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Design Structure Matrix Approach Applied to Lunar Habitat Design

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Abstract: Lunar habitat design is a complex endeavor characterized by complicated task-composition, numerous internal iterations, and intense task-coupling. The design process of assembled building in terrestrial construction and the system composition of lunar habitats have been constructed. However, there is insufficient experience to fully understand lunar habitat design missions and likewise there is insufficient coordination between architects and various disciplines. The task flow for sequencing optimization can be determined using a design structure matrix (DSM), which is widely used in engineering. The DSM can reveal necessary interfaces within the lunar habitat system as per relevant interface variables and processes. By decomposing the lunar habitat design process, an initial activity-based DSM is established in the present study. Informational interactions between each design task and its respective intensity are statistically investigated to clarify them across the four dimensions of energy, space, materials, and information. A sequencing algorithm is applied to optimize the design process. Finally, 20 design tasks of lunar habitat design are clarified among four phases: Pre-planning, spatial design, environmental design, and optimization. Related disciplines should coordinate in the design process according to the optimization results, and use the optimized task coupling relationship to build the requirement model and design model in an orderly manner to improve the design efficiency.

Keywords: design structure matrix; lunar habitat; system engineering; architecture design

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1. Introduction

The world's aviation organizations have launched numerous deep space exploration development strategies and plans over the past several decades. The National Aeronautics and Space Administration (NASA) Deep Space Exploration Roadmap, updated in 2006, indicates the initial research on lunar outposts in 2018 [1]. The European Space Agency (ESA) "SMART" program has made scientific and technical preparations for the establishment of a lunar base [2] and conducted a series of studies on in situ construction. The "Space Development Vision" of the Japanese Aerospace Exploration Agency (JAXA) plans to establish a lunar solar research base by 2025 with international cooperation [3]. The China National Space Administration (CNSA) and Roscosmos jointly released the "International Lunar Research Station Roadmap" in 2021 [4], which describes the first phase of a lunar research station beginning in 2035.

The world's space agencies have repeatedly cooperated with architectural design institutions to launch lunar research station proposals. ESA and Foster + Partners, for example, proposed a lunar habitat concept based on an inflatable structure and lunar soil 3D printing technology in 2013 [5] (Figure 1a). Vienna established the Moon Village Association (MVA) in 2019 [6], followed by a vertical module proposal in collaboration with the Massachusetts Institute of Technology (MIT) and SOM Architects [7] (Figure 1b). In the same year, JAXA collaborated with Kajima Corporation and three universities to develop a lunar research station proposal [8] (Figure 1c). NASA, ICON Company, and BIG Architects collaborated to launch a joint Earth–Moon 3D printing proposal in 2020 [9] (Figure 1d). Lunar habitats are of interest to many academics and space-exploration organizations—as scientific research stations to explore the lunar environment and its resources, as outposts to explore other planets, and even as alternative habitats for human beings in the future.

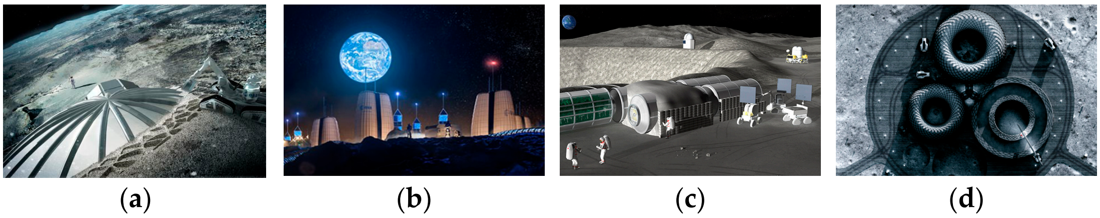


Figure 1. Lunar habitat schemes launched by architectural institutes. (**a**) Foster + Partners; (**b**) SOM; (**c**) Kajima Corporation; and (**d**) BIG.

The lunar habitat is a complex system. Its design process encompasses multiple elements and multi-disciplinary technologies (Figure 2). There is, naturally, no effective experience of the relationships between subsystems of lunar habitats; nor is the coordination between architects of various disciplines fully understood due to a lack of systematic, theoretical analysis. The lunar base built with in situ resources includes load-bearing structures, electrical distribution systems, aqueous heating systems, potable water systems, air systems, and orbital transportation systems [10]. NASA has proposed a lunar base construction process and compared it with the terrestrial construction industry, demonstrating the economic necessity of considering the full life cycle in the planning phase [11], but from a more macro perspective and without focusing on the design process. *Out of This World: The New Field of Space Architecture* by A. Scott Howe and Brent Sherwood provides a systematic discussion of the definition, types, and architectural design elements of space architecture [12]. Sandra H.M.'s *Architecture for Astronauts* provides a theoretical and methodological approach to space architecture according to functional use by astronauts [13]. In *Space Architecture Education for Engineers and Architects*, Sandra provides an overview of the decision-making approach to an entire project from both an engineering perspective and an architectural perspective [14]. In *Space Habitats and Habitability*, the human factors and habitability of work and living spaces in Antarctic research stations, ground-based simulation laboratories, manned spacecraft, and space stations are explored [15]. The engineering, physiological, and psychological aspects of the process are discussed in Haym Benaroya's *Building Habitats on the Moon* [16]. The current research on lunar habitat systems can be roughly divided into two categories: functional components and physical element composition (Table 1).

