An Operations Management Method for a Logistics Network of Distributed Life Support Systems on the Lunar Surface

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A logistics network is proposed for manned wide-area exploration on the lunar surface. A logistics carrier operation problem has been formulated and solved using Lagrangian decomposition and coordination, developed for operations management of Advanced Life Support Systems. The method can solve operations scheduling problems consisting of two rovers and a logistics carrier, which are then modeled in limited axial movement. This paper describes how to generate an operations schedule for the logistics carrier which is calculated considering both the rover positions and supply possibilities in the logistics network.

Nomenclature

B_{ji}	= index describing whether vehicle *i* is connected with job *j* (i.e., not connected if = 0; connected if = 1)
Ch_{CO2}	= carbon dioxide discharge rate of crew
Ch_{O2}	= amount of crew oxygen consumption
c_j	= unit switching cost of job *j*
d_{it}	= position of vehicle *i* on a timeslot *t*
$d_{it,obj}$	= object position of vehicle *i*
D_{Li}	= lower bound position of vehicle *i*
D_{Ui}	= upper bound position of vehicle *i*
El_{M1}	= production rate of electrolysis reaction of Habitation Module 1
h_i	= unit supply cost of vehicle *i* on a timeslot *t*
i	= numbers of module, rover, and logistics carrier (i=1, 2, …, I)
j	= job number (j=1, 2, …, J)
l	= Lagrangian function
M_{M1O2}	= amount of oxygen in module of Habitation Module 1
M_{Rm1O2}	= amount of oxygen in module of Pressurized Rover 1
M_{Rm2O2}	= amount of oxygen in module of Pressurized Rover 2
N_{Mh}	= number of crew
pC_{sa}	= carbon production rate of CO_2 reductor
pH_{2El}	= hydrogen production rate of electrolysis reaction
pO_{2El}	= oxygen production rate of electrolysis reaction
pO_{2Sa}	= oxygen production rate of CO_2 reductor
rH_{2O}	= water consumption rate of electrolysis reaction
rO_{2M1}	= amount of oxygen supply to module in Habitation Module 1
rO_{2Rm1}	= amount of oxygen supply to module in Pressurized Rover 1
rO_{2Rm2}	= amount of oxygen supply to module in Pressurized Rover 2
Sa_{M1}	= production rate of sabattier reaction of Habitation Module 1
sw_{jt}	= amount of oxygen supply
t	= timeslot number (t=1, 2, …, T)
Ta_{LcO2}	= amount of oxygen in tank of Logistics Carrier
Ta_{M1O2}	= amount of oxygen in tank of Habitation Module 1
Ta_{M1W}	= amount of water in module of Habitation Module 1
Ta_{Rm1O2}	= amount of oxygen in tank of Pressurized Rover 1

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Ta_{Rm2O2} = amount of oxygen in tank of Pressurized Rover 2
v_{ijt} = velocity of vehicle *i* due to job *j* on timeslot *t*
Wfc = amount of water supply from fuel cell
Wh = amount of water consumption of crew
x_{imax} = amount of maximum supply of vehicle *i* on timeslot *t*
x_{it} = amount of supply of vehicle *i* on timeslot *t*
δ_{jt} = index of describing whether to execute job *j* on timeslot *t* (i.e., go back =-1; stop =0; go forward=1)

I. Introduction

The Apollo Project, which lasted from 1961 to 1972 in the US, conducted six landings on the lunar surface from 1969. During the course of this project, lunar roving vehicles were carried to the lunar surface on Apollo 15, 16, and 17 in 1971 and 1972. In Apollo 15 the astronauts drove the vehicle for 27.6km. One of the lasting lessons of the Apollo program is that surface mobility is key to improving the efficiency of humans on the lunar surface[1].

