 shows this famous drawing for the villa that is symmetrical about two orthogonal axes.

Bill Hillier described the salient properties of Centrality as arising from and applying to elements, for which Vila Rotonda affords an apt exemplar:

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[2] As a caveat -- to avoid a potential confound between the topology and the geometry -- please be aware that although Palladio used rectangular rooms that fit together within a grid topology to lay out Villa Emo and many of his other houses, it does not necessarily translate into a system of "golden section" rectangles or other proportional dogmas. Lionel March rebutted very effectively a romantic view that Villa Emo was all about golden rectangles, showing that instead it is based upon whole-number rations. Writing that it "is so very wrong when testing by the numbers," March shows convincingly that Palladio mentions the Golden Section only minimally in his <u>Four Books</u> and did not use it in Villa Emo (March, 2001, p. 101).

. . . in close spatial proximity defining the limits of the central area. All we would need to know to understand centrality in such cases would be to identify the focus, describe the limits and map the various functions in their locations. As soon as we take time into account, however, we find that centrality is often neither clear nor stable, either in its focus or its limits. . . .

Centrality, then, is clearly not a simple state, but a process with both spatial and functional aspects. . . . It follows that to understand centrality in a way that will be robust enough to guide decisions in the future, we must seek to understand it as a spatio-functional process, not simply as a state, or a series of states at particular points in time. . . .

To understand centrality then we must investigate the relation between its spatial and its functional dynamics. . . Centrality is a special case of our need to understand the relation between structure and function . . . (Hillier, 1999, pp. 108-109).

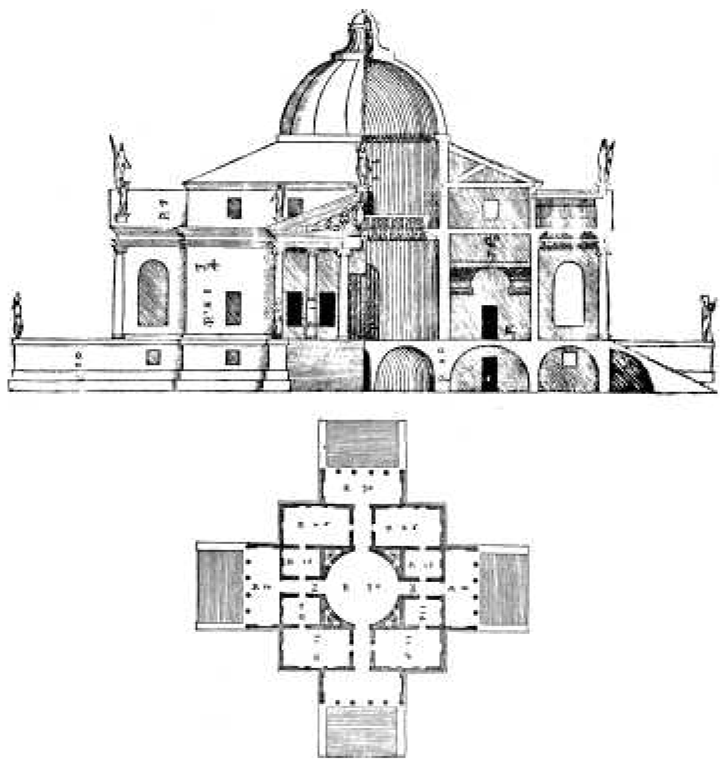


FIGURE 4. Andrea Palladio's design (1570) for the Villa Rotonda at Capra, Italy. Original woodcut, in the public domain.

Centrality is, well, *central* to many aerospace vehicles. Airplanes display bilateral symmetry across the centerline. Space launch vehicle stacks often align symmetrically around the vertical centerline from the bottom of the booster to the top of the fairing around the payload. The Space Shuttle shows bilateral symmetry about the center axes in both the Orbiter and the External Tank. In the Apollo program, the axially assembled Command and Service Module docked on-axis with the Lunar Module. In the LDAC-2, the Ascent Module occupies an analogous central and bi-axial symmetric place. However, in the preceding study, we found:

Symmetry About the Thrust Axis -- It is more important for the Lunar Lander modules to be arranged symmetrically in balance about the thrust vector than that the major mass should align directly upon the thrust axis through the Descent Module (Cohen; 2009, July; p. 21).

This finding means that specifically for NASA's Altair and generally for similar Lunar Landers, the flight dynamics and controls rules will require that the masses balance about the thrust axis through the Descent Module (which, with 33,800 kg has most of Altair's mass), and the common assumption is that the Ascent Module (6,800 kg) should align also on the thrust axis (for more about Altair mass, please see Cohen, 2009, September, AIAA-2009-6404, p. 20).

This finding means that the distribution of objects and their masses about the center vertical thrust axis is more important than that the major feature – the rotunda or the Ascent Module – should sit right on the vertical vector where the two axes of symmetry cross. In a spacecraft configuration, it may seem self-evident that all the elements should naturally line up along one central axis. However, when this assumption is applied to a more multi-functional and complex *cum* temporary lunar base such as a Lunar Lander may provide, the inference of centrality brings important consequences. It also leads the design analysis study to question the assumptions of axiality and centrality. FIGURES 5 and 6 show a comparison of near bi-axial symmetry in the Villa Capra (Villa Rotonda) and in a NASA model of the Altair Lunar Lander, LDAC-2 configuration. In the Villa, the feature that gives it its familiar name, the Rotunda, occupies the central place. In both these illustrations, there is a strong dynamic of centrality.

Centrality, therefore is neither a static nor immovable set of relationships, but rather a process that can change as a mission progresses, as the vehicle expends propellant and other consumables so that mass properties change, as operations change, and a functions fulfill their purpose. The center of focus changes also as the crew shifts from the Ascent Module to a habitat module or an EVA airlock. Understanding these dynamic aspects of centrality and symmetry sets the stage for the method of analysis.

FIGURE 5. Oblique view of Villa Rotonda, Capra, Italy, showing the biaxial symmetry. Courtesy of Roberto@GLAV, Copyright GLAV Photo.

III. Process of Trade and Analysis

The *TAC-0* Space Architecture analysis and trade process follows a subject-specific sequence of steps that identify and filter the possible subsets of the key elements. Although this paper lays them out somewhat linearly, in fact these steps are highly iterative, and do not necessarily flow always in consecutive order.

For the **first step**, the *TAC-0* study defines the Point of Departure, which means understanding the context: the 2005 ESAS Report, 2006 Constellation Lunar Lander RFI response, 2007 LDAC-1, and 2008 LLDS afford a rich background of options that help to bound the design problem space (Cohen, 2009, SAE-2009-01-2366).