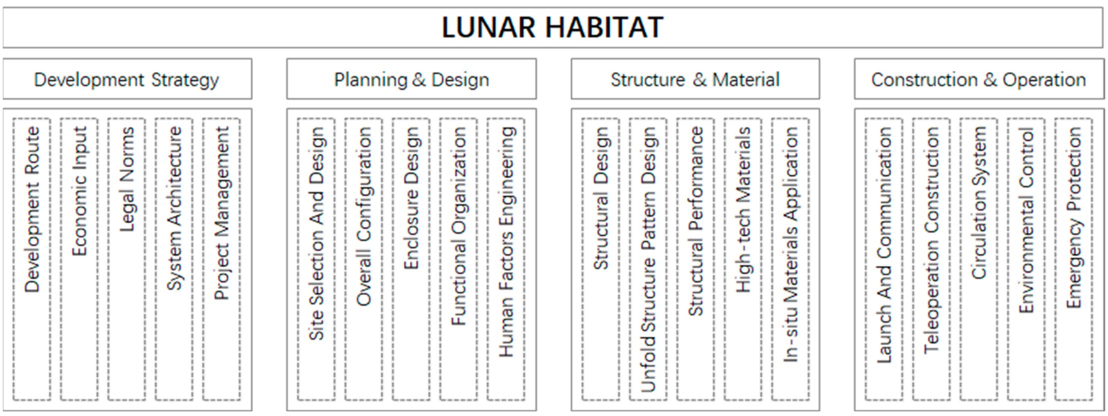


Figure 2. Lunar habitat cross-disciplinary overview.

Table 1. Composition of lunar habitat systems.

Functional Components		**Physical Element Composition**	
SLEEP	Rest Preparing for sleep Sleep Storage	RESIDENTIAL CABIN	Living, working space and facilities Agricultural cultivation Airlock cabin Evacuation space and facilities Structural systems
HYGIENE	Full and partial body-cleaning Changing clothes Toilet Storage		
FOOD	Meal preparation Serving meals Storage Planting	STORAGE FACILITY	Refrigeration materials Hazardous materials General materials Surface equipment Maintenance equipment Temporary protective structures
WORK	Operation Experiment Communication Training		
LEISURE	Exercise Rest Casual conversation	SUPPORT FACILITY	Transportation infrastructure Communication infrastructure Waste management equipment Life support equipment Electric power system Thermal systems Mobile systems Industrial processing facilities Pipelines
MEDICAL	Emergency treatment Health care Monitoring		
AUXILIARY	Energy equipment Environment control equipment Transportation Suit replacement		

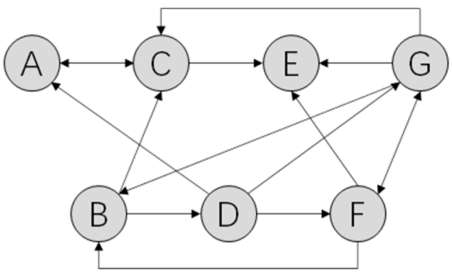
The systematic characteristics of the lunar habitat include four main components.

(1) Multiple objectives: The initial stage of constructing the lunar habitat involves scientific exploration and resource exploitation across various scientific and engineering objectives (e.g., geological exploration, space environment exploration, in situ resource utilization). The objectives at the advanced stage involve the construction of communities and cities.
(2) Multiple subjects: Experts in aerospace engineering, structural engineering, environmental engineering, human-factor engineering, materials, energy, and other fields and from various professions and institutions must interact across the whole life cycle of the project.
(3) Multiple constraints: At the macro level, aerospace engineering as a whole is constrained by the policy context. At the meso level, technological development supports the construction of the lunar habitat. At the micro level, environmental and human factors of architectural design affect various spatial components of the project. There are contradictory constraints at each level.
(4) Multiple development stages: The lunar habitat design research process includes the stages of demand clarification, scheme design, materialization and manufacturing, testing, and optimization in the decision-making stage. No stage is completely linear.

Per the above, the lunar habitat is a typical system-engineering project. Although existing studies have been summarized in terms of functional composition, the mode of cooperation among various disciplines is still unclear, and the main problem is that the system design process cannot be sorted out for complex coupling patterns if it is judged only based on terrestrial experience. Therefore, in order to improve the efficiency of lunar architectural design and reduce the time and economic loss caused by rework iterations, the design process needs to be defined and needs to be further optimized. In this study, we developed a design structure matrix (also referred to as a "dependency structure matrix") to explore the coupling relationships among subsystems and to smooth the sequential design task flow optimization. The design structure matrix (DSM) is a model-based system engineering tool that can clearly display dependencies between elements in various domains (e.g., product, organization, process) in the development of a complex project. The importance of model-based systems engineering (MBSE) has grown significantly in various industries and academia in recent years. The International Council on Systems Engineering (INCOSE) has defined MBSE as a key element of systems engineering.

2. DSM Concept

The DSM uses an n-order square matrix to show interactions among elements, which is conducive to the visual analysis of a complex project. The DSM shown in Figure 3b reveals dependencies between units in Figure 3a, with diagonal lines indicating units (components, teams, processes) and non-diagonal markers indicating the relationships between the corresponding units.



(a)

	A	B	C	D	E	F	G
A	A		X	X			
B		B				X	X
C	X	X	C				X
D		X		D			
E			X		E	X	X
F				X		F	X
G				X		X	G

(b)

	B	D	F	G	A	C	E
B	B		X	X			
D	X	D					
F		X	F	X			
G		X	X	G			
A		X			A	X	
C	X			X	X	C	
E			X	X		X	E

(c)

Figure 3. Design unit conversion to DSM. (**a**) Relationship between units; (**b**) initial DSM; and (**c**) optimized DSM.