For the next lunar landing we do not want to arrive at any random destination, but instead a location of our choosing. After their landing, the crewmembers will be able to explore the lunar surface at a range stretching beyond a hundred kilometers from their habitation module with the use of a logistics carrier and pressurized rovers. Included in the lunar outpost will be habitation modules, logistic carriers, in situ resource utilization (ISRU), extravehicular activity (EVA) systems, and the pressurized rovers. The EVA systems and pressurized rovers make it possible for the crewmembers to conduct multiple exploratory missions to predetermined sites. Within the range of the expedition there will be several logistics carriers, each capable of providing life support necessities to a full crew for up to one week during their missions. By operating the exploration system with a combination of logistics carriers and manned pressurized rovers, the crew can explore a much wider range safely with back up systems in case of emergency. With such distributed life support system operations, in order to determine how much life support supplies will be required, we have to decide where, when, how much, and what types of supplies are going to be stored in order to meet the expedition's needs and those needs can vary with each operation. If the supplies are inappropriately stored at any point, regardless of whether or not there is a sufficient amount of supplies on the lunar surface, this inappropriate storage will inevitably lead to a lack of supplies. It is very important to develop a logistics network on the lunar surface and control the method through which life support systems distribute supplies. The purpose of this research is to provide a method to make such dynamic resource allocations. To this end an algorithm was developed to include each element of the operation. The Lagrangian Decomposition and Coordination (LDC) method[2-4], which was developed for Advanced Life Support Systems (ALSS), is here applied to the study of logistics carrier operations planning in a logistics network on the lunar surface.

II. Logistics Network on Lunar Surface

Life support systems and the supplies for life support are movable and operated as decentralized units at multiple exploration sites to facilitate the exploration of a wider area on the lunar surface with the assistance of pressurized rovers and the logistics carriers. It is necessary for the logistics network to operate by using the integrated operation method. Figure 1 illustrates the concept. Multiple exploration sites are located around a habitation module from which investigations are to be conducted with pressurized rovers and logistics carriers. In this study each such investigation consists of discrete units, which I call jobs. Each job consists of one or two rovers and one logistics carrier. The movements of the logistics carrier will be determined by the separate requirements of each rover and a response of the logistics carrier to a single demand from a rover will constitute the smallest unit of activity or job. There are similar examples in industrial area, such as Vehicle Routing Problems (VRP) and Automated Guided Vehicle (AGV) Routing Problems (AGVRP). However, there are differences between routing problems in industry and logistics networks on the lunar surface. In the logistics network, crew members consume the materials of life, a limited supply of which are stored in the manned rover for up to a week. Moreover, the rovers do not run on a set of tracks so that their position is not always well defined like the AGV in the factory. To maximize reliability and to decrease planning complexities, the lunar logistics network will require an autonomous distributed control system where components are operated separately far from each other.

As mentioned above a simulator for the Advanced Life Support Systems (ALSS) was developed earlier and for this study, using the LDC method, we integrate a distributed control method into the simulator. In the next section I show the results of a study of its application to logistics carrier operations planning in the logistics network on the lunar surface.

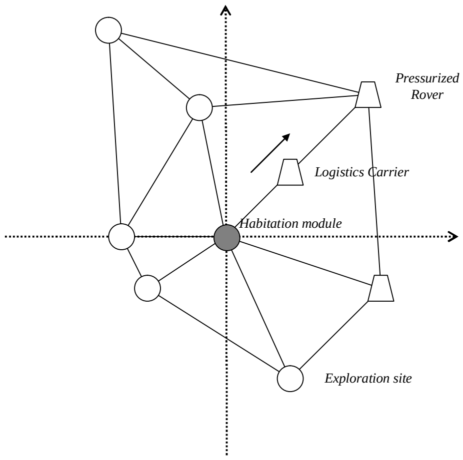


Figure 1 Logistics Network on the Lunar Surface.

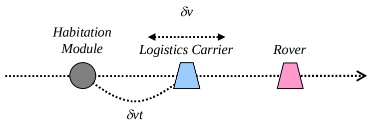


Figure 2 Movement Model of Rover and Logistics Carrier on the Lunar Surface.

III. Scheduling Algorithm

A. Formulation of Lagrangian decomposition and coordination method

Because of advances in computer technology, solutions in large scale combination problems have become feasible by the use of optimization methods. In such cases, a decomposition method is generally used in which the problem is broken down into partial problems. When the problem is decomposable in this way, the minimization of the partial problems leads to the minimization of the whole problem[5,6]. The LDC method is particularly suitable to logistics carrier operations planning in a logistics network on the lunar surface. Fig. 2 shows the movement model of rovers and logistics carrier in limited axial movement where, v is velocity, t is time, and δ is the direction of the logistic carrier's movement. Each requirement for supply by the rover places a demand on the logistics carrier's activity and each such demand constitutes a job in this scheduling algorithm.