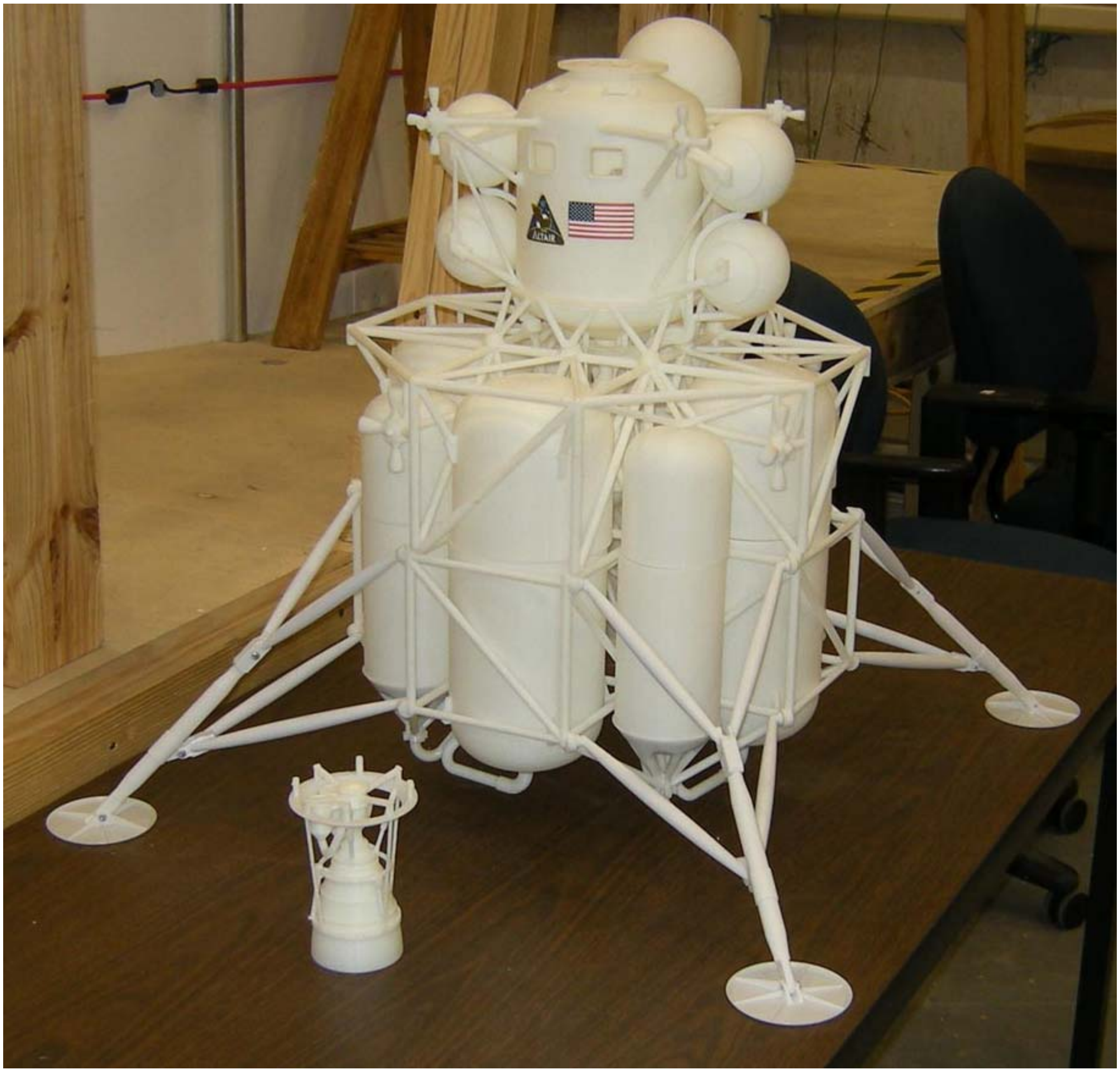


FIGURE 6. Near bi-axial symmetry in the NASA Altair Lunar Lander. Author photo.

As the **second step,** the Analysis Phase focuses on the functional criteria and how they interact with the design parameters to support fulfilling the human factors and crew safety criteria and FOMs. This analysis develops the Functional Allocation Matrix shown in Table 1, which shows the places to allocate the key functions: the Ascent Module (AM), Habitation Cabin (Hab), Airlock (AL), and Descent Module, including the EVA "front porch" and unpressurized cargo stowage (DM). FIGURE 1 shows a diagram of these four elements or locations. FIGURE 2 shows drawings of these elements.

The **third step** consists of the Architectural Configuration Study, in which we assess combinations and arrangements of the "ideal" modules or units that we have identified. This step involves the application of a simple permutation algorithm to generate all the possible configurations given the number of elements and the rules or constraints upon them.

The **fourth step** is the development of the crew productivity and crew safety FOMs and the application of their metrics to the admissible habitable module configurations.

TABLE 2. Parameters for the Human Factors and Crew Safety Criteria to Evaluate the Altair Living and Working Environments: Highlighted Metrics

IVA Working Environment	IVA Living Environment	EVA Working Environment
– **Ascent Module Flight** • Deck/Pilot Station • Controls and Displays • Pilot eye-point • Piloting window design • Pilot view-angles • Personal restraints – **Scheduling/Planning** • Crew Time Model • Task Assignment • Task Selection – **Communications** – **IVA Working Environment** • Work Stations • Ergonomic envelopes • Anthropometrics – **Science Accommodations** • Up to 500kg Pressurized Payload Down-mass in Habitat Cabin or Airlock • 100k Payload Up-mass of returned scientific samples	– **Habitability Accommodations** • Sleep stations • Seating • Galley and food stowage • Hygiene facility • Waste Management • Housekeeping • Cleaning/Disinfecting • Acoustics • Thermal Comfort • Lighting • Clothing – **Recreation** • Communications with Family • Exercise/workout – **Medical Care** – **Scheduling/Crew Time Model** – **IVA Circulation** • Access to Modules • Egress from Modules **Window View from Modules for Crew Morale**	– **EVA Airlock Design Criteria** • Save crew time • Conserve atmosphere • Exclude Dust • Minimize pumpdown power • Minimize pump cooling – **Window and camera views to monitor EVA activities** – **Communications** – **Configuration 1 Suit IVA** Accommodation and Access – **Configuration 2 Suit** • Don/Doff • Egress from Airlock and Ingress • Safe Access to the Surface • IVA Access for contingencies – **Science Accommodations** • Up to 500kg Unpressurized Payload Down-mass in Habitat Cabin or Airlock

A. Permutation Analysis

March and Steadman first proposed using permutation analysis as a method for architectural design analysis to reduce the time and cost of the analytical process (1971, pp. 306-308). . Yona Friedman advocated a somewhat broader approach of using permutation analysis to develop "a complete set of solutions as an acceptable answer," from which the designer then eliminates potential solutions subtractively until the remaining solutions are credible and meet the requirements (Friedman, 1975, pp. 19-21). The permutation Analysis begins with a simple mathematical statement of how the Lunar Lander configuration generates permutations.

EQUATION 1 $$P = n!$$

where P = the number of possible permutations, based on the factorial of n elements, assumed to be arranged in a linear array or chain, where the first element occurs in the front or at one pole and the last element occurs at the back or at the other pole.

EQUATION 2
$$P = \frac{n!*(offset)}{(polarity)}$$

Polarity = the degree to which the permutation chain is polar. If there is a distinction between the front and the back, the polarity value = 1. If there is no distinction between the front and the back of the chain, then there is no polarity and approximately half the total possible permutations are redundant, the polarity value =2.

