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Manned lunar landing mission scale analysis and flight scheme selection based on mission architecture matrix

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ABSTRACT

At present, the moon is still an important and preferred destination for human beings to visit due to the abundant resources and its potential to be the stepping-stone and platform of deep space exploration in the future. The manned lunar exploration has very important and profound meaning for leading technology innovation and manifesting comprehensive power of a country. Mission scale analysis and flight scheme selection are key problems for top-level projection and are still remaining to be researched systematically and deeply.

This paper focus on the scale analysis of manned lunar landing mission and the optimal selection of flight schemes. At first, the basic configurations and the overall technical specifications of flight vehicle system were presented based on the investigation of traditional vehicles and developing trend of new vehicles. Afterwards, the fundamental elements of flight scheme were defined and the Mission Architecture Matrix was constructed. Based on Mission Architecture Matrix, the scale evaluation method was demonstrated. Finally, the qualitative selection model based on Analytic Hierarchy Process and Gray comprehensive evaluation method were established, the optimal scheme with economic and technical feasibility was given based on these two models. The validity of all models in this paper was tested and verified by different testing examples. The results show that EOR-LOR architecture is the best flight scheme for a short-period manned lunar exploration mission.

To the best of our knowledge, it is the very first time that the concept of Mission Architecture Matrix was proposed. The reverse calculating algorithm based on Mission Architecture Matrix could improve the efficiency of mission scale analysis and the presented comprehensive evaluation model could make the selection of flight scheme more objective. These models and methods in this paper could be technical references for preliminary design of manned lunar landing mission.

1. Introduction

In the 1960s and 1970s, seven Apollo manned spaceships were launched to the moon by the United States, six of them landed on the moon successfully, and twelve astronauts set foot on the moon, which took a big step in human history. The success of Apollo program laid the United States a leading position in the field of space technology.

With the development of deep space exploration technology, manned lunar missions are put on the agenda by some countries in recent years. Many researchers have carried out research on the lunar transportation architecture as it plays an important role in implementing a manned lunar mission. In January 2004, the former US President George W. Bush announced a new vision that the US would return humans to the moon by 2020. As a part of this vision, NASA submitted an Exploration Systems Architecture Study (ESAS) Final Report [1]. In this report, different kinds of lunar transportation architectures were considered comprehensively. In order to enable an extensive analysis of possible configurations for the NASA Moon-Mars Exploration Vision, Willard L. Simmons et al. used Object Process Network (OPN), to create a Moon-Mars Exploration Architecture Generator. This generator could enumerate hundreds of unique exploration architectures [2]. By using this generator, Gergana A. Bounova et al. selected three Mars and five lunar exploration architectures based on six qualitative criteria, which are used to evaluate the usability and priority of the exploration architectures. The initial mass to low earth orbit (IMLEO) of these eight exploration architectures was calculated [3]. In China, Sheng et al. studied seven lunar exploration architectures considering the IMLEO and reliability [4]. Peng et al. researched five lunar exploration architectures [5]. IMLEO and the requirement of launch vehicle were discussed. In this paper, we will use “architecture” to infer to exploration architecture.

However, the number of architectures is so large and the traditional

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descriptive method of them is so qualitative, and architectures are often illustrated by a flowchart or general natural language and cannot be used to calculate mission scale directly. This causes difficulties in efficiency of IMLEO analysis. Although Willard L. Simmons has proposed a description matrix for Moon-Mars Exploration architectures [6], but the main function of the matrix is to generate different exploration architectures and some details such as rendezvous and docking have not been defined clearly and thus is hard to be used for IMLEO analysis.

Therefore, in this paper, we proposed a new mathematical description model named Mission Architecture Matrix (MAM) and demonstrated a novel IMLEO analysis method based on this matrix in order to solve the problem mentioned above. The matrix in this paper can match all proposed architectures in a fixed structure, showing the process and features of each architecture directly and clearly. Therefore, different architectures for a certain mission can be quantitative analyzed, and this method is obviously more convenient and programmable than non-quantitative description and research methods of NASA or ESA [1,2]. What's more, MAM has a good scalability for crew module, flight phase and evaluation factors.

Notably, this work has been successfully used in preliminary research upon manned lunar landing mission of China.

And there is limited research focus on the quantitative evaluation of lunar architectures based on the comprehensive evaluation method, though the qualitative comparison has been seen in some research. This paper built up a comprehensive evaluation model, which based on analytic hierarchy process (AHP) and gray evaluation method, to evaluate six lunar architectures. The four evaluation indexes in this comprehensive evaluation model are respectively IMLEO, mission duration, reliability and the technology readiness level (SRL) of China's heavy-lift launch vehicle. It should be noted that all kinds of lunar architectures could be evaluated by this comprehensive evaluation method, not just limit to these ten lunar architectures, and the number of evaluation indexes could also be expanded.

2. The lunar architectures to be evaluated

The lunar architecture normally is a combination of transportation nodes, which consist of Low Earth Orbit (LEO), Earth-Moon L1 Lagrange point and Low Lunar Orbit (LLO). Respectively, these translate to Earth Orbit Rendezvous (EOR), Earth-Moon Lagrange rendezvous (ELR) and Lunar Orbit Rendezvous (LOR) architecture. If spacecraft doesn't rendezvous and dock at any nodes, we call it a “direct” architecture. Each kind of architecture could be further subdivided according to launch times. Obviously, the Apollo mission is 1-launch LOR architecture.

This paper takes six lunar architectures into account. There are four kinds of spacecraft involved, including Upper-Stage Rocket (USR), Orbit Transfer Stage (OTS), Crew Module (CM) and Lunar Module (LM). The CM consists of Propulsion Module (PM) and Re-entry Module (RM), while Descent stage (DS) and Ascent Stage (AS) compose the LM.

2.1. Architecture 1: 1-launch LOR architecture

This architecture is as same as Apollo mission (shown in Fig. 1).

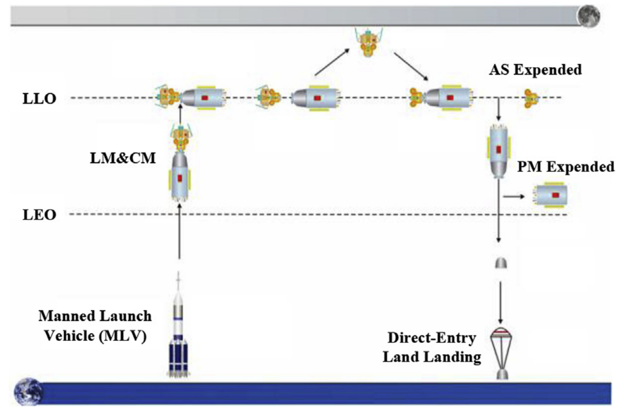

Fig. 1. Architecture 1: 1-launch LOR architecture.

2.2. Architecture 2: 2-launch LOR architecture

The Cargo Launch Vehicle (CLV) and the Manned Launch Vehicle (MLV) perform trans-lunar insertion to transfer the LM and CM to earth-to-moon transfer orbit respectively. The LM and CM then perform lunar-orbit insertion. Two vehicles initially rendezvous and dock in LLO. The entire crew then transfers to the LM, undocks from the CM, and the DS performs a descent to the lunar surface. After finishing the task on the lunar surface, the AS returns the crew to lunar orbit where the LM and CM dock, and the crew transfers back to the CM. The CM then returns the crew to Earth with a direct entry and land touchdown.