Assume that the cost of operation is the sum of four terms: (1) the switching cost of the logistic carrier's movement, (2) distance moved, (3) amount of deviation from target position of a rover, and (4) the product of distance from the habitation module and the exhaustion rate of the required supplies. Then an objective function can be expressed using the Eq. (1). The first term measures the switching cost of a logistics carrier's movement, the second term measures the cost of the distance moved, the third term measures the fractional distance from the target position, and the fourth term is the product of the unit supply cost, the distance from the habitation module and the exhaustion rate of the supplies. In the first term the unit switching cost of job j, c_j is multiplied by the switching index of job j on timeslot t, $(1-\delta_{jt-1})\delta_{jt}$. In the second term the unit switching cost of job j, c_j is multiplied by the switching index of job j on timeslot t, δ_{jt} . In the fourth term the unit supply cost of logistics carrier i on timeslot t, h_i is multiplied by the index B_{ji}, by the distance of logistics carrier i from habitation module, d_{ij}/D_{imax}, and by the exhaustion of supply in logistics carrier i from the maximum capacity on the timeslot t, $(x_{imax}-x_{it})/x_{imax}$.

$$min \quad \sum_{t=1}^{T}\sum_{j=1}^{J}\left[c_j\left(1-\left|\delta_{jt-1}\right|\right)\cdot\left|\delta_{jt}\right| + c_j\left|\delta_{jt}\right| + \left(d_{ij,obj}-d_{ij}\right)\Big/d_{ij,obj} + h_i\left(B_{ji}\,d_{ij}/D_{i\max}\right)\left(x_{i\max}-x_{it}\right)\Big/x_{i\max}\right] \tag{1}$$

As constraint conditions for the above equation, the change of logistics carrier position, the constraint of lower bound of logistics carrier position, the constraint of upper bound of logistics carrier position, and the constraint of a competition on a logistics carrier (not allowing simultaneous use of a logistics carrier) are defined as Eqs. (2) to (5).

$$\text{subject to} \quad d_{it+1} = d_{it} + \sum_{j=1}^{J} \delta_{jt} v_{ijt} t \quad \forall i,t \tag{2}$$

$$d_{it} \geq D_{Li} \quad \forall i,t \tag{3}$$

$$d_{it} \leq D_{Ui} \quad \forall i,t \tag{4}$$

$$\sum_{j}^{J} \delta_{jt} B_{ji} \leq 1 \quad \forall i,t \tag{5}$$

B. Lagrangian relaxation

Next, an optimization problem with constraints is replaced by one without constraints by using Lagrangian multipliers. This is referred to as a Lagrangian relaxation. That is, the formulation of an optimization problem is changed from a strict formulation in which constraints must be satisfied to a relaxed formulation in which constraint violations must be reduced. In Eqs. (1) to (5), introducing Lagrangian multipliers denoted by λ, where λ may be thought of as a use fee or a way of measuring competition for the use of a logistics carrier, then Eq. (5) is relaxed as follows:

$$\begin{aligned} \min \quad & \sum_{t=1}^{T} \sum_{j=1}^{J} \Big[c_j \left(1 - \left|\delta_{jt-1}\right|\right) \cdot \left|\delta_{jt}\right| + c_j \left|\delta_{jt}\right| + \left(d_{ij,obj} - d_{ij}\right) \big/ d_{ij,obj} \\ & + h_i \left(B_{ji}\, d_i / D_{i\max}\right) \left(x_{i\max} - x_{it}\right) \big/ x_{i\max} \Big] + \sum_{t=1}^{T} \sum_{i}^{I} \lambda_{it} \left(\sum_{j=1}^{J} \delta_{jt} B_{ji} - 1 \right) \end{aligned} \tag{6}$$

subject to Eqs. (2) - (4)

where λ also represents the use fee of a logistics carrier.