There are two types of markers in the DSM: Boolean, which indicate the presence or absence of a relationship; and numeric, which indicate the strength of a relationship by the size of a number. The numerical type is more precise. Keeney [17] used weak, medium, and strong levels for subjective scoring. Pimmler and Eppinger [18] defined the dependence intensity of each unit in a DSM according to space dependence, energy dependence, material dependence, and information dependence; the value of each interface in the matrix was obtained by summing the values from the four interactions. The advantage of this method is that it is easy to weight the total dependence values and to make the origins of the dependencies between cells clear to research and development (R&D) personnel. DSM (I, j) denotes the values of the i-th row and j-th column in the matrix. The matrix is subsequently optimized via an algorithm to increase the efficiency of the R&D process (Figure 3c).

Complex projects modeled with a DSM consist of a corresponding "system architecture", which refers to the structure of the system including its constituent elements, interactions between elements, interactions between elements and the system environment, and the design and evolutionary mechanisms that enhance the system's functionality and behavior [19]. The system architecture of a project can fall into four categories.

(1) Product architecture, which refers to the components and their interactions in the physical space and is based on components and/or subsystems and their relationships;
(2) Organization architecture, which refers to people (or teams) and their interactions within the structure;
(3) Process architecture, which refers to individual activities, interactions between activities, information flow, and other dependencies;

(4) Parameter architecture, which refers to less temporal correlations than processes and models low-level relationships between design decisions and parameters, sets of equations, subroutine parameter exchanges, etc.

The four types of architecture can be static or dynamic. Various analysis algorithms are available for matrix optimization. The static DSM contains system units that do not change over time and are mainly analyzed using clustering algorithms. The dynamic DSM contains elements that are time-ordered and have interdependent feedforward and feedback relationships between the execution of upstream and downstream tasks. It is mainly analyzed using sequencing methods such as partitioning, tearing, banding, simulation, and eigenvalue analysis (Table 2).

Table 2. Analysis of DSM types.

Main	Secondary	Optimization Algorithm
Static (not time-dependent)	Component-based DSM	Clustering
	Team-based DSM	
Dynamic (time-dependent)	Activity-based DSM	Sequencing
	Parameter-based DSM	

The DSM has already been applied in the aerospace engineering context. Tullis and Bied [20] investigated the frequency with which crew members switch from performing one function to another, as well as the equipment supporting each function. After formulating their matrix, the associations between functional tasks and between devices were measured using hierarchical clustering and multidimensional scaling. S. Austin et al. [21] used a data flow diagram (DFD) to optimize the architectural design process and reduce the difficulty of communication between parties after converting the diagram into matrix form and reordering to group and minimize iterations. Brady [22] added operational phases to the interface DSM, then added technical risk factors to the technical-risk DSM. Two projects in NASA's Discovery Program (NEAR and Mars Pathfinder) were analyzed and compared as case studies to validate this pattern of independent subsystems using highly separated development activities; the model served to identify essential components and assist the team in risk assessment. NASA's Goddard Space Flight Center (GSFC) used integrated concurrent engineering to reveal the five phases of a design process, the interrelationships between disciplines in the design team, and a set of initial assumptions that could be made to facilitate a highly structured approach to the complex, iterative space-system design process [23]. Additionally, in isolated, confined, and extreme (ICE) environments for limited space design, DSM is used for ship cabin design to enhance the design efficiency of the modular system [24]. In terrestrial construction, an assembly building construction was built with risk communication, rework probability and core tasks with the goal of minimizing the cost and time [25]. The relationship between activities in post-disaster reconstruction was decomposed through the hierarchical work of the project process [26].

3. DSM Approach within Lunar Habitat Design

The development and evolution of complex systems typically encompasses multiple disciplinary fields and are highly iterative in nature. This is indeed the case for lunar habitat design activities. Complex correlations and coupling between different system components and activities involve the physical principles of the space environment, various interfaces, and numerous working relationships. As lunar habitat design phases progress, the overall design requirements involve a number of key performance parameters. The steps of the lunar habitat design process were modeled here as a DSM. This allowed us to clarify the informational interactions among various design elements, thus reducing their intensity at different stages of the process via computational optimization. The research technological roadmap is shown in Figure 4.

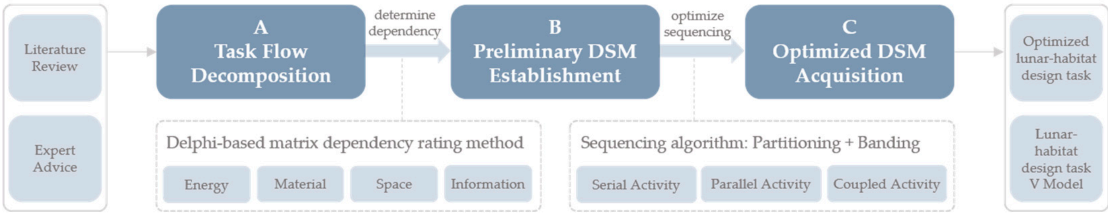


Figure 4. The research technological roadmap.

3.1. Initial Activity-Based DSM Establishment

The steps in the design of the lunar habitat system align with the dynamic DSM model. The prefabrication and construction of lunar habitat elements can be modified as per the process of constructing in situ assembled buildings. This includes a design-tasking phase in which the scale, construction requirements, and other issues are determined. A preliminary design phase serves to determine the form, function, and structure of the project. A deepening design phase concretizes the preliminary design and yields detailed site plans. The whole process of production, transportation, and construction of the structures is outlined in the building disassembly design phase. Adjustments during the actual construction process are planned in the design completion phase.