Offset =the number of positions that the elements can occupy along the side of the linear chain. Offset varies from .1 as the lowest credible fraction, to 1 as the default for no side positions, 2 for one side position, to 2*n for positions that can be occupied on both sides of the chain. For offsets that involve greater depth than one discretionary position in the element chain. Having established the state equation for the Lunar Lander pressurized modules configuration, the initial condition is:

EQUATION 3
$$P = \frac{5!*2(offset)}{2(polarity)} = 120$$

Equation 3 displays the characteristics of these elements in terms of which are pressurized or unpressurized.

TABLE 3. Pressurized and Unpressurized Properties of the Key Elements

Key Element	Pressurized	Unpressurized	Comment
Ascent Module (AM)	X	X*	*Unpressurized for Outpost missions and contingencies.
Airlock (AL)	X	X	Pressurized for flight, unpressurized for EVA egress
Habitation Cabin (Hab)	X		May be a separate module or part of another module.
Front Porch (FP)		X	Serves EVA crew
Vertical Separation (Vert)	X	X	May be pressurized for access to modules close to surface or an unpressurized ladder.

The next step is to articulate a series of rules that will reduce the number of admissible permutations. These rules are all negative in the sense that they seek to rule out possibilities from the equation. It can reduce the offset, the polarity, or the core permutation array. FIGURE 7 displays four options for permutations on a 3x3 cell grid. This grid represents the topology of possible adjacencies drawn as an elevation or side view of the lander. The definition of topology means that the relationship among objects located on the surface does not change whether the surface is stretched, twisted, or otherwise deformed, so long as it is not torn. This persistence of the relationships means also that the grid can represent a horizontal, vertical, bent or stretched surface. The surface itself does not have vector-directionality, but the assemblage of configuration elements may infer that directionality onto the topological surface.

These metrics impose restrictions on the universe of possible permutation topologies. The topologies in FIGURE 7 all show examples of permissible configurations in the absence of elimination rules. FIGURE 8 shows examples of two of these configurations. The Ascent Module is beige, the Habitat Module is green, and the Airlock is brown. The connective tunnels are red. It would be feasible to prepare such a drawing for each of the 120 permutations, but it is not necessary to make that effort.

Example A. AM at Distal End, AL & FP on the Surface

AM	Hab	Vert
		AL
		FP

Example B. AM at Distal End, AL, FP on top of the DM

AM	Hab	AL
		FP
		Vert

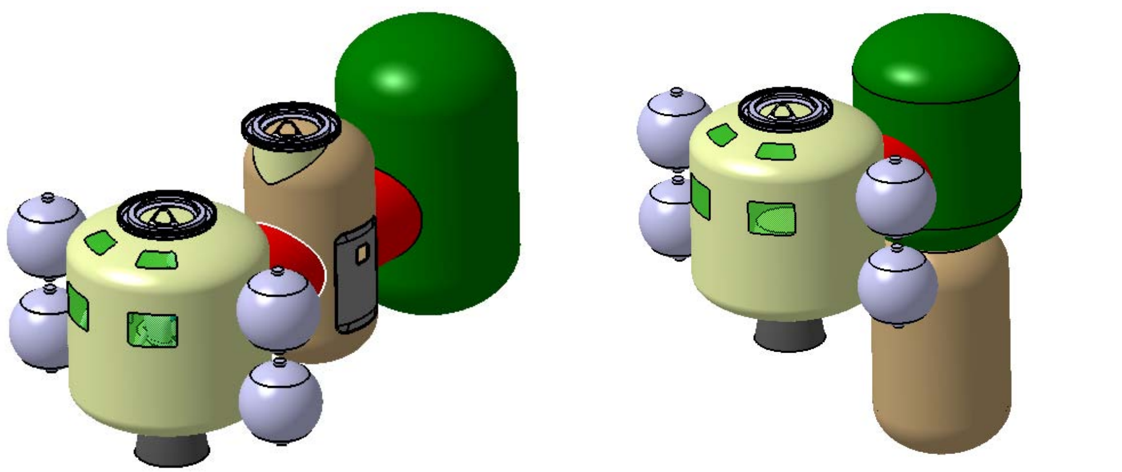
Example C. AL in the Center with two Tunnel Connectors.

AM	AL	Hab
	FP	
	Vert	

Example D. Center-Vertical Stack, AL & FP on the Surface.

AM	Vert	
	Hab	
	AL	FP

FIGURE 7. Examples A to D of the Lunar Lander Key Element Topology on the Descent Module (DM)



Example C. Airlock in the Center with Two Tunnel Connections.

Example D. Center–Vertical Stack with the Airlock close to the Surface.

FIGURE 8. Examples of Pressurized Module Configurations from the Key Element Topology. Drawing credit: Abid Ali-Khan

TABLE 4 presents the metrics from the human factors/crew productivity and crew safety FOMS. These metrics provide the guidance to reduce the permutations to a manageable number. Achieving such a *manageable number* can lead to practical conclusions about acceptable configurations that meet crew safety and crew productivity criteria.

B. Developing the Crew Productivity and Crew Safety Metrics

The two sets of criteria that apply to this study are human factors and crew safety, conveyed as Crew Productivity (CP) and the Probability of Loss of Crew (PLOC). TABLE 4 shows how these metrics map onto the Lunar Lander IVA and EVA environments.

1. Crew Productivity Figure of Merit

The main criterion for human factors is the ***Crew Productivity FOM.*** Crew Productivity (CP) means **how well the Lunar Lander system supports the crew.** The high level criteria for CP are:

- *To be effective in carrying out the mission accurately and successfully,*
- *To be efficient in performing tasks in a timely manner with reasonable use of available resources,*
- *To optimize the human suitability of the operational environment.*

The most immediate metric for crew productivity is the availability and use of **crew time in space** -- the most precious commodity in NASA's human spaceflight program. An assessment of crew time necessarily factors in the error rate as one of the primary metrics

2. Probability of Loss of Crew (PLOC) FOM (Crew Safety)

The ***Crew Safety FOM*** applies primarily to when the Lunar Lander is in flight during descent, landing, launch from the lunar surface, and rendezvous and docking with the Orion. The main impact is to ensure that the Ascent Module is able to separate from the Descent Module and its pressurized connection to the other pressurized modules. This concern for the configurations of the pressurized modules arises principally for launch from the surface and abort on descent.

CxP-70000C, the Constellation Architecture Requirements Document (CARD) states:

[Ex-0011-05] The Constellation Architecture shall limit the risk of Loss of Crew (LOC) for a Lunar Sortie mission to no greater than 1 in 100 (p. 45).

NASA's statement of the purpose of the Human System Integration Requirements, NASA CxP-70024, puts crew safety in the context of human-rating the spacecraft:

The Constellation Program must meet NASA's Agency-level human rating requirements, which are intended to ensure crew survival without permanent disability (p. 12).

The Northrop Grumman understanding of Loss of Crew (LOC) is death of or permanently debilitating injury to one or more crew members.