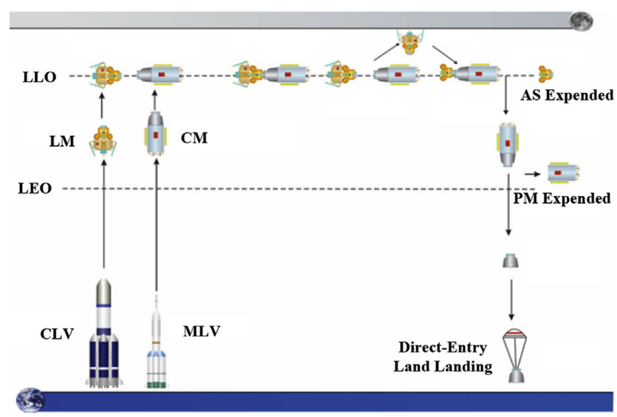

Fig. 2. Architecture 2: 2-launch LOR architecture.

The architecture 2 is showed in Fig. 2.

2.3. Architecture 3: 2-launch EOR-LOR architecture

The CLV delivers the LM and OTS to LEO. Then the MLV sends the CM to LEO and dock with LM. The OTS performs the trans-lunar insertion for both LM and CM. The steps followed are as same as architecture 1. The architecture 3 is showed in Fig. 3.

2.4. Architecture 4: 3-launch EOR architecture

The CLV1 delivers the OTS1 to LEO. The CLV2 delivers the OTS2 and LM to LEO and dock with OTS1. Then the MLV sends the CM to LEO

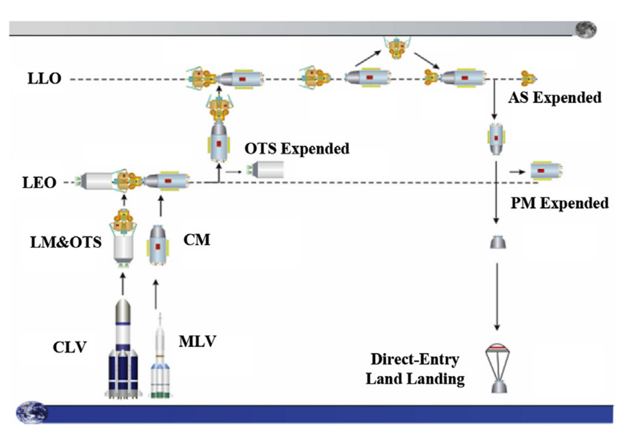

Fig. 3. Architecture 3: 2-launch EOR-LOR architecture.

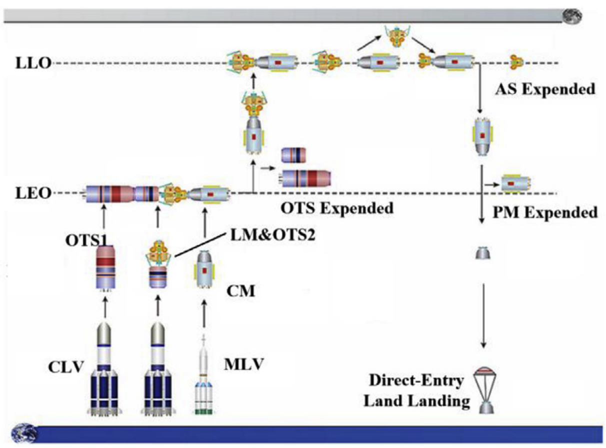

Fig. 4. Architecture 4: 3-launch EOR architecture.

and dock with LM. The OTS performs the trans-lunar insertion for both LM and SM. The architecture 4 is showed in Fig. 4.

2.5. Architecture 5: 4-launch EOR-LOR architecture

In this architecture, the OTS is separated into three parts. The transport process is similar to architecture 4. The architecture 5 is showed in Fig. 5.

2.6. Architecture 6: 3-launch EOR-LOR architecture

This architecture is not as same as architecture 3. In this architecture, the LM is delivered to earth-to-moon transfer orbit directly. The CM and OTS dock in LEO, then the USR and OTS performs the trans-lunar insertion for CM. The LM and CM dock in LLO. The architecture 6 is showed in Fig. 6.

The launch times and dock times of these six architectures is shown in Table 1.

3. Mission architecture matrix

3.1. Transportation nodes analysis

It is unquestionable that the Earth surface and lunar surface are the indispensable nodes for manned lunar landing mission. Earth orbit and lunar orbit are two significant nodes for traditional mission architecture. Additionally, some researchers found that lunar Lagrange points have many advantages in manned lunar landing mission [7]. The solution of CRTBP (Circular Restricted Three Body Problem) demonstrated that there exist five equilibrium points in Earth-Moon system. As

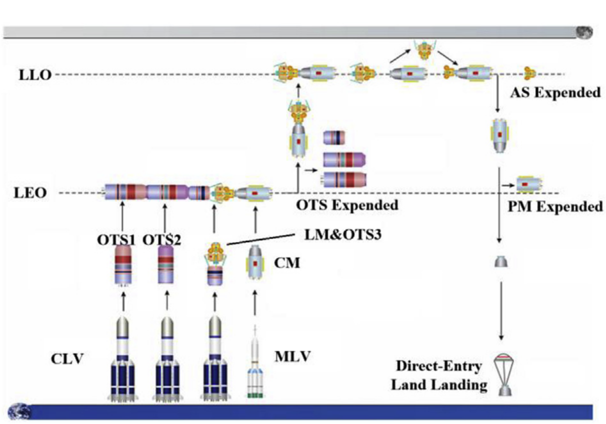

Fig. 5. Architecture 5: 4-launch EOR-LOR architecture.

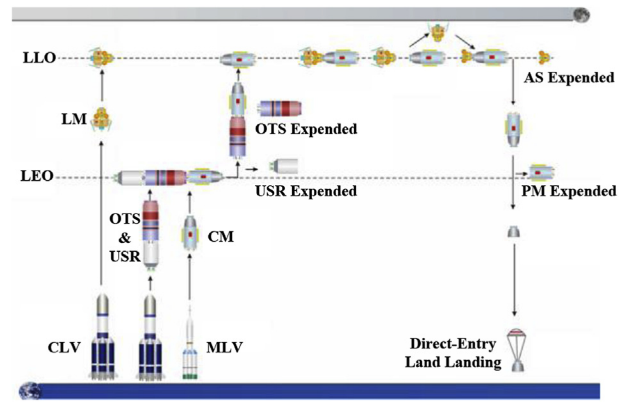

Fig. 6. Architecture 6: 3-launch EOR-LOR architecture.

Table 1
Six manned lunar mission architectures in this paper.

Mission architectures		Launch times	Rendezvous and docking times in LEO	Rendezvous and docking times in LLO
LOR	1	1	0	1
	2	1	0	2
EOR-LOR	3	2	1	1
	4	3	2	1
	5	4	3	1
	6	3	1	2

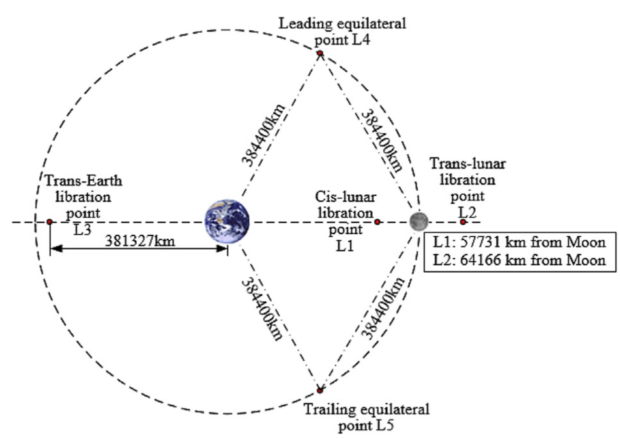

Fig. 7. Earth-moon system libration points.

indicated in Fig. 7, of these five libration points, three collinear points (L1, L2, and L3) lie on the line between the mass bodies. The other two libration points (L4 and L5) create equilateral triangles with the two mass bodies. The distance of these points from the mass bodies is determined by the relative mass of those two bodies [8].