C. Decomposition to partial problems

A decision variable vector $\boldsymbol{\delta}$ and a logistics carrier position variable vector $\boldsymbol{d}$ related to Eqs. (6) and (2) to (4), are decomposed for individual jobs. Hence, minimizing the problem expressed using Eqs. (6) and (2) to (4) is equivalent to independently minimizing partial problems which are expressed using Eqs. (7), (8), (3) and (4) related to job j. This formulation can minimize complexity using Dynamic Programming (DP) for solving partial problems.

$$\begin{aligned} \min \quad l_j = & \sum_{t=1}^{T} \Big[c_j \left(1 - \left|\delta_{jt-1}\right|\right) \left|\delta_{jt}\right| + c_j \left|\delta_{jt}\right| + \left(d_{ij,obj} - d_{ij}\right) \big/ d_{ij,obj} \\ & + h_i \left(B_{ji}\, d_{ij} / D_{i\max}\right) \left(x_{i\max} - x_{it}\right) \big/ x_{i\max} \Big] + \sum_{t=1}^{T} \sum_{i}^{I} \lambda_{it} \delta_{jt} B_{ji} \end{aligned} \tag{7}$$

$$\text{subject to} \quad d_{it+1} = d_{it} + \delta_{jt} v_{ijt} t \quad \forall i,t \tag{8}$$

Although Eqs. (7), (8), (3) and (4) represent scheduling problems corresponding to individual jobs, these problems are related to each other so that the result of one scheduling influences another scheduling since there are terms related to interference of supply and competition for a logistics carrier. A devised point in the present formulation is to introduce the term B_{ji} in Eq. (7) and to decompose terms not explicitly expressed for individual jobs. This is because in decision-making for an individual job after decomposition, a good result is obtained by considering only a state that is directly applicable to the execution of the job. Before introducing the term B_{ji}, good results were not obtained due to excessive interference.

D. Cooperation by Lagrangian Decomposition and Coordination Method

Computation is performed so that individual scheduling as a whole gradually comes into cooperation while iteratively solving the partial problems. At this time, if the Lagrangian multipliers are suitably determined, more effective searching can be expected than random searching. Here, the Lagrangian multipliers are determined using the auction concept[6]. When a competition occurs on a logistic carrier on a timeslot, the setting of an appropriate price allows one job to put back to another timeslot, so that the job with the more critical need retains use of the logistics carrier albeit paying a high use fee. That is, even if individual jobs behave ‘egotistically’, adjusting the price of the logistics carrier may resolve the competition and result in an improved schedule. What is meant by ‘egotistically’ is that the Lagrangian multipliers in individual jobs (partial problems) are minimized. For the adjustment of the price, the direction of a price change is determined using the subgradient method. As the subgradients of this problem, λ represents the number of instances of completion for the of logistics carrier.

Subsequently, using the duality gap expressed in Eq. (11), a created schedule is evaluated. A duality gap signifies the difference between Lagrangian multipliers of a main problem expressed by Eq. (9) and a dual problem expressed by Eq. (10), and also implies a discrepancy (poor price setting) between a set price and a price in real life. In this computation, when the duality gap falls below a threshold or when the subgradient becomes 0, the iteration is terminated. A procedure for this computation is shown in Fig. 3. Following the procedure, the interference of states and competition for devices will be eliminated.

Main problem: $$l_l = \min_x l(x,\lambda) \quad (9)$$

Dual problem: $$l_u = \max_\lambda \min_x l(x,\lambda) \quad (10)$$

Duality gap: $$l_u - l_l \quad (11)$$

Step 1: Initialize Lagrangian multipliers

Set the Lagrangian multipliers λ =0.

Step 2: Solve partial problems

Solve partial problems consisting of Eqs. (7), (8), (3) and (4) related to jobs j; and seek schedule vectors δ_{jt} for the individual jobs.

Step 3: Seek subgradients of the Lagrangian multipliers.

Seek subgradients of λ.

$$subgrad(\boldsymbol{\lambda}) = \{\cdots, \partial l / \partial \lambda, \cdots\};.$$

Step 4: Update Lagrangian multipliers

$$\boldsymbol{\lambda} = \boldsymbol{\lambda} + s_i \cdot subgrad(\boldsymbol{\lambda})$$ s_i: step width

Step 5: Correct solutions of partial problems to feasible ones

When there is a constraint violation in the schedule obtained in Step 2, the schedule is corrected to a feasible one. In the present computation, when a competition occurs, the job is moved forward or back to the nearest unoccupied timeslot.

Step 6: Seek a duality gap

Compute the Lagrangian functions l_l and l_u with respect to the schedules obtained in Steps 2 and 5 to obtain the duality gap l_u - l_l.

Step 7: Conditions of termination

The computation is terminated when one of the following conditions is established. The duality gap falls below a threshold. Subgradients become 0, and this means that the Lagrangian multipliers converge.