C. Rules and Permutations

The permutation equation can alleviate a great deal of that work. It makes it unnecessary to lay out each of the 120 permutations manually. Instead, the permutation modeling approach makes it possible to apply rules to reduce the number of layouts needed to represent the allowable configurations. Note how the permutations in FIGURE 9 do not necessarily fare as well as those in FIGURE 2, upon applying three rules derived from the crew productivity and safety FOM metrics. These rules state:

RULE 1. The AM may have no more than one parting plane, therefore Example E is invalid. This rule derives from PLOC for abort on descent and launch from the surface.

RULE 2. An unpressurized element such as the Front Porch may not interrupt the chain of pressurized elements; therefore Examples F and H are invalid. This rule derives from CP for saving crew time. It would be an unacceptable burden on the crew to spend from one to three hours to suit up to go EVA no more than five meters from the AM to the Airlock or Habitat, and then need to reverse the process to return.

RULE 3. The AM may not occur below the vertical connection to the lunar surface, therefore Example G is invalid. This rule derives from PLOC because having the AM under the DM top deck such that it needed to be moved to another position before launch from the surface could add too much complexity. It could also interfere with abort on descent.

TABLE 4. Definition of the Metrics Crew Safety and Human Factors/Crew Productivity Metrics						
FOM	**Statement of Metric**	**Type of Variable**	**Units of Measure**	**Allowable Range**	**Rule**	**Comments**
Crew Safety	Ascent Module Launch on Abort During Descent / Launch from Surface	Logical	True / False	True	Descent Module and other Structure may not obstruct AM departure trajectory	Folding the configuration for compact descent then unfolding for launch may be too complex.
Crew Safety	Minimize complexity and risk of separating the AM from the lander.	Integer	Whole number	0, 1	AM pressurized parting planes may not exceed one.	Range may expand with more reliable disconnect technology
Crew Productivity	Maximize the availability and use of crew time to perform the mission.	Logical	True / False	True	Crew may not be required to perform EVA routinely to pass from one pressurized volume to another.	Crew time is the most precious commodity in the Constellation Program
Crew Productivity	Provide minimally interrupted IVA access among the pressurized modules	Real	Day, given as a percent of time pressurized	Initially, 100%, 95 to 90% may be acceptable.	IVA circulation may not be excessively interrupted by a depressurized Airlock.	A scenario might be possible where rapid, "routine" EVA allows the Airlock to be repressurized between egress & ingress.
Crew Productivity	Provide efficient and safe access from the Ascent Module to the lunar surface and back.	Probability	Percentage	TBD	The surface ConOps may not expose the crew to the danger of falling from the Airlock or vertical circulation system.	The Lunar Lander must support safe surface operations.

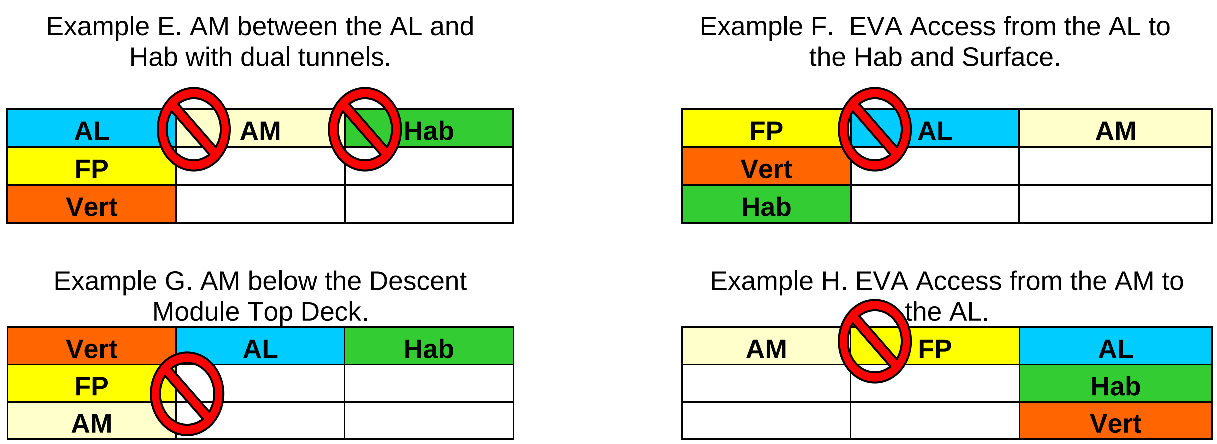


FIGURE 9. Examples E through H of the Lunar Lander Key Element Topology on the Descent Module (DM)

These rules significantly reduce the number of allowable permutations, but without going through the exposition of all 120 P, it is difficult to estimate how many options they remove from the grid. However, these three rules have another effect, which is to make the chain of permutations unipolar around the AM. These three rules imply that the AM must always be on the top of the DM deck, connected to another pressurized element. The linear chain therefore must begin with the AM. Making the chain unipolar transforms the equation:

EQUATION 4

$$P = \frac{4!*2(offset)}{1(polarity)} = 48$$

This transformation reduces P from 120 to 48, a reduction of nearly two thirds. However the three rules also eliminate some series of permutations that would involve placing the FP between any two pressurized elements, not just adjacent to the AM. Now, applying Rule 2 more completely, where v is the logic symbol for exclusive OR, the chain of permutations becomes:

EQUATION 5

$$P = 1(AM) * 3(Hab \vee AL \vee Vert) * 2(Hab \vee AL \vee Vert) * 2(AL \vee Vert \vee FP) * 1(Vert \vee FP) = 12$$

This result, 12 configurations, now becomes small enough to be manageable for systematic diagramming. The next step is to establish one more rule:

RULE 4. The FP may not occur in a branch without the AL before it.

This rule has the effect of reducing the offset allowance to 1/1.5, therefore

EQUATION 6

$$P = \frac{12}{1.5} = 8$$

Before demonstrating the final application of this algorithm, it is important to state the caveat that element position on the topological grid counts as unique only insofar as it does not replicate the sequence of another permutation. FIGURE 10 shows the eight allowable permutations for a "flyable" configuration in grids 1 through 8. Grid 9 is not a unique permutation because it is permutationally identical to Grid 8. All these grids place the AM at the front or beginning of the permutation chain, in the upper left cell. Each of these rows shows interesting features and relationships.

The top row, permutations 1 to 3, has the Hab module adjacent to the AM in all cases, with three permutations in the right column generated by variation in the order of the Airlock, Vertical connection, and the front porch. Grid 1 represents the LDAC-1 minimum functionality lander and implies the Northrop Grumman LLDS concept, with all three pressurized elements on the DM top deck, with the EVA Front Porch and an unpressurized ladder for the Vertical Connector. Grid 2 keeps the Airlock on the top deck, but varies the order of the Vertical Connector and the EVA Front Porch so that the space-suited crew would step off the ladder onto the Front Porch, from which they would deploy equipment for the mission. Grid 3 puts the Airlock and Front porch close to the lunar surface or "on it" for the easiest EVA egress and ingress. The Vertical Connector between the Habitat and the Airlock would be pressurized.