Trans-Earth libration point L3, leading equilateral point L4, and trailing equilateral point L5 are too far away from the Moon to support a Manned Lunar Landing Mission. Therefore, L3, L4 and L5 libration points cannot be used as transportation nodes. Despite the fact that the cis-lunar libration point L1 and trans-lunar libration point L2 are "unstable", fortunately, the Δv cost for orbital maintenance is very low [9]; In the meantime, a spacecraft at L1 or L2 halo orbit also has direct and continuous communication access to Earth [10]. Taking these two collinear Earth-Moon L1 and L2 Lagrange points as mission staging nodes allows access to all lunar latitudes while providing a continuous launch window to and from the lunar surface [11]. A spacecraft at L2 Lagrange point also has the capability to land on the dark side of Moon where no spacecraft has ever been before. So it is appropriate to use L1

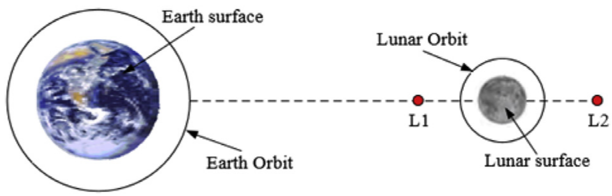

Fig. 8. The main transportation nodes.

Table 2
Basic flight phases definition.

No.	Flight Phases	Flight Events
1	E_Launching	Earth to orbit
2	E_orbit_Flight	Earth orbit rendezvous, docking, assembly or flight
3	E_Depart	Earth departure
4	E_P_Transfer	Earth to parking orbit injection, interplanetary travel, Mid-Course Correction (MCC) and arrival
5	P_flight_D	Parking orbit (lunar orbit, L1 point or L2 point) flight, docking\undocking before descending
6	M_surface_Descending	Descent to the surface of Moon
7	Surface_Operating	Operating on the surface of Moon
8	M_surface_Ascending	Ascending from surface of Moon to Parking orbit
9	P_flight_A	Parking orbit (lunar orbit, L1 point or L2 point) flight, docking\undocking after ascending
10	P_E_Transfer	Parking orbit to Earth injection, interplanetary travel, MCC and arrival
11	E_Re-entry	Earth atmosphere re-entry
12	E_surface_Descending	Descent to the Earth's surface (end of mission)

and L2.

Therefore, the main transportation nodes that support manned lunar landing mission are Earth surface, Earth orbit, lunar orbit, Earth-Moon system Lagrange points L1 and L2 and lunar surface (See Fig. 8).

3.2. Basic flight phases definition

Based on the main transportation nodes elaborated in III.I, we define the basic flight phases of manned lunar landing mission (see Table 2). It is worth noting that the nodes lunar orbit, lunar Lagrange points L1 and L2 are regarded as parking orbits which play the role of staging location in a mission.

As shown in Table 2, 12 basic flight phases from Earth launching to Earth return are defined in our research while each flight phase may have several flight events. These flight phases will provide framework and be the basis for mission architecture description.

3.3. Mission architecture matrix construction

As previously described, a mission architecture is the combination of basic flight phases; meanwhile, a certain flight phase is a combination of one or more flight events (seen Fig. 9).

Accordingly, the description of an architecture depends on the detailed illustration of each flight event, including the explanation of these three conditions:

1) Flight vehicles involved/not involved in the event;
2) Which vehicle is the one that conduct orbital maneuver in the event?
3) If the event is rendezvous, then which one of vehicles is active and which one is passive?

In this paper, we suppose that in a rendezvous event, the active vehicle is considered as the one who applies the impulse of RVD (Rendezvous and Docking), and the passive vehicle is just waiting in its orbit for the coming of the active vehicle without any maneuver.

With the intention of illuminating a certain flight event and constructing the mission architecture matrix to illustrate an architecture eventually, we define some variables firstly (see Table 3).

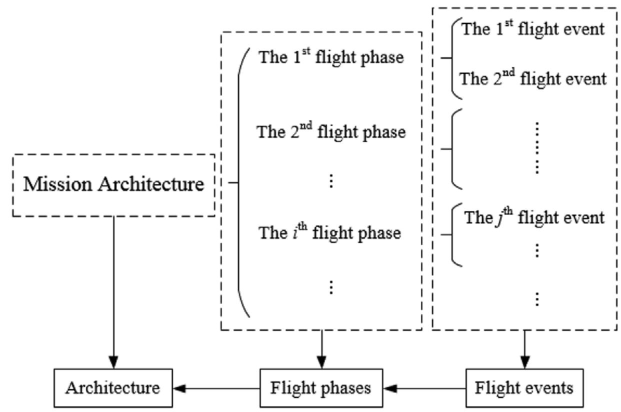

Fig. 9. Mission architecture construction elements.

Table 3
Definition of variables for Mission Architecture Matrix construction.

Variables	Meaning
BFP	The ID number of *Basic Flight Phase*, see in Table 2
RVD	The symbol of *Rendezvous and Docking*
RM	The flight condition of *Reentry Module of Crew Module*
PM	The flight condition of *Propulsion Module of Crew Module*
DS	The flight condition of *Descent Stage of Lunar Module*
AS	The flight condition of *Ascent Stage of Lunar Module*
*OTS*1	The flight condition of *Orbit Transfer Stage* 1
*OTS*2	The flight condition of *Orbit Transfer Stage* 2
*OTS*3	The flight condition of *Orbit Transfer Stage* 3
*USR*1	The flight condition of *Upper-Stage Rocket* 1 (for CM)
*USR*2	The flight condition of *Upper-Stage Rocket* 2 (for LM)
IMV	The symbol of *Impulse Maneuver Vehicle*
Δv	Delta-*v* cost of a maneuver (m/s)

Using these variables listed in Table 3, we can start to build mission architecture matrix, the process of which is as follows.