The theory of lunar habitat design is not yet fully developed; there is no perfect model description of the system. The decomposition of the system into subsystems and elements under the subsystems relies mainly on the collation of reference information and the experience of experts. The pre-planning phase provides a detailed understanding of the mission requirements and issues such as site selection, whether the structures are movable, and whether modular combinations are appropriate. In the overall design phase, the function of the lunar habitat and its organizational model are determined; the form is designed and materials are selected for the envelope. The functional (spatial) design phase proceeds. Finally, in the optimization stage, digital and physical models are created to simulate the environment, construction process, and operation and maintenance of the structure.

By refining and integrating the above design process, we decomposed the whole design process into 20 tasks (Table 3), which can be ranked to construct the lunar-habitat DSM. Each stage contains different design tasks, which are associated with different architectural elements; there is a large amount of informational output and feedback between them. For example, the design of the form influences the choice of structure. The design of the scale and form of the interior space influences the overall configuration. The choice of site influences the interior environment and the choice of construction materials. If the design process is not planned in an integrated manner, irreconcilable conflicts between various disciplines and design activities will emerge throughout the service life of the habitat.

Table 3. Breakdown of lunar habitat design tasks.

Phase	Design Tasks
Pre-planning phase	Task definition, siting analysis, mobility determination, module connection pattern determination
Overall design phase	Functional definition, functional organization, form design, structural selection, envelope design
Spatial design phase	Scale determination, form determination, interface design, facility design, equipment design, physical system design, physical environment creation
Optimization phase	Model building, environmental simulation, construction simulation, performance simulation

3.2. Dependencies between Determined Elements

The DSM can visualize interactions among design elements and quantitatively reflect the intensity of informational interactions between elements, thus providing data support for clustering calculation. Here, we use Pimmler and Eppinger's [18] method of determining the matrix correlation according to the relationship between space, energy, materials, and information.

Energy dependency in the lunar habitat refers to the need for energy transfer between two elements (e.g., equipment providing energy for the creation of the physical environment). Spatial dependency refers to the adjacency or direction between two elements in the physical space with a need for material exchange between two elements. Under material dependency, for example, the site itself provides the basis for the choice of envelope materials. Information dependency refers to the need for information or signal exchange between two elements, for example, where the site provides the preliminary information for designing the form. These dependencies are mostly unidirectional, so the matrix is not a top-down, symmetrical structure. When scoring each dependency, there are only two options: 0 (no dependency) and 1 (dependency).

After determining the dependency assessment criteria, a group decision method needs to be selected. The face-to-face meeting (FTF), in which participants discuss the outcome in an interactive manner, tends to swiftly yield agreed-upon decisions but may not provide the utmost fairness and objectivity due to herd mentality, halo effect, or other problems. The nominal group technique (NGT) is a method of qualitative analysis that involves controlled communication. Each participant first establishes an uncommunicated, independent opinion, which is then broadcast alongside those of others before a decision is made, which preserves the exchange of opinions and the autonomy of each decision-maker.

The Delphi method is a highly structured decision-making method that is anonymous, independent, and suitable for planning and forecasting even when informational resources are scarce and where there are many influencing factors. Jukrin Moon [27] proposed a complex system-matrix-building method using group decision-making techniques. First, the matrix is defined; experts are selected, initial research is conducted, elements to-be-discussed are screened, opinions are exchanged, and elements are re-screened before obtaining the final matrix.

We used a Delphi-based matrix dependency rating method to establish a DSM based on the four dimensions of space, energy, materials, and information. After establishing the initial matrix framework, eight experts in the fields of lunar base energy research, in situ construction research, extreme climate building design research, and assembly building design research were recruited for further assistance. The experts were first informed of the purpose of the scoring process and given a demonstration of how the questionnaire would function. The questionnaires were then distributed to the experts and collected upon completion. Per the Boolean strength type, more than half of the experts rated the items as having dependency (1) and less than half as having no dependency (0). The final strength of the links between the design elements in the lunar habitat design process matrix was determined accordingly (Figure 5).

The relationship between the four dimensions of energy, space, materials, and information can be seen in the initial DSM. The tasks are linked from the highest to lowest degree of information dependence (orange, n = 88), space dependence (green, n = 73), energy dependence (yellow, n = 14), and material dependence (blue, n = 10). Pre-planning and post-optimization provide informational feedforward and feedback to the lunar-habitat design, so information dependency is mainly concentrated in the pre-planning (A) and optimized (D) designs. Spatial dependence, energy dependence, and material dependence are mainly concentrated in A, overall (B), and spatial (C) designs.

The spatial level covers three exercising and receiving parties of spatial dependence. At the energy level, exercising parties include A, B, and C; the receivers are mainly C. Site selection, function, envelope structure, scale, facilities, equipment, and the physical environment are the main constraints. Facilities, equipment, material systems, and the physical environment are the objects of action. At the material level, the imposing parties are A, B, and C, while the receiving party is mainly B. The constraints are mainly based on site selection, function, structure, scale, and equipment, while the objects of action are form, structure, envelope, and the material system.