The middle row, permutations 4 to 6 uses a "center stack" in which the crew would pass through a pressurized element – either the Airlock or the Vertical Connector to reach the Habitat Module. In Grid 4, the Airlock egresses onto the Front Porch, and the crew would descend the ladder to the surface, much like Grid 1, In Grid 2, the order of the Front Porch and ladder are reversed, so that the crew descend the ladder onto the front porch, as in Grid 2. In grid 6, the Vertical Connector serves the unique role as a pressurized passage for two connections, horizontally between the Ascent Module and Habitat, and vertically between the AM/Hab and the Airlock. As in Grid 3, the Airlock and Front Porch are closest to the surface.

The bottom row, permutations 7 through 9 shows an alternative approach to vertical stacking. In both cases, the Habitat module and the Airlock are below the Descent Module top deck. In Grid 7 the pressurized Vertical Connector attaches to the Airlock. The crew must access the Habitat Module through the airlock. Grid 8 shows the alternative vertical stack, with the Habitat and Airlock below the DM deck, but the pressurized vertical connector connects to the Habitat Module. The crew enters the Airlock through the Habitat, and egresses to the surface on the Front Porch. Grid 9 shows the same permutation, the same topological sequence as Grid 8, and is included in this Figure to demonstrate how changes in position do not necessarily mean a new permutation.

1

AM	Hab	AL
		FP
		Vert

2

AM	Hab	AL
		Vert
		FP

3

AM	Hab	Vert
		AL
		FP

4

AM	AL	Hab
	FP	
	Vert	

5

AM	AL	Hab
	Vert	
	FP	

6

AM	Vert	Hab
	AL	
	FP	

7

AM	Vert	
	AL	Hab
	FP	

8

AM	Vert	
	Hab	
	AL	FP

9

AM	Vert	Hab
		AL
		FP

FIGURE 10. Array of Permutations for Lunar Lander as Grid Topologies, 1-8 being the eight unique "flyable" options.

D. Applying the Human Factors and Crew Safety FOMs to Evaluate the Flyable Configurations

The previous section applied the human factors and crew safety FOMs to create rules that reduced the universe of all possible permutations to a set of eight configurations that qualify as "flyable" configurations. It used one CP metric: not requiring EVA to pass from one pressurized module to another. FIGURE 11 revisits the topologies in FIGURE 9. It shows the elimination of the configurations that do not meet this IVA crew circulation *metric*. These three eliminated configurations are 4, 5, and 7.

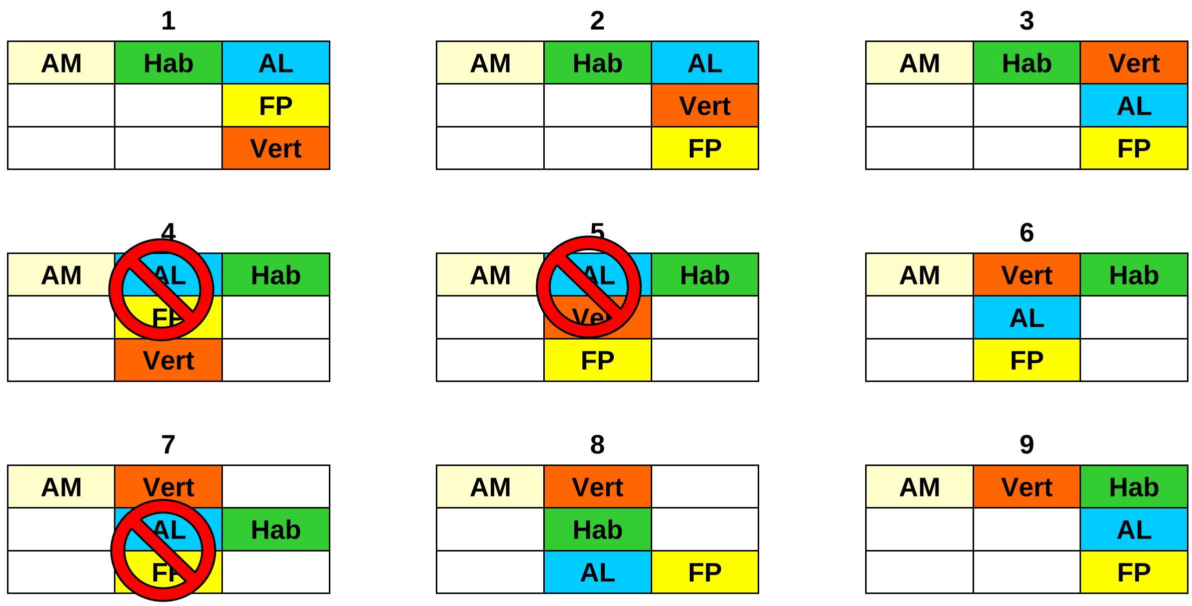


FIGURE 11. Elimination of three of the eight pressurized module connection patterns based upon the IVA circulation metric.

FIGURE 12 shows the five configurations that qualify under this application of the IVA Circulation metric. These five configurations are all viable options for the Lunar Lander,

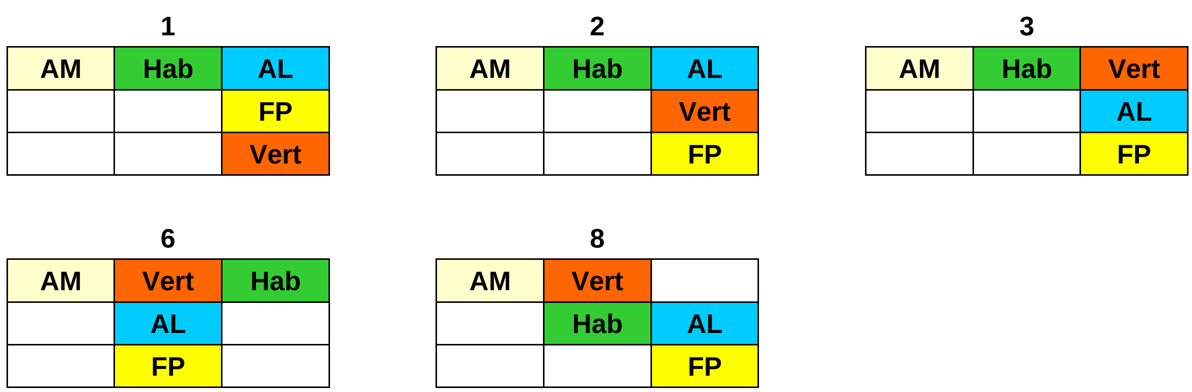


FIGURE 12. The five configurations for Lunar Lander modules that qualify under the crew productivity and safety metrics.

Having completed the permutation exercise, the next step is to apply more CP metrics as to evaluate these configurations further. This refined evaluation needs only a small number of the potential ***metrics*** for the human factors and crew safety FOMs. The essential analysis draws – at least initially -- upon just two of the metrics: IVA circulation and Safe Access to the Surface.