3.3.1. FEV (Flight Event Vector) construction

The underlying elements of mission architecture are flight events. There are many events happening in a certain architecture from launching a vehicle to Earth orbit at the beginning of a mission to returning the astronauts to Earth safely in the end. Concerning the *j*th event in a mission, we define a 13-dimensional row vector *FEV* (*Flight Event Vector*) to describe the event:

$$(FEV)_j = [BFP\ \ RVD\ \ RM\ \ PM\ \ DS\ \ AS\ \ OTS1\ \ OTS2\ \ OTS3\ \ USR1\ \ USR2\ \ IMV\ \ \Delta v] \tag{1}$$

Where:

$$BFP = 1,2,3,\ \ldots,12 \tag{2}$$

$$RVD = \begin{cases} 0 & \text{if the event is not rendezvous and docking} \\ 1 & \text{if the event is rendezvous and docking} \end{cases} \tag{3}$$

$$RM,\ PM,\ DS,\ AS,\ OTS1,\ OTS2,\ OTS3,\ USR1,\ USR2 = \begin{cases} 0 & \textit{not involved in the event} \\ 1 & \textit{involved in the event} \end{cases} \quad (RVD = 0) \tag{4}$$

$$RM,\ PM,\ DS,\ AS,\ OTS1,\ OTS2,\ OTS3,\ USR1,\ USR2 = \begin{cases} 0 & \textit{not involved in the event} \\ 2 & \textit{passive vehicle} \\ 3 & \textit{active vehicle} \end{cases} \quad (RVD = 1) \tag{5}$$

$$IMV = \begin{cases} 0 & no\ \ orbital\ \ maneuver \\ 1 & reentry\ \ module\ \ of\ \ \text{CEV} \\ 2 & propulsion\ \ module\ \ of\ \ \text{CEV} \\ 3 & descent\ \ stage\ \ of\ \ \text{LL} \\ 4 & ascent\ \ stage\ \ of\ \ \text{LL} \\ 5 & orbit\ \ transfer\ \ stage\ \ 1 \\ 6 & orbit\ \ transfer\ \ stage\ \ 2 \\ 7 & orbit\ \ transfer\ \ stage\ \ 3 \\ 8 & upper-stage\ \ rocket\ \ 1 \\ 9 & upper-stage\ \ rocket\ \ 2 \end{cases} \tag{6}$$

The last element of $(FEV)_j$ vector Δv is the true value of the orbital maneuver delta-v cost in jth event. We have to emphasize here that each variable in formula(4) and formula(5) correspondingly represents the flight condition explained at the beginning of section III.II of each vehicle.

3.3.2. FPM (flight phase matrix) construction

For the ith flight phase of an architecture, if there are k flight events that would be conducted totally, then this flight phase could be described using FPM:

$$(FPM)_i = \begin{bmatrix} (FEV)_1 \\ (FEV)_2 \\ \vdots \\ (FEV)_k \end{bmatrix} \tag{7}$$

3.3.3. MAM (mission architecture matrix) construction

For a certain architecture, if it was formed by n flight phases in total, then the Mission Architecture Matrix would be finally constructed by formula(8):

$$MAM = \begin{bmatrix} (FPM)_1 \\ (FPM)_2 \\ \vdots \\ (FPM)_n \end{bmatrix} \tag{8}$$

Through the three steps above, we have finished the description of a manned lunar landing mission architecture by means of MAM which has following traits:

1) MAM provides a strict mathematical expression for an architecture;
2) MAM is cascaded by FEV according to the time sequence, so it is easy to be understood;
3) MAM can be used to calculate mission scale (IMLEO, Initial Mass in Low Earth Orbit) directly.

Finally, we proposed a mathematical model for mission architecture description, MAM. Based on MAM, we can analysis the mission scale efficiently.

4. Evaluation indexes calculation

There are four evaluation indexes considered, including IMLEO, mission duration, reliability and the SRL of China's heavy-lift launch vehicle. The indexes are expressed in x_1, x_2, x_3, x_4.

4.1. IMLEO calculation

In this study, mission scale means the total mass of flight vehicle system that would be launched to Low Earth Orbit, namely the IMLEO. The total mass of each vehicle is composed of dry weight and propellant mass. In order to evaluate mission scale, we define some variables at first.

m_f = the dry weight of a vehicle
m_p = the mass of propellant carried by a vehicle
f_i = the ratio of dry weight of a vehicle to its total weight, $f_i = m_f/(m_f + m_p)$
m_0 = the total weight of a vehicle, $m_0 = m_f + m_p$
I_{sp} = the specific impulse of engine
Δv = the orbital maneuver delta-v
g_0 = the gravitational acceleration, $g_0 = 9.8\ \text{m/s}^2$
$(M_{fvs})_j$ = the total weight of flight vehicle system after the orbital maneuver of jth flight event
M_j = the 9-dimensional vector defined to save the mass of each vehicle

$M_j = [m_{rm}\ m_{pm}\ m_{ds}\ m_{as}\ m_{ots1}\ m_{ots2}\ m_{ots3}\ m_{usr1}\ m_{usr2}]$, each element represents the mass of reentry module, propulsion module, descent stage, ascent stage, orbit transfer stage 1, orbit transfer stage 2, orbit transfer stage 3, upper-stage rocket 1 and upper-stage rocket 2 at the end of jth event respectively. Specially, M_0 represents the mass of each vehicle at the beginning of first flight event.

Considering that the propellant consumed by flight vehicle system in $(j+1)$th flight event can be regarded as the "inertial weight" of jth flight event, the evaluation of IMLEO should start from the last flight event to the first event of a mission, which is the so called "reverse calculation" method.

Generally, because of the multi-task adaptability, the new generation of CM and LM do not need to be developed to many types, so their dry weight are known initially while the mass of propellant carried by them need to be calculated. However, the dry weight of OTS and USR cannot be determined before a mission which is because the weight differential of propellant carried by them in different missions is always significant and thus lead to the mass changes of their tanks, this is also the reason why the type spectrum and serialization are the mainstream of development of OTS and USR. Nevertheless, the f_i of OTS and USR, as one of their technical indexes, is known.

To sum up, the initial conditions of mission scale evaluation are showed in Table 4.

Provided that the dimension of MAM of a certain mission architecture is $m \times 13$ (the number of flight events is m), $j = 0,1,2, \ldots,m$, then the mission scale evaluation can be conducted through the following procedure based on MAM.

1) Let $j = m$, starting calculation from the last flight event

When the last flight event is completed, all propellants carried by the flight vehicle system will be used up theoretically, at this time, the vector M_j is:

$$M_j = M_m = [(m_f)_{rm}\ (m_f)_{pm}\ (m_f)_{ds}\ (m_f)_{as}\ X_1\ X_2\ X_3\ X_4\ X_5] \tag{9}$$

Table 4
Variables known and needed to be calculated.

	Reentry module	Propulsion module	Descent stage	Ascent sgate	Orbit transfer stage 1	Orbit transfer stage 2	Orbit transfer stage 3	Upper-stage rocket 1	Upper-stage rocket 2
m_f	$(m_f)_{rm}$	$(m_f)_{pm}$	$(m_f)_{ds}$	$(m_f)_{as}$	X_1	X_2	X_3	X_4	X_5
f_i	—	—	—	—	$(f_i)_{ots1}$	$(f_i)_{ots2}$	$(f_i)_{ots3}$	$(f_i)_{usr1}$	$(f_i)_{usr2}$

Note: —: not used; blue: known; orange: unknown, need to be calculated

In order to obtain the solution of X, we firstly give them initial values:

$$M_j = M_m = [(m_f)_{rm}\ (m_f)_{pm}\ (m_f)_{ds}\ (m_f)_{as}\ (X_1)_0\ (X_2)_0\ (X_3)_0\ (X_4)_0\ (X_5)_0] \tag{10}$$

2) Calculating the total weight of flight vehicle system at the end of the jth event

a) If $(MAM)_{j,2} = 0$ ($RVD = 0$, this event is not rendezvous and docking)

Here the subscript "j,2" of $(MAM)_{j,2}$ means the element of jth row and 2nd column of the matrix MAM, the same below.