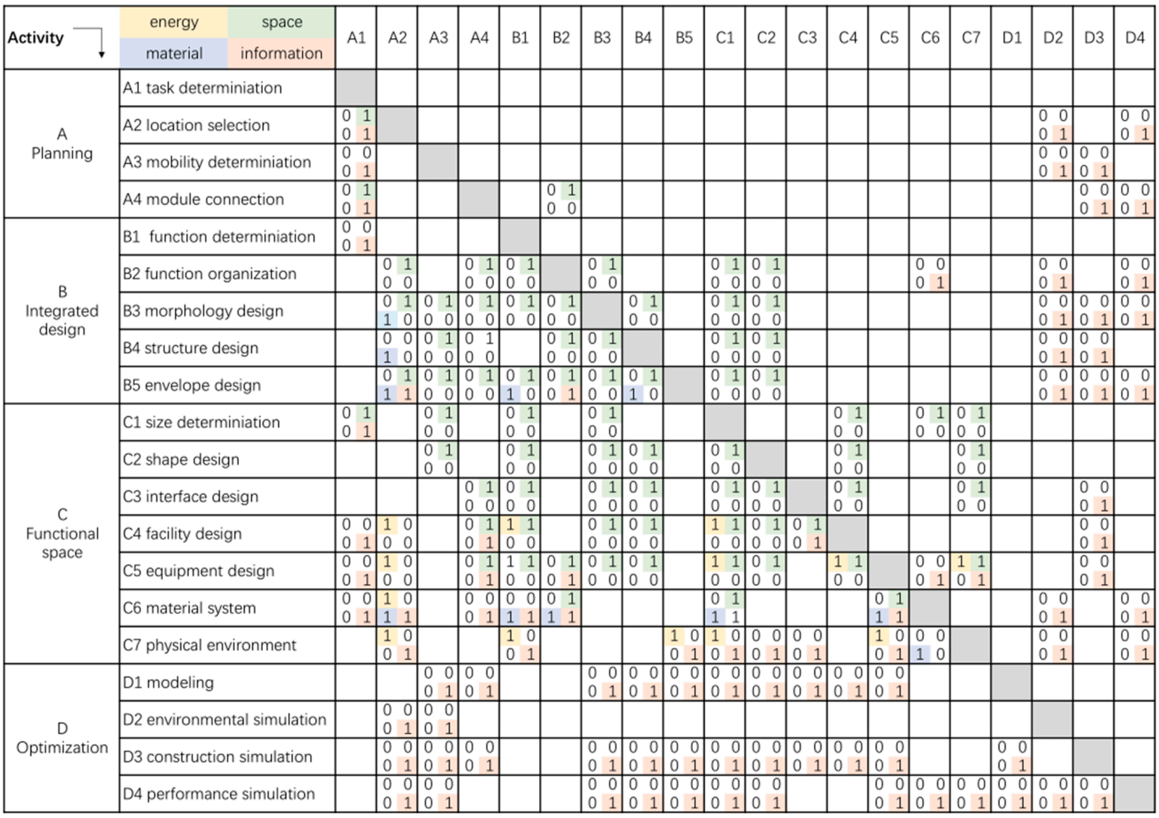


Figure 5. Initial activity-based DSM.

3.3. DSM Optimization

The dynamic DSM optimization serves to reduce iterations and rework by reordering activities to push feedback markers toward the lower left corner of the matrix (diagonal), or to block diagonalization. Objective functions include minimizing the amount of feedback in the DSM [28], minimizing the feedback length [29], and reducing the total project iteration time [30] to optimize the total project coordination cost. Optimization methods include the path searching method, powers of the adjacency matrix method, reachability matrix method, triangularization algorithm, and depth first search algorithm, all of which sort and group tasks to minimize iterations. Within each grouping, serial activities represent a sequential forward process; parallel activities represent an independent parallel process with no dependencies and coupled activities represent an interactive, feedforward- and feedback-dependent process [31].

The DSM of the lunar-habitat design process is first ordered according to partitioning, resulting in three main phases. The first process is mission definition, which is carried out independently and requires the definition of mission objectives (planetary exploration, resource exploitation, future travel or habitation) as well as the number of days and personnel necessary to initiate the design process. The second phase is the determination of functions, which can only be carried out once the functions required for the lunar habitat (e.g., living, research) are clearly defined. The third phase contains a large number of design tasks and is a more complex, coupled system. The third phase does not guide the sequencing of design tasks effectively on its first run, so the tasks are secondarily sequenced via banding.

The four tasks of site analysis, functional organization, module connection design, and mobility determination are carried out sequentially, unlike the first and second processes where task and function determination form a pre-planning phase. The next five tasks, in order, are form design, scale determination, structural selection, spatial form determination, and facility design, together forming a spatial design phase. The next six tasks define the environmental design phase, starting with interface design and physical system design (which are parallel and can be carried out simultaneously) followed by equipment design, then environmental simulation, envelope design, and physical environment design.

The final three tasks of model building, construction simulation, and performance simulation can be redefined in this order as the optimized design phase. Environmental simulation takes place in the previous phase, which provides informational feedback to the previous phase and thus needs to be carried out before the rest of the simulation process (Figure 6). The optimization phase thus has roughly four stages: pre-planning, spatial design, environmental design, and optimization design, each with a specific sequence of tasks (Figure 7). The results of the DSM optimization combined with the V model can form a theoretical model of the lunar architectural design task as shown in Figure 8.