1. IVA Circulation Metric

The importance of IVA circulation is that the crew inside the spacecraft should be able to access all parts of the living and working environment while there is a crew outside performing an EVA. This "Lesson Learned" came from the Skylab missions. On the Apollo-Skylab missions, the pressurized volume connection sequence was:

Command Module (CM) – Multiple Docking Adapter (MDA) – EVA Airlock (A.L.) – "Saturn Orbital Workshop" (OWS)

When two crew members went EVA through the airlock, the safety protocols required the airlock to remain depressurized with the Gemini-surplus hatch open for the duration of the EVA. The third crew member would be required to retreat to the Command Module in case there was a failure in the airlock or its hatches. In that contingency, the EVA crew would enter the CM and return to Earth directly. DIAGRAM 1 illustrates this situation

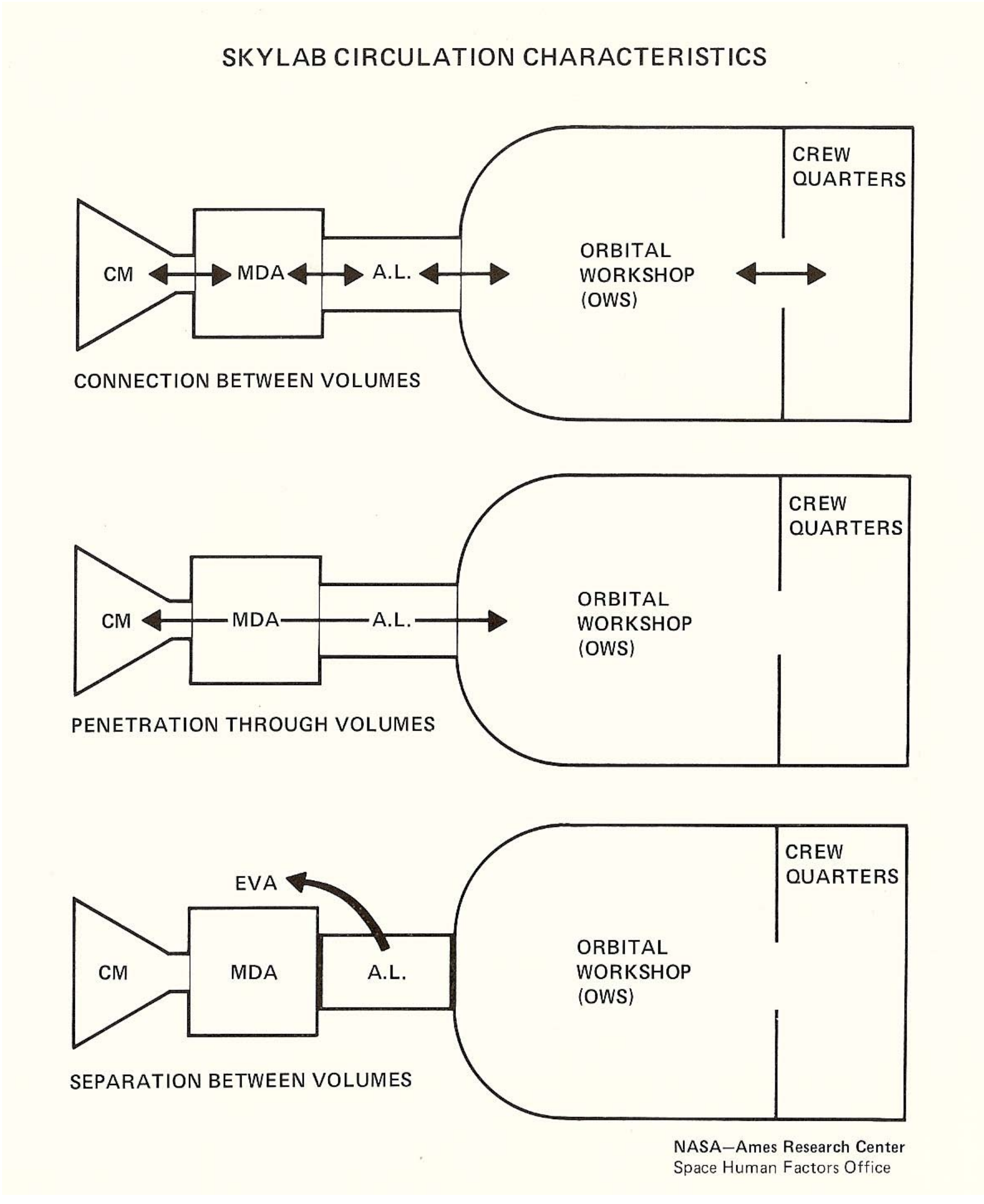


DIAGRAM 1. Arrangement of circulation volumes on Skylab (Cohen, Rosenberg 1985, page 4-16).

Essentially, the same conditions apply to the Lunar Lander; depressurizing the airlock for an EVA in a connection sequence where it cuts off circulation between the Habitat and the Ascent Module would compel the IVA crew to retreat to the AM for the duration of the EVA. Making that arrangement into a standard operating procedure would make a huge impact upon the crew's IVA productivity because they would be isolated from science and housekeeping and other tasks during their time inside.

2. Safe Access to the Surface Metric

The next Crew Productivity Metric to apply is *Safe Access to the Surface*. This metric applies particularly to trading the pressurized tunnel versus unpressurized ladder for the four to six meter Vertical Connection between the Ascent Module and the surface. Configurations 1 and 2 place the Airlock on top of the Descent Module deck, so that the crew would use the unpressurized ladder to descend to the lunar surface. Configurations 3, 6, and 8 incorporate pressurized vertical tunnels with the ladder inside. They confer the advantage of the crew being able to make the descent from the Ascent Module and the climb back up to it in a shirtsleeves environment, rather than wearing a Configuration 2 EVA suit with portable life support system (PLSS) backpack that weighs 100 to 150kg, and is quite bulky.

FIGURE 13 portrays Configuration 8 in which the Vertical Connection pressurized tunnel connects the Ascent Module to the Habitat and Airlock. In this rendering, the Habitat Cabin and Airlock are combined in a single pressurized unit. The bottom of the Airlock is only 1.4m above the lunar surface.

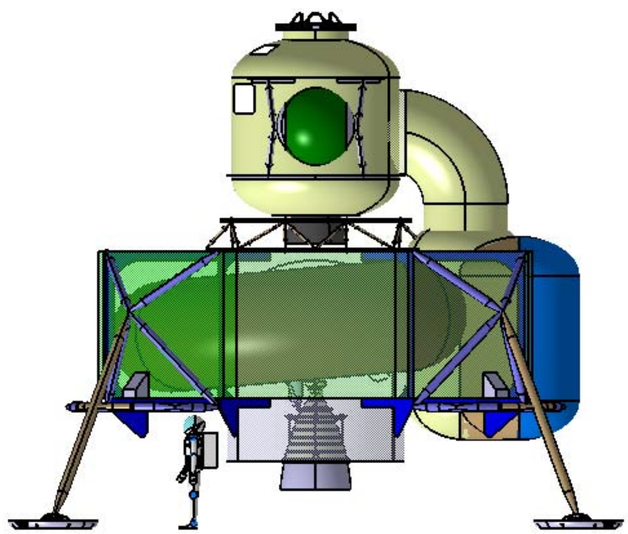


FIGURE 13. Configuration 8 with the Pressurized Tunnel Connecting the Ascent Module on the top deck to the Habitat Module below it. Drawing Credit: Abid Ali-Khan.