As defined in formula(4), the total weight of flight vehicle system at the end of the jth event can be expressed by formula(11).

$$(M_{fvs})_j = M_j(1)\cdot(MAM)_{j,3} + M_j(2)\cdot(MAM)_{j,4} + ... + M_j(9)\cdot(MAM)_{j,11} = \sum_{k=1}^{9} M_j(k)\cdot(MAM)_{j,k+2} \tag{11}$$

b) If $(MAM)_{j,2} = 1$ ($RVD = 1$, this event is rendezvous and docking)

As defined in formula(5), for the convenient and intuitive purpose, the active vehicle and passive vehicle in this RVD event are described by the number 3 and 2 respectively. As mentioned in section III.III, the orbital maneuver for RVD is conducted by the active vehicle in this study and thus passive vehicle can be seen as not taking part in RVD events, so we can replace number 3 by 1 for the active vehicle and replace 2 by 0 (same as no RVD event) for the passive vehicle. For the purpose of calculation the unified variable ε can be conducted:

$$\varepsilon = \frac{(MAM)_{j,k+2}\cdot((MAM)_{j,k+2} - 2)}{(MAM)_{j,k+2} - 0.1} \tag{12}$$

Then the total weight of flight vehicle system at the end of the jth event can be expressed by formula(13):

$$(M_{fvs})_j = \sum_{k=1}^{9} M_j(k)\cdot[\varepsilon] \tag{13}$$

where $[\varepsilon]$ means the largest integer less than ε.

3) Calculating the mass of propellant consumed in jth event

Because $(M_{fvs})_j$ calculated above is the total weight of flight vehicle system at the end of the jth event, the orbital maneuver in this event is to give $(M_{fvs})_j$ the velocity increment. Thus the mass of propellant consumed in jth event can be estimated using Ziolkovsky formula:

$$m_p = (M_{fvs})_j\left(e^{\frac{\Delta v}{I_{sp}\cdot g_0}} - 1\right) \tag{14}$$

Where:

$$\Delta v = (MAM)_{j,13} \tag{15}$$

4) Calculating vector $M_{j\text{-}1}$

In a single event, only the mass of vehicle who applied the impulse of orbital maneuver will change, so we just need to update its weight. Let

$$y = (MAM)_{j,12} \tag{16}$$

If $y = 0$, there is no orbital maneuver in jth event, then

$$M_{j-1}(y) = M_j(y) \tag{17}$$

If $y \neq 0$, then

$$M_{j-1}(y) = M_j(y) + m_p \tag{18}$$

Other vehicles' weights remain unchanged

$$M_{j-1}(z) = M_j(z), \quad (z = 1,2,...,9\ \ and\ \ z \neq y) \tag{19}$$

5) Let $j = j$-1, repeating the procedure from 2) to 5) until we get the vector M_0.

6) Checking the constraints of f_i

From the process above, we know that propellants consumed by each vehicle can be expressed by a vector M_p:

$$M_p = M_0 - M_m \tag{20}$$

Then the f_i constraints are as follows:

$$\begin{cases} (f_i)_{ots1} = (X_1)_0/[(X_1)_0 + M_p(5)] \\ (f_i)_{ots2} = (X_2)_0/[(X_2)_0 + M_p(6)] \\ (f_i)_{ots3} = (X_3)_0/[(X_3)_0 + M_p(7)] \\ (f_i)_{usr1} = (X_4)_0/[(X_4)_0 + M_p(8)] \\ (f_i)_{usr2} = (X_5)_0/[(X_5)_0 + M_p(9)] \end{cases} \tag{21}$$

If formula(21) could not be satisfied, we should modify the initial values of M_m (see in formula(10)) and repeat the procedure from 1) to 6) until the f_i constraints were satisfied.

7) Mission scale evaluation

Finally, the mass of each flight vehicle can be obtained as follows:

a) Crew Module

$$m_{cev} = M_0(1) + M_0(2) \tag{22}$$

b) Lunar Module

$$m_{ll} = M_0(3) + M_0(4) \tag{23}$$

c) Orbit Transfer Stage

$$\begin{cases} m_{ots1} = M_0(5) \\ m_{ots2} = M_0(6) \\ m_{ots3} = M_0(7) \end{cases} \tag{24}$$

d) Upper-Stage Rocket

$$m_{usr1} = M_0(8) \tag{25}$$

$$m_{usr2} = M_0(9) \tag{26}$$

At last, the mission scale (IMLEO) can be expressed with the following formula:

$$\text{IMLEO} = m_{cev} + m_{ll} + m_{ots1} + m_{ots2} + m_{ots3} + m_{usr1} + m_{usr2} \tag{27}$$

Generally, formula (21) cannot be satisfied in one iteration, meanwhile, the input and output of scale analysis method do not have explicit relationships, so we cannot obtain IMLEO directly through formula(27). We have to modify the initial values of X_i (i = 1,2 ...,5) continuously to get the final solution, during this process, Newton iteration method is a good choice for finding the solution quickly.

To figure out mission scale of 6 architectures, it is assumed that the number of astronauts taking part in the mission is 3 and 2 of them operate landing on the moon, which is the same as Apollo mission. The spacecraft uses N_2O_4/hyperthyroidism as the propellant, and the mixing ratio of the two is 1.6, and the ratio is 328s [12]. Here are the results of mission scale measured by mass about the six architectures (Table 5). Max LEO or LTO (Lunar Transfer Orbit) mass means the max launch mass of all launches in a certain architecture. Max LEO requirement mass just means the larger one between max LEO and max LTO mass converted to LEO mass, and it also indicates the max launch mass during the whole mission in real launches. Total LEO mass includes mass of all launches during the mission.

4.2. Mission duration

The mission duration of manned lunar mission is affected by the

Table 5
Mission mass scales of 6 architectures.

No.	CM mass/ton	LM mass/ton	OST&USR mass/ton	Max LEO Launch mass/ton
1	15.3	33.4	NA	NA
2	21.2	28.8	NA	NA
3	15.3	33.4	90.2	123.6
4	15.3	33.4	104.0	69.6
5	15.3	33.4	108.1	64.9
6	22.5	28.8	53.3	30.2

No.	Max LTO Launch mass/ton	Max LTO convert to LEO mass/ton	Max LEO requirement mass/ton	Total LEO mass (equivalent)/ton
1	48.7	131.4	131.4	131.4
2	28.8	77.8	77.8	135
3	NA	NA	123.6	138.9
4	NA	NA	69.6	152.7
5	NA	NA	64.9	156.7
6	28.8	77.8	77.8	153.6

Table 6
The duration of each event.

Events	Duration/day
Shortest time interval between two launches	3
Rendezvous and docking	2
Transfer from earth to moon	3
Lunar descent and landing	1
Lunar surface activities	2
Lunar ascent	1
Transfer from moon to earth	3

launch window, the duration of the rendezvous and docking, the length of the transit and the duration of the lunar work etc.. The duration of each event is shown in Table 6, which is consisted of data from the existing task practice [13].

For the Architecture 2 and Architecture 6, the CM and LM are launch to the LLO respectively, and then rendezvous and docking in LLO. In order to reduce the fuel consumption, the CM and LM are required to launch to the same lunar orbit plane. There are only two chances in a month to launch the CM and LM to the same lunar orbit plane if we adopt co-planar orbital transfer. In other words, for the Architecture 2 and Architecture 6, the launch of CM has to wait at least 14 days after LM's launch.

Fig. 10 shows both total mission duration and crew on board duration.