	A1	B1	B2	A2	A4	B3	A3	B4	C1	C2	C4	C3	C6	C5	C7	B5	D2	D3	D1	D4
A1 task determiniation																				
B1 function determiniation	1																			
B2 function organization		1		1	1	1			1	1			1				1			1
A2 location	1																1			1
A4 module connection	1		1															1		1
B3 morphology design		1	1	1	1		1	1	1	1							1	1		1
A3 mobility	1																1	1		
B4 structure design			1	1	1	1	1		1	1							1	1		
C1 size determiniation	1	1				1	1				1		1		1					
C2 shape design		1				1	1	1	1		1				1					
C4 facility design	1	1		1	1	1		1	1	1		1						1		
C3 interface design		1			1	1		1	1	1	1				1			1		
C6 material system	1	1	1	1	1				1					1			1			1
C5 equipment design	1	1	1	1	1	1		1	1	1	1		1		1			1		
C7 physical environment		1		1					1	1		1	1	1		1	1			1
B5 envelope design		1	1	1	1	1	1	1	1	1							1	1		1
D2 environmental simulation				1			1													
D3 construction simulation				1	1	1	1	1	1	1	1	1		1		1			1	
D1 modeling					1	1	1	1	1	1	1	1		1		1				
D4 performance simulation				1		1	1	1	1	1			1	1	1	1	1	1	1	

Figure 6. Optimized activity-based DSM.

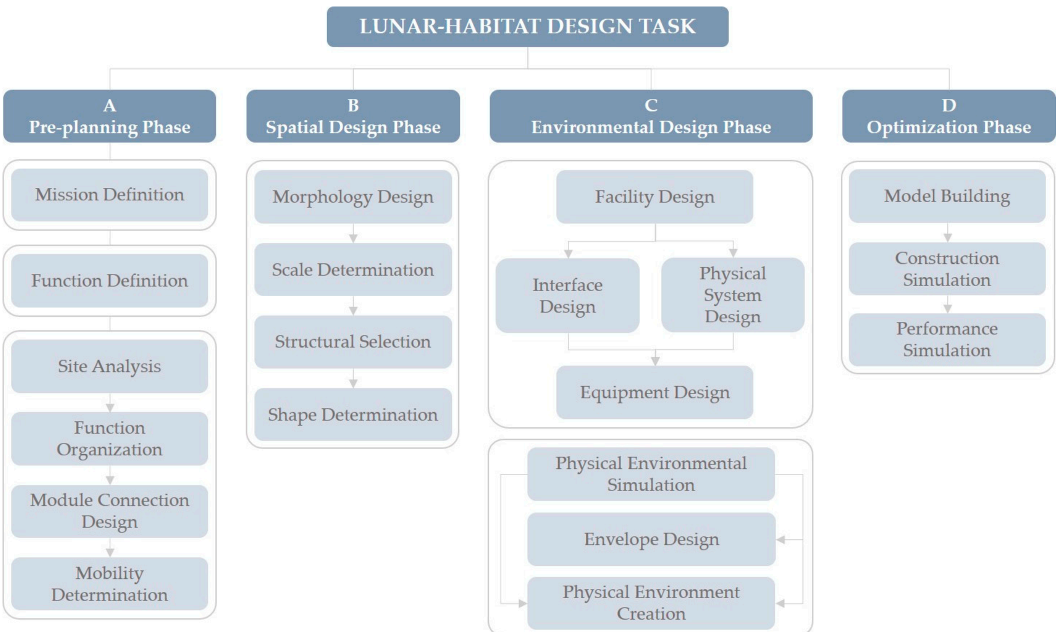


Figure 7. Optimized lunar-habitat design task.

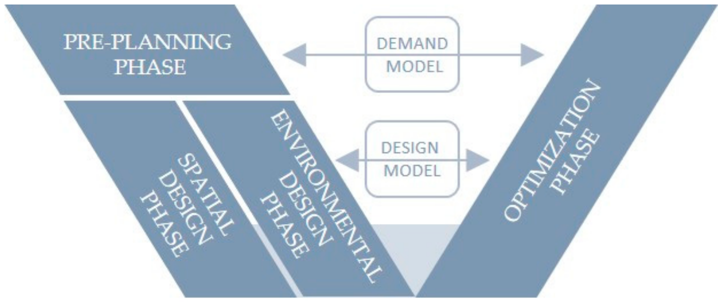


Figure 8. Lunar-habitat design task V Model.

4. Discussion

Lunar-habitat design is a novel endeavor for architects and aerospace engineers. The functional and physical components of a lunar habitat system can be summarized based on previous research, but the system design process differs significantly from the traditional architectural design model. An efficient and clear design process has yet to be established. This paper proposes the following solutions for complex lunar-habitat design projects, which have many internal iterations and intense task-coupling characteristics.

First, a DSM is constructed to express the task flow. Project tasks are decoupled and inter-task dependencies across the four dimensions of energy, space, materials, and information are derived. Informational dependency is higher than spatial dependency, energy dependency, or material dependency. The lower triangle of the matrix reflects the overall feedback of the project tasks. Engineers and designers can use the DSM to identify tasks with a high amount of feedback. They can also follow the matrix to identify in which dimension of the task is there feedforward or feedback to the tasks before and after the present stage.

The feedback/feedforward mechanism of each degree of the 20 design tasks in different dimensions is used as a basis for optimization, which proceeds via a ranking algorithm. The pre-planning, spatial design, environmental design, and optimization design phases include internal design tasks that are serial, parallel, and coupled. Re-ordering the design flow minimizes the coupling of design tasks for enhanced efficiency.