The purpose of the EVA Front Porch is to provide a measure of safety by placing a platform with railings outside the EVA hatch. The Front Porch gives the crew a place to step out without fear of falling to the surface and where they can stage and deploy equipment out from the airlock and back into the airlock. In the permutation analysis, there was only one Front Porch in the equation.

However, when the airlock is on the Descent Module top deck, so that there is an unpressurized descent to the surface, and the single Front Porch is at the bottom of the ladder, it leaves the *Safe Access to the Surface* metric unsatisfied. It would still be potentially hazardous to step out of the Airlock with only the top of the ladder there. The configurations 2 and 5 are the ones with this condition (but configuration 5 was already eliminated in FIGURE 9).

Here, there is an alternative to eliminating the configuration. It would be possible to add a *second* Front Porch at the top of the ladder to provide that measure of safety at the Airlock hatch. Adding this second Front Porch would add mass, of course, but perhaps not more than a few 10s of kilograms. Also, with the second Front Porch at the top of the ladder, it might be feasible to reduce the size and mass of the one at the bottom of the ladder

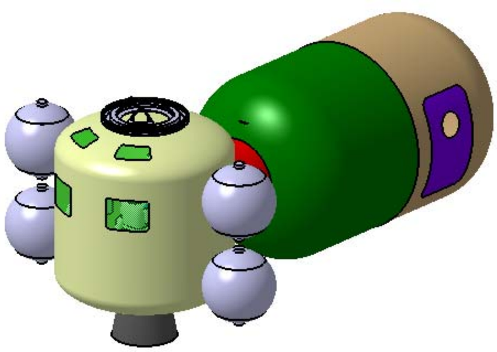
This trade involves the savings in crew time and reduction in stress to translate vertically in shirtsleeves versus in a pressure suit and the safer access it affords to the lunar surface. It must also consider the challenge to the crew of carrying equipment up and down, and hauling the scientific sample boxes up to the Ascent Module for return to earth. These activities raise substantial human performance issues from the biomedical and human factors perspectives. Eventually it will also become necessary to trade the advantages of the shirtsleeves Vertical Connection versus the mass of the tunnel; it will also be necessary to trade the mass of a second front porch versus the increase in safety it affords.

E. Combinations of Modules

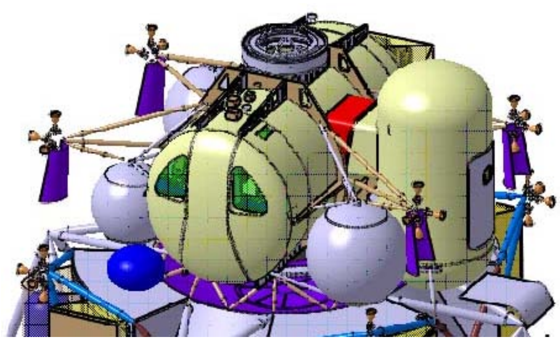
One set of alternatives involves combining the three key elements into fewer modules. These possible combinations act as a kind of overlay over the permutations based on the crew productivity and safety metrics. NASA's 2005 Exploration Systems Architecture Study report examined three such options:

A. *Separate Ascent Module, with Airlock and Habitat combined into one module*
B. *Separate Airlock, with the Ascent Module and Habitat combined into one module.*
C. *All three elements combined into a single module.*

Configurations 1, 2, and 8 in FIGURE 11 could all represent ESAS option A with the separate Ascent Module and combined Habitat cabin and Airlock. A version of this configuration appears in FIGURE 14.



a. Pressurized Module configuration based on ESAS Option A. Separate Ascent Module and Combined Habitat / Airlock.



b. Northrop Grumman 2008 Lunar Lander Development Study Configuration, topologically similar to ESAS Option B. with separate Airlock and Combined Ascent Module/Habitat.

FIGURE 14. Two Configurations that Combine Pressurized Modules. Drawing Credit Abid Ali-Khan.

FIGURE 15 shows this configuration on the Descent Module top deck. FIGURE 16 shows a transparent view of the Configurations 1, 2, and 8 interpreted as a combined Airlock and Habitat module.

Configurations 1and 2 in FIGURE 11 could both represent ESAS option B. The Northrop Grumman concept for the 2008 Lunar Lander Development Study configuration appears in FIGURE 13. It grew from adding habitation volume to the Ascent Module in NASA's 2007 LDAC-1 Altair concept. In this respect it resembles the connection pattern of the ESAS option B. FIGURE 16 shows a transparent view of the Configuration 2 combined Ascent Module and Habitat cabin.

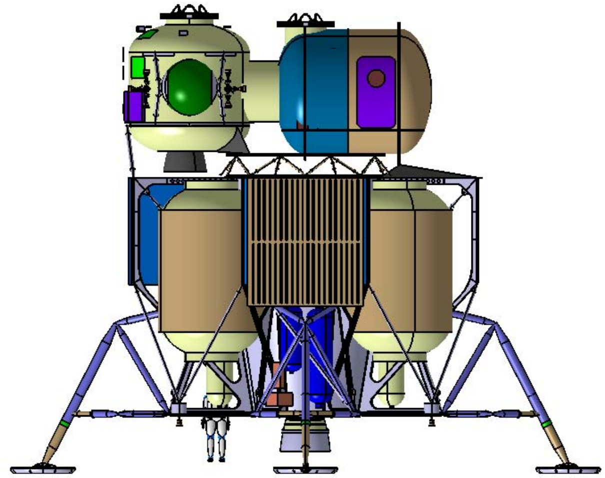


FIGURE 15. Configurations 1, 2, and 6 as Combined Airlock and Habitat Cabin with Separate Ascent Module on the Descent Module. Drawing Credit Abid Ali-Khan.