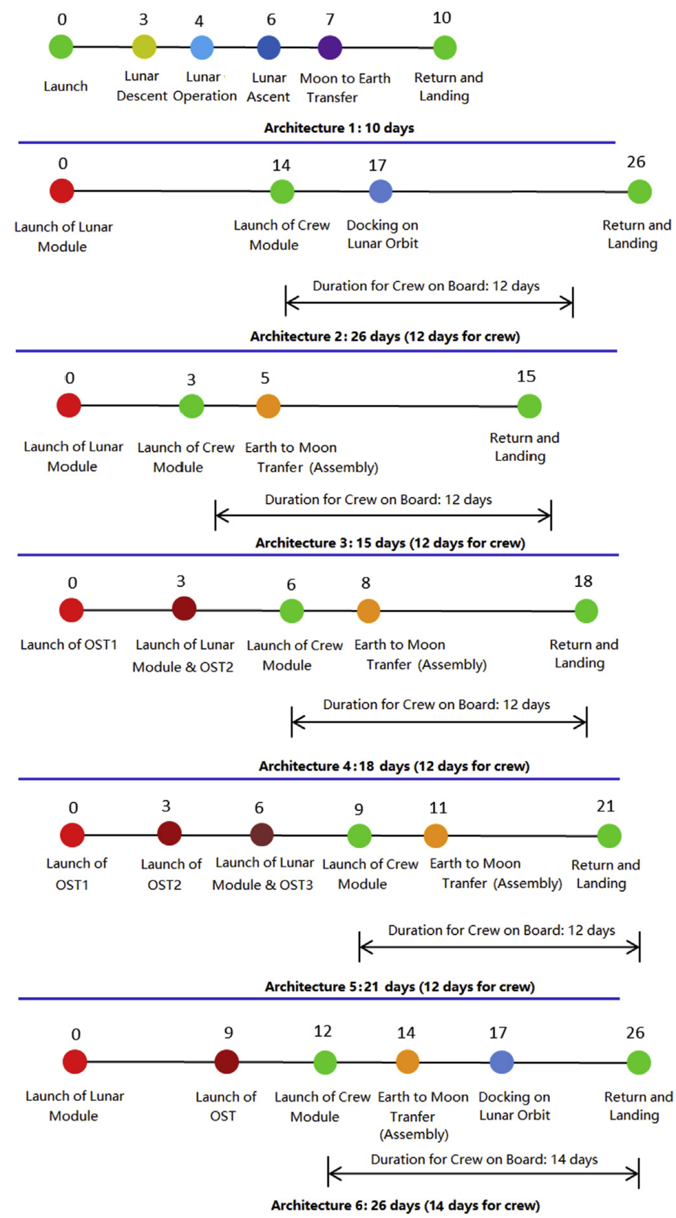

Fig. 10. Synthesis score of 6 architectures (consider the SRL of launch vehicle).

4.3. Reliability

The manned lunar mission architecture is made up of a series of flight phases in sequence. We assume that the architecture contains k phases, the probability of loss of mission in phase i is pi (i = 1,2,⋯,k), then the reliability of the architecture is

$$R = \prod_{i=1}^{k} (1 - p_i) \tag{28}$$

In the actual situation, the p_i ($i = 1,2,\cdots,k$) are often quite small. When we expand formula (28), the high order small could be neglected

$$R \approx 1 - \sum_{i=1}^{k} p_i \tag{29}$$

According to formula (29), the reliability of the architecture could be calculated just using addition and subtraction operations. According

Table 7
The probability of loss of mission in each phase.

Events	Loss of Mission/%	Fatal probability/%	loss of Crew/%
CLV to LEO	0.81	0	0
MLV to LEO	0.22	23	0.05
Dock in LEO	0.4	0	0
CLV to Moon	0.4	1	0
MLV to Moon	0.17	5	0.01
CLV Lunar Capture	1	0	0
MLV Lunar Capture	1	8	0.08
Dock in LMO	0.6	33	0.2
Lunar Descent	0.1	10	0.01
Lunar Landing	1	10	0.1
Lunar Operations	0.47	82	0.39
Lunar Ascent	0.05	100	0.05
Ascent Docking	0.26	100	0.26
Lunar Departure	0.25	100	0.25
Return & Entry	0.58	53	0.31
Landing	0.04	100	0.04

Table 8
The value of evaluation indexes.

Evaluation index	Architecture 1	Architecture 2	Architecture 3	Architecture 4	Architecture 5	Architecture 6
Mission duration/day	10	26	15	18	21	26
Crew on board duration/day	10	12	12	12	12	14
Total LEO/t	131.4	135	138.9	152.7	156.7	153.6
LEO Carrying capacity requirement/t	131.4	77.8	123.6	69.6	64.9	77.8
Mission success/%	95.35	92.83	94.14	92.93	91.72	91.62
Lose of Mission/%	4.65	7.17	5.86	7.07	8.28	8.38
Lose of Crew/%	0.68	1.01	0.81	0.96	1.12	1.32
SRL of launch vehicle	2	4	2	4	4	4

to NASA's Exploration System Architecture Study [1], the probability of loss of mission in each phase is shown in Table 7.

Table 7 mainly described the reliability of events in the mission, and for other time duration, the reliability also should be considered.

Most of the system failures were less than 1e-5 failures per hour or better. For manned lunar mission, the probability of LM vehicle failure was 4.86e-5 per hour and the CLV/MLV vehicle quiescent failure rate was 6.51e-5 per hour. Multiplying the summation of these two by 24 gives the 2.73e-3 per-day result for mission failure and 1e-3 per-day for catastrophic failure (loss of crew) [1].

Thus we can calculate both mission reliability and crew safety during mission time when there is no event for 6 architectures according to mission duration in Fig. 10. The result was shown in Table 8.

4.4. The SRL of China'S heavy-lift launch vehicle

The TRL was first proposed by NASA in the 1980s. The original definition included seven levels to measure the development degree and knowledge of specific technologies. In the 1990s, NASA adopted the current nine-level scale, the higher the level, the more mature the technology [14,15].

According to TRL, Bran Sauser proposed System Ready Level (SRL), which can be more applicable to large integrated systems such as launch vehicles [16]. SRL index was defined by the current state of the development of a system, as shown in Fig. 11.

Long March 5 is now China's largest launch vehicle currently with a maximum payload capacity of 25 tons to LEO and 14 tons to GTO. For the manned lunar mission, if the requirement of LEO capacity is about 50 tons, then the 5-m diameter body and engine technology of Long March 5 could be inherited well, with a higher SRL level about 4 according to the definition of SRL, with an operational capability that satisfies mission needs but not most cost-effective.

However, if the LEO capacity requirement exceeds 100 tons, China has to develop new heavy-lift launch vehicle such as long-march IX, which was now being integrated into a full system [17], with a lower SRL level about 2.

Thus, the SRL indexes of 6 architectures are 2, 4, 2, 4 4, 4, considering China's heavy-lift launch vehicle.

4.5. The value of evaluation indexes

The evaluation indexes of these six architectures from former parts are shown in Table 8. It is worth noting that mass scale and mission success (as well as lose of mission) contains effect of astronauts.

5. Comprehensive evaluation model

The comprehensive evaluation methods, which use mathematical methods to convert the multi-indexes into a certain evaluation value, have been widely applied in various fields. There are many modern comprehensive evaluation methods, such as analytic hierarchy process (AHP), fuzzy comprehensive evaluation method, artificial neural network evaluation method, gray evaluation method, data envelopment analysis method, etc.. These methods can also be used in combination.