The lunar habitat design process is similar to that of some architectural structures in terrestrial construction, but each stage of the process does markedly differ. In the pre-planning phase, mission and functional definitions are fundamental tasks; the number of days, number of personnel, and goals of the lunar presence must be determined before subsequent design work can continue. Site analysis determines the materials and energy sources to be used. Determination of the modular connection pattern and whether the building is movable (or partially movable) also influences the further spatial and environmental design.

In the spatial design phase, the form and structure are reliant on in situ materials and construction techniques. The process is similar to that of an in situ-assembled building, but the form, materials, and techniques of the lunar environment differ entirely from those of Earth. In the environmental design phase, the internal environment of the lunar habitat—which must support normal human physiological indicators in isolated, confined, and extreme conditions, as well as psychological health in a small space with long-term isolation—must be taken into account. The design of the environment is more challenging than Earth-based, in situ projects and has a direct impact on the health of its occupants. Building Information Modeling (BIM) on the ground can be used to gain experience with lunar habitats, but computer simulations must be carried out in a specific physical environment engine rather than the Earth environment.

The proposed DSM is not without limitations. The lunar habitat is highly systematic and its functional composition was simplified here. In reality, the design of living, research, and auxiliary spaces would be split into different tasks, which would be coupled differently in the spatial, material, and energy dimensions. This study involved sequencing based on an extremely simplified process; the tasks in an actual project would consist of more detailed subtasks that could be further refined. Further, multiple optimization methods can be compared in the future. The sequencing methods applied in this study are partitioning and banding, which are relatively basic. In practice, functions could be constructed with specific optimization objectives (e.g., cost, time) where genetic algorithms may provide more targeted optimization.

5. Conclusions

Based on previous reports of in situ assembly building design, we decomposed lunar habitat design tasks and clarified various construction goals and tasks in a new environment in this study. Experts assisted in determining the coupling between each task across the four dimensions of energy, space, materials, and information. We established an activity DSM and obtained the dimensions in which each task feeds forward and back with other tasks. The DSM was sequenced and optimized to optimize the design process over four phases: Pre-planning, spatial design, environmental design, and optimization with 20 tasks within them.

This work may contribute to continued lunar-habitat design and construction research, as we clarified lunar-habitat design tasks, improved design efficiency by reducing coupling, and expanded the boundaries of architectural research. The introduction of the DSM into the architectural design context may provide insights into the design of buildings in terrestrial construction. For buildings in extreme environments, for example, the dependence of individual design tasks across space, energy, materials, and information dimensions is relevant. In areas where transport is not well-developed, structural selection and envelope design are dependent on local materials [32]; in areas with harsh climates, spatial and environmental design are dependent on the local climate [33].

Additionally, DSM usage can effectively optimize design processes for assembled buildings in accordance with established cost targets [34]. In this study, the objective function is chosen to be relatively simple because it is at the early stage of lunar habitat design development. In the future, lunar-habitat designers can refine and perfect the activity-based DSM and develop optimization targets under specific functional relationships such as time and cost. In addition, since a lunar habitat is a complex system with a large number of components, the component-based DSM can be further refined based on the composition and process summarized in this paper, and since a lunar habitat is a multi-disciplinary cooperation process, the multidisciplinary division of labor can be refined to build the team-based DSM. On this basis, the above two DSMs can be combined with the activity-based DSM in this study to establish a domain mapping matrix (DMM) and a multiple-domain matrix (MDM), so as to build a more complete lunar-habitat design system.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Constellation Program Overview. Available online: https://www.nasa.gov/pdf/163092main_constellation_program_overview.pdf (accessed on 1 May 2013).
2. Foing, B.H.; Racca, G.D.; Marini, A.; Evrard, E.; Stagnaro, L.; Almeida, M.; Koschny, D.; Frew, D.J.; Zender, J.; Heather, J.P.; et al. SMART-1 mission to the moon: Status, first results and goals. *Adv. Space Res.* **2006**, *37*, 6–13. [CrossRef]
3. Moon and Planetary Exploration in JAXA. Available online: https://www.nasa.gov/pdf/164272main_2nd_exp_conf_12_InternationalExplorationPerspective_KMatsumoto.pdf (accessed on 5 December 2006).
4. Partner Guide for International Lunar Research Station. Available online: http://www.cnsa.gov.cn/n6758823/n6758838/c6812147/content.html (accessed on 6 June 2021).
5. Cesaretti, G.; Dini, E.; Kestelier, X.D.; Colla, V.; Pambaguian, L. Building components for an outpost on the Lunar soil by means of a novel 3D printing technology. *Acta Astronaut.* **2014**, *93*, 430–450. [CrossRef]

6. Sherwood, B. Space Architecture for Moon Village. *Acta Astronaut.* **2017**, *139*, 396–406. [CrossRef]
7. Inocente, D.; Koop, C.; Petrov, G.I.; Hoffman, J.A.; Sumini, V.; Makaya, D.A.; Arnhof, M.; Lakk, H.; Lamaze, B.; Cowley, D.A.; et al. Master Planning and Space Architecture for a Moon Village. In Proceedings of the 70th International Astronautical Congress, Washington, DC, USA, 21 October 2019.
8. The JAXA Space Exploration Innovation Hub Center Co-Produces Results on Remote and Automatic Control to Build Lunar Base. Available online: https://global.jaxa.jp/press/2019/03/20190328a.html (accessed on 28 March 2019).
9. ICON Receives Funding from NASA and Launches "PROJECT OLYMPUS" to Reach for the Stars with Off-World Construction System for the Moon. Available online: https://www.iconbuild.com/updates/icon-receives-funding-from-nasa-and-launches-project-olympus (accessed on 1 October 2020).
10. Ellery, A. Leveraging in situ resources for lunar base construction. *Can. J. Civ. Eng.* **2021**, *49*, 657–674. [CrossRef]
11. Lunar Mega Project: Processes, Work Flow and Terminology of the Terrestrial Construction Industry versus the Space Industry. Available online: https://ntrs.nasa.gov/api/citations/20200002898/downloads/20200002898.pdf (accessed on 22 April 2020).
12. Howe, A.S.; Sherwood, B. *Out of This World: The New Field of Space Architecture*; American Institute of Aeronautics and Astronautics: Reston, VA, USA, 2009; pp. 205–224.
13. Sandra, H.M. *Architecture for Astronauts—An Activity based Approach*; Springer: Berlin, Germany, 2011; pp. 6–11.
14. Sandra, H.M. *Space Architecture Education for Engineers and Architects*; Springer: Berlin, Germany, 2016; pp. 9–48.
15. Sandra, H.M. *Space Habitats and Habitability*; Springer: Berlin, Germany, 2021; pp. 77–128.
16. Benaroya, H. *Building Habitats on the Moon*; Springer: Berlin, Germany, 2018; pp. 299–300.
17. Keeney, R. Value-focused thinking: Identifying decision opportunities and creating alternatives. *Eur. J. Oper. Res.* **1997**, *92*, 537–549. [CrossRef]
18. Pimmler, T.U.; Eppinger, S.D. Integration Analysis of Product Decompositions. In Proceedings of the ASME 1994 Design Technical Conferences, Minneapolis, MN, USA, 11 September 1994.
19. Eppinger, S.D.; Browning, T.R. *Design Structure Matrix Methods and Applications*; MIT Press: Cambridge, MA, USA, 2012; pp. 2–6.
20. Space Station Functional Relationships Analysis Final Technical Report (NASA-CR-177497). Available online: https://ntrs.nasa.gov/api/citations/19890008636/downloads/19890008636.pdf (accessed on 1 August 1988).
21. Austin, S.; Baldwin, A.N.; Newton, A. A Data Flow Model to Plan and Manage the Building Design Process. *J. Eng. Des.* **1996**, *7*, 3–25. [CrossRef]
22. Brady, T.K. Utilization of Dependency Structure Matrix Analysis to Assess Complex Project Designs. In Proceedings of the ASME 2002 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Montreal, QC, Canada, 29 September–2 October 2002.
23. Avnet, M.S.; Weigel, A.L. An application of the Design Structure Matrix to Integrated Concurrent Engineering. *Acta Astronaut.* **2010**, *66*, 937–949. [CrossRef]
24. Gunawan, G.; Yanuar, Y.; Waskita, F.A.; Kurniawan, A. Modularization of Ship Engine Room Using Design Structure Matrix (DSM) Based on The Genetic Algorithm. *Eng. J.* **2020**, *24*, 205–216. [CrossRef]
25. Shen, K.C.; Li, X.D.; Cao, X.Y.; Zhang, Z.H. Prefabricated Construction Process Optimization Based on Rework Risk. *J. Constr. Eng. Manag.* **2022**, *148*, 04022031. [CrossRef]
26. Hong, T.; Zhong, Q.P.; Chen, C. Process optimization for post disaster reconstruction project based on industrial design structure matrix (DSM). *Soft Comput.* **2021**, *26*, 8731–8743.
27. Moon, J.; Lee, D.; Lee, T.; Ahn, J.; Shin, J.; Yoon, K.; Choi, D. Group Decision Procedure to Model the Dependency Structure of Complex Systems: Framework and Case Study for Critical Infrastructures. *Syst. Eng.* **2015**, *18*, 323–338. [CrossRef]
28. Zummo, K.J. A Methodology for the Integration of Design Teams for the Development of Complex Systems. Ph.D. Thesis, Southern Methodist University, Dallas, TX, USA, 2010.
29. Peykani, P.; Gheidar-Kheljani, J.; Shahabadi, S.; Ghodsypour, S.H.; Nouri, M. A two-phase resource-constrained project scheduling approach for design and development of complex product systems. *Oper. Res.* **2023**, *23*, 17. [CrossRef]
30. Abdelsalam, H.M.E.; Bao, H.P. A simulation-based optimization framework for product development cycle time reduction. *IEEE Trans. Eng. Manag.* **2006**, *53*, 69–85. [CrossRef]
31. Gunawan, I.; Ahsan, K. Project scheduling improvement using design structure matrix. *Int. J. Proj. Organ. Manag.* **2010**, *2*, 311–327. [CrossRef]
32. Bodach, S.; Lang, W.; Hamhaber, J. Climate responsive building design strategies of vernacular architecture in Nepal. *Energy Build.* **2014**, *81*, 227–242. [CrossRef]
33. Amraoui, K.; Sriti, L.; Di Turi, S.; Ruggiero, F.; Kaihoul, A. Exploring building's envelope thermal behavior of the neo-vernacular residential architecture in a hot and dry climate region of Algeria. *Build. Simul.* **2021**, *14*, 1567–1584. [CrossRef]
34. Lee, J.; Park, M.; Lee, H.S.; Kim, T.; Kim, S.; Hyun, H. Workflow dependency approach for modular building construction manufacturing process using Dependency Structure Matrix (DSM). *KSCE J. Civ. Eng.* **2017**, *21*, 1525–1535. [CrossRef]