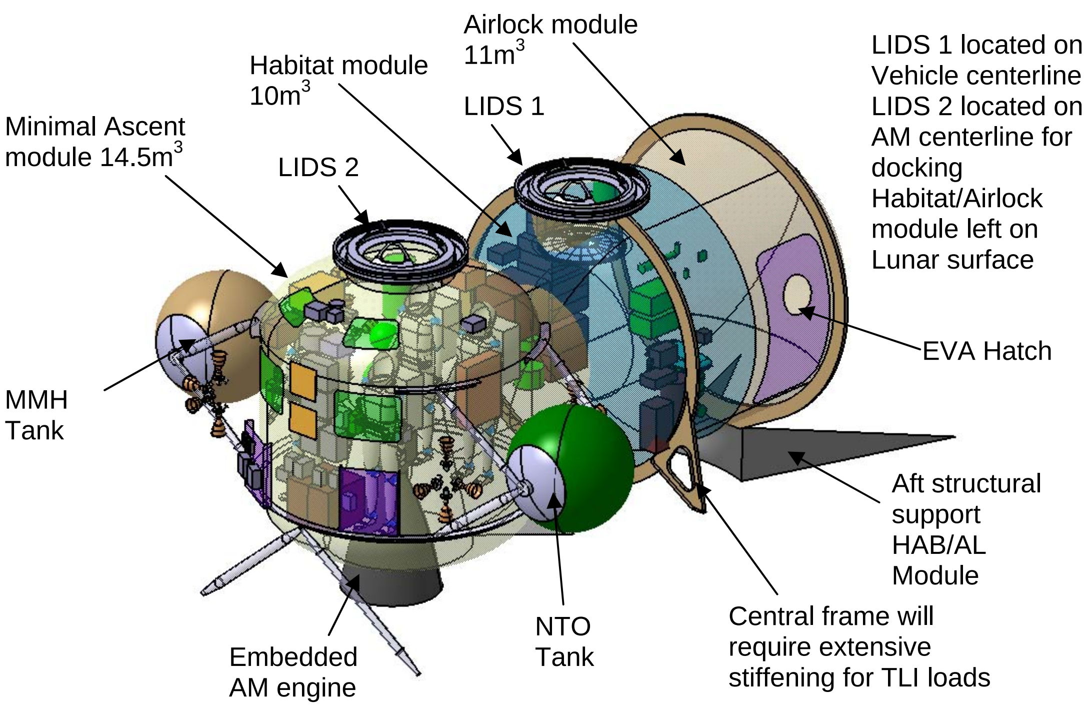


FIGURE 16. Transparent View of the Combined Habitat/Airlock and Separate Ascent Module Configuration. Drawing Credit: Abid Ali-Khan.

IV. Findings

The Findings include results for the Functional Allocation Matrix, the explication of the configurations that will accommodate those functions, the development of the crew productivity and safety metrics, and the permutation analysis that defines the universe of possible configurations. The findings show how to reduce the configurations mathematically to a manageable number, and the application of these FOMS to the permutations to identify the "flyable" configurations and finally the ones that meet the relevant CP FOMs.

A. Functional Allocation Matrix

The Functional Allocation Matrix identifies the 32 functions stated in NASA's Altair Conceptual Development Contract trade study Statement of Work, and the Constellation Program documents including the Constellation Architecture Requirements Document CxP-70000, the Human System Integration Requirements CxP-70024, and the Constellation Design Reference Missions CxP-70007. It was feasible to assign all these functions to at least one of the pressurized modules or to the Descent Module.

B. Configuration

The *TAC-0* Lunar Lander configuration subject to this analysis consists of three pressurized modules, the Ascent Module, the Airlock, and the Habitat volume or cabin. It includes three connective elements, the Low Impact Docking System, the Front Porch, and the Vertical Connection between the Ascent Module and the lunar surface. In this analysis, the LIDS proved *de minimus.* The tunnels between the pressurized modules are merely incidental to the larger configuration. The inquiry into the architectural properties of configuration was vital to understanding that the centrality of the Ascent Module does not need to dictate where all the other modules should be located. On the contrary, the recognition that centrality is a process rather than a static arrangement showed that the Lunar Lander configuration is changing over the course of the mission as it fulfills mission phases and consumes propellant and consumables.

C. Crew Safety FOM and Metrics

The analysis applied the crew safety criteria to the in-flight segment of the Lunar Lander mission, pertaining to launch from the lunar surface and abort during descent. The crew safety metrics came first in the trade and analysis process to generate the eight "flyable configurations." These metrics played an important role for flight, but did nothing to address the crew operations on the surface.

D. Human Factors Criteria and Crew Productivity FOM Metrics

The human factors criteria and their crew productivity FOM metrics proved pivotal in reducing the eight "flyable" configurations to the five most eligible for Lunar Lander. The essence of the crew productivity metric is the measure of how well the system supports the crew. Applying this metric showed plainly how the design of the configuration can help or hinder the crew in performing their mission duties.

E. Spacecraft Environment Parameters

The characteristics of Lunar Lander and its mission delineated three environments for which to develop the crew productivity and safety metrics. These three environments are the IVA working environment, the IVA living environment, and the EVA working environment. While these environments share a few common metrics such as *communications*, by and large they generate their own families of metrics.

F. Permutation Analysis

The trade study aspect of this analysis hinged upon a permutation state equation representing the configuration mathematically. As by applying the CP and PLOC to the permutation state equation, it was possible to incrementally reduce the allowable number of configurations from the initial universe of 120 down to the manageable number of eight "flyable" configurations.

G. Translating the FOMs into Rules

The way this reduction in the number of configurations occurred was by translating the particular metrics from crew productivity and crew safety into specific negative rules that would eliminate possible permutations. The crew safety metrics affected the allowable position for the Ascent Module relative to the Descent Module and the number of other pressurized modules that could connect safely to the Ascent Module. One human factor metric applied to the reduction of the permutations, that the crew should not be required to go suit up and go EVA between pressurized modules.

H. IVA Circulation Metric

The IVA Circulation metric precluded placing the Airlock in the circulation path between the Ascent Module and the Habitat, thereby ruling-out three of the eight "flyable" configurations.

I. Vertical Connection

The main issue to trade for the remaining five configurations is the Vertical Connection, and whether it should be a pressurized tunnel or an unpressurized ladder. The Lunar Lander's connection to crew safety on the lunar surface begins with the vertical connection from the Ascent Module and Habitat to the base of the lander. It would be easier and safer for the crew to make the ascent and descent of a ladder in shirtsleeves inside a pressurized tunnel than in a bulky EVA suit, gripping the rungs with thick and stiffly inflated gloves. The location of the airlock at the top or the bottom of this ladder can have far-reaching effects for crew mobility and safety on the vertical vector.

J. Front Porch

For an unpressurized ladder, a further issue arises concerning whether it might need two front porches: one on the Descent Module top deck and the other at the foot of the ladder. Both these issues involve human factors criteria and crew productivity and safety FOM metrics for safe access to the surface. Subsequently, these metrics will engage the system mass and cost criteria for the tunnel versus the ladder and one front porch versus two. In a further analysis, this question of the number of porches will feed back recursively to the number of possible permutations and flyable configurations.

V. Conclusion

This study demonstrates how the Northrop Grumman trade and analysis approach enables the rapid sorting and disposition of the possible configurations in a design universe. It shows the value of the topological approach to a rule-based method of configuration analysis using the permutation algorithm. The crew productivity and safety metrics play a central role in performing the analysis of configurations for the pressurized modules. Applying these metrics made it possible to reduce the possible permutations from a universe of 120 to a more manageable set of eight "flyable" Lunar Lander configurations. Applying the IVA Circulation metric reduced the allowable configurations from eight to five. These "final five" configurations all represent viable candidates for the Lunar Lander, and afford the basis for a new round of trade study and analysis. It will be necessary to introduce the mass and cost metrics at this stage to trade the crew productivity benefit of a pressurized Vertical Connection Tunnel or a second Front Porch for the unpressurized ladder against the corresponding burden in mass.

Acknowledgments

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