This paper adopted AHP in combination with gray evaluation method to evaluate six manned lunar mission architectures. Combining two methods can inherit the advantages of both methods. For this study, the combination of these two methods has the following two advantages:

1) There are four evaluation indexes in this study, the weight of these four evaluation indexes is not easy to determine. If we determine the weight subjectively, the evaluation result probably not corresponds to the reality. However, if the AHP was used to ascertain the weight, the risk of miscalculation could be reduced greatly. By utilizing the AHP, we only need to give the relative importance of four evaluation indexes, which is much more reliable than determine the explicit weight.
2) The four evaluation indexes of this study can be quantified, and the relative optimal value of each evaluation index in six architectures is also unproblematic to be acquired, which makes it simple and reliable to calculate the correlation degree by gray evaluation method. The evaluation result is intuitive.

5.1. The AHP

AHP is mainly used to solve the problem which the influence of the

SRL	Name	Definition
5	*Operations & Support*	Execute a support program that meets operational support performance requirements and sustains the system in the most cost-effective manor over its total life cycle.
4	*Production & Development*	Achieve operational capability that satisfies mission needs.
3	*System Development & Demonstration*	Develop a system or increment of capability; reduce integration and manufacturing risk; ensure operational supportability; reduce logistics footprint; implement human systems integration; design for producibility; ensure affordability and protection of critical program information; and demonstrate system integration, interoperability, safety, and utility.
2	*Technology Development*	Reduce technology risks and determine appropriate set of technologies to integrate into a full system.
1	*Concept Refinement*	Refine initial concept. Develop system/technology development strategy

Fig. 11. System readiness levels.

Table 9
The fundamental scale.

Scale	Definition	Explanation
1	Equal importance.	Two activities contribute equally to the objective.
3	Moderate importance of one over another.	Experience and judgment strongly favor one activity over another.
5	Essential or strong importance.	Experience and judgment strongly favor one activity over another.
7	Very strong importance.	An activity is strongly favored and its dominance demonstrated in practice.
9	Extreme importance.	The evidence favoring one activity over another is of the highest possible order of affirmation.
2,4,6,8	Intermediate values between the two adjacent judgments.	When compromise is needed.

evaluation indexes is difficult to quantify or the people's subjective choice plays a significant role in evaluation. It was developed by Thomas L. Saaty in the 1970s and has been expansively researched since then [18]. The AHP is a hierarchical and systematic evaluation method that combines qualitative analysis with quantitative calculation.

The core of the AHP is to build up a comparison matrix, which contains the relative importance of any two indexes. This step should be done by experts who have a deep understanding on the importance of the indicators.

We assume that there are n indexes, the importance ratio of index i and index j is a_{ij}, then the comparison matrix is.

$$A= (a_{ij})_{n\times n},\ a_{ij} = \frac{1}{a_{ji}} \tag{31}$$

where $a_{ij} = 1/a_{ji}$, that is, the comparison matrix $\boldsymbol{A}$ is a reciprocal matrix. There are 9 scales of a_{ij}, the meaning of each scale is shown in Table 9 [20,21].

For matrix $\boldsymbol{A}$, if

$$a_{ij}\cdot a_{jk} = a_{ik},\ i,\ j,\ k = 1,2,\ \cdots,n \tag{32}$$

then matrix $\boldsymbol{A}$ is also called consistent matrix.

If comparison matrix $\boldsymbol{A}$ is a consistent matrix, then the normalized eigenvector of characteristic root n is the weight vector. However, comparison matrix $\boldsymbol{A}$ is often inconsistent, if we use the normalized eigenvector of the largest characteristic root $\lambda_{\max}$ as weight vector, then the inconsistency of matrix A should be within an allowable range. So we have to check the inconsistency of comparison matrix $\boldsymbol{A}$. Thomas L. Saaty used consistence ratio CR to check the inconsistency of matrix $\boldsymbol{A}$, when

$$CR = \frac{CI}{RI} < 0.1 \tag{33}$$

the inconsistency of $\boldsymbol{A}$ could be considered in the allowable range. The CI in equation (33) is coincidence indicator

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{34}$$

The RI in equation (33) is random index. The values of RI are shown in Table 10.

Table 10
The value of RI.

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.52

5.2. The gray evaluation method

The gray evaluation method was proposed by Julong Deng in 1982 [19]. The key point of the gray evaluation method is gray correlation degree analysis. The advantage of the gray evaluation method is that it does not require a lot of observation data, and the distribution of the data is not required, and it is also practicable even though the data does not meet the statistical requirements.

The key point of the gray evaluation method is correlation degree analysis. The correlation degree indicates the similarity between the index and its corresponding optimal index, the higher the correlation degree, the better the index. The steps of gray evaluation method are as follows:

1) Determining the optimal index set $\boldsymbol{A}^*$

$$A^* = [a_1^*,\ a_2^*,\cdots,a_n^*] \tag{35}$$

where $a_j^*(j = 1,2,\cdots,n)$ represents the optimal value of index j. The optimal value can be chosen from all evaluated architectures, it can also be a recognized optimal value.

2) Building index matrix $\boldsymbol{B}$

$$B=\begin{bmatrix} a_1^* & a_2^* & \cdots & a_n^* \\ a_1^1 & a_2^1 & \cdots & a_n^1 \\ \vdots & \vdots & \ddots & \vdots \\ a_1^m & a_2^m & \cdots & a_n^m \end{bmatrix} \tag{36}$$

where a_j^i is the value of index j in architecture i.

3) Standardizing the indexes (in matrix $\boldsymbol{C}$)

The standardization method is

$$c_j^i = \frac{a_j^i - a_j^{min}}{a_j^{max} - a_j^{min}} \tag{37}$$

where a_j^{min} is the minimum value of index j in all architectures; a_j^{max} is the maximum value of index j in all architectures.

4) Calculating the correlation degree (in matrix $\boldsymbol{E}$)

The correlation degree of index j of architecture i is

$$\xi_i(j) = \frac{\min\limits_i \min\limits_j |c_j^* - c_j^i| + \rho \max\limits_i \max\limits_j |c_j^* - c_j^i|}{|c_j^* - c_j^i| + \rho \max\limits_i \max\limits_j |c_j^* - c_j^i|} \tag{38}$$

where $\rho\in[0,1]$, generally take $\rho = 0.5$.

5.3. Synthesis score calculation

According to weight $w(j)$ from formula (31)–(34) according to Table 9 in AHP and correlation degree $\xi_i(j)$ from formula (38), the synthesis score of architecture i is

$$r_i = \sum_{j=1}^{n} w(j)\cdot\xi_i(j) \tag{39}$$

6. Architectures comprehensive evaluation

Using the comprehensive evaluation model that established above, the manned lunar mission architectures could be evaluated. The first step of evaluation is to determine the relative importance of four indexes. For the manned space mission, reliability is always the most important, the second is the feasibility. So we assume that the relative importance of four indexes is: reliability x_3 > SRL of China's heavy-lift launch vehicle x_4 > IMLEO x_1 > mission duration x_2.

Table 11
The relative importance of four indexes.

index	x_1	x_2	x_3	x_4
x_1	1	3	1/4	1/3
x_2	1/3	1	1/5	1/4
x_3	4	5	1	2
x_4	3	4	1/2	1

Considering the mission loss rate and crew loss rate, the reliability can be calculated by these two rates. As we find the two rates are closely related, and thus we use mission loss rate to represent the reliability, which is more common in engineering system.

The definition of elements in pairwise comparison matrix is concluded in Table 9. According to the definition we constructed the pairwise comparison matrix for four indexes by engineering experience as an example [22], and it shows the relative importance of four indexes in Table 11.

The weight of four indexes (IMLEO, mission duration, reliability by mission and crew loss rate, SRL by order) is solved by utilizing the AHP:

$$w= [0.1374, 0.0698, 0.4887, 0.3041]^T \tag{40}$$

the $CR = 0.0423 < 0.1$, comparison matrix $\boldsymbol{A}$ passes the consistence test.

As seen from Table 8, the optimal index set is

$$A^* = [131.4, 10,0,6.45] \tag{41}$$

Where the optimal values of IMLEO, mission duration and SRL come from six architectures; the optimal value of reliability by mission and crew loss rate is theoretical optimum 0.

The index matrix is

$$B=\begin{bmatrix} 131.4 & 10 & 0 & 4 \\ 131.4 & 10 & 0.0465 & 2 \\ 135.0 & 26 & 0.0717 & 4 \\ 138.9 & 15 & 0.0586 & 2 \\ 152.7 & 18 & 0.0707 & 4 \\ 156.7 & 21 & 0.0828 & 4 \\ 153.6 & 26 & 0.0838 & 4 \end{bmatrix} \tag{42}$$

The standardized matrix $\boldsymbol{C}$ is calculated by using the gray evaluation method with formula (37):

$$\mathbf{C} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 0.5549 & 0 \\ 0.1423 & 1 & 0.8556 & 1 \\ 0.2964 & 0.3125 & 0.6993 & 0 \\ 0.8419 & 0.5 & 0.8437 & 1 \\ 1 & 0.6875 & 0.9881 & 1 \\ 0.8775 & 1 & 1 & 1 \end{bmatrix} \tag{43}$$

Then calculate the correlation degree matrix E by formula (38):

$$E=\begin{bmatrix} 1 & 1 & 0.4740 & 0.3333 \\ 0.7785 & 0.3333 & 0.3688 & 1 \\ 0.6278 & 0.6154 & 0.4169 & 0.3333 \\ 0.3726 & 0.5000 & 0.3721 & 1 \\ 0.3333 & 0.4211 & 0.3360 & 1 \\ 0.3630 & 0.3333 & 0.3333 & 1 \end{bmatrix} \tag{44}$$

The evaluation result is

$$R=E\cdot w= [0.5402, 0.6146, 0.4343, 0.5720, 0.5435, 0.5401]^T \tag{45}$$

If we did not consider the constraint of SRL by launch vehicles,

$$E' = \begin{bmatrix} 1 & 1 & 0.4740 \\ 0.7785 & 0.3333 & 0.3688 \\ 0.6278 & 0.6154 & 0.4169 \\ 0.3726 & 0.5000 & 0.3721 \\ 0.3333 & 0.4211 & 0.3360 \\ 0.3630 & 0.3333 & 0.3333 \end{bmatrix} \tag{46}$$

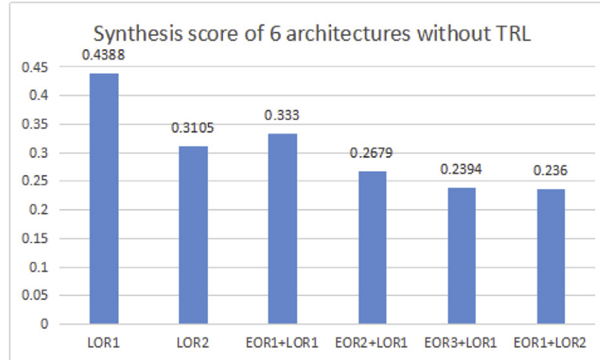

Fig. 12. Synthesis score of 6 architectures (Do not consider the SRL of launch vehicle).

$$w' = [0.1374, 0.0698, 0.4887]^T \tag{47}$$

The evaluation result is

$$\boldsymbol{R}' = \mathbf{E}'\cdot\mathbf{w}' = [0.4388, 0.3105, 0.3330, 0.2679, 0.2394, 0.2360]^T \tag{48}$$

The results are shown as Fig. 12and Fig. 13.

When do not consider the SRL (Fig. 12), the score of Architecture 1 is significantly higher than other architectures, which is consistent with the actual situation, for its low IMLEO, mission duration and high reliability. This architecture was just adopted in the Apollo project with an available LEO capacity of 150t, which totally meet the LEO capacity requirements of all 6 architectures and thus ignored the SRL [13]. Therefore the correctness and applicability of the method is further proved.

As a comparison, if we take SRL into consideration, the histogram of the evaluation results is presented in Fig. 13. We can draw a conclusion that if we take IMLEO, mission duration, reliability and the SRL of launch vehicle these four factors into account, architecture 2 scores highest for its high IMLEO and SRL, with other indexes not too low. And architecture 1, 4, 5, 6 scores closely and they are also suitable modes for China's manned lunar mission now, while architecture 3 is not that promising. What's more, comparing to Fig. 11 which does not consider SRL, the score of architecture 1 is not highest, which indicates that SRL will make other architectures with higher SRL indexes (architecture 2, 4, 5, 6) score relatively higher.

Different engineering technology environment means different SRL indexes, so this result is just adjust to the current level of China's launch vehicle technology, so it can provide some reference for the demonstration of China's manned lunar mission at present stage.

Though we only evaluated six manned lunar mission architectures, the comprehensive evaluation model in this paper possesses favorable generality, applicable to all kinds of Moon/Mars mission architectures.

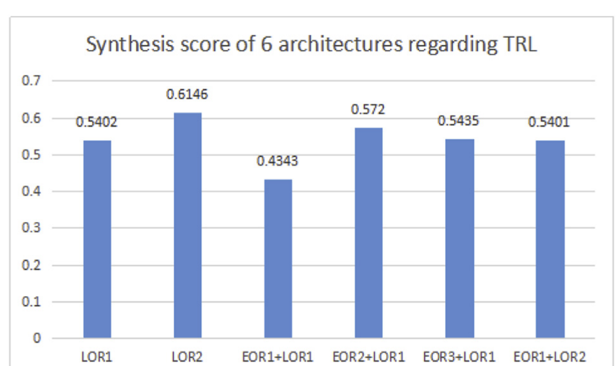

Fig. 13. Synthesis score of 6 architectures (consider the SRL of launch vehicle).

7. Conclusion

1) This paper adopted AHP in combination with gray evaluation method to evaluate six manned lunar mission architectures. The IMLEO, mission duration, reliability and the SRL of China's heavy-lift launch vehicle were taken into account. The evaluation result indicates that Architecture 5 (the 4-launch EOR-LOR architecture, three rendezvous in LEO, one in LLO) is the most suitable architecture for present China. Architecture 1 (1-luanch LOR), architecture 2 (2-launch LOR) and architecture 4 (4-launch EOR-LOR) all could be alternative architecture for Architecture 5.
2) If we don't consider the SRL of launch vehicle, the score of Architecture 1 (the 1-launch LOR architecture) is obviously higher than other architectures as a consequence of its low IMLEO, mission duration and high reliability. Therefore, if the launch vehicle satisfies the launching requirement, such as 150t Saturn V in Apollo mission, Architecture 1 could be the best choice for manned lunar mission.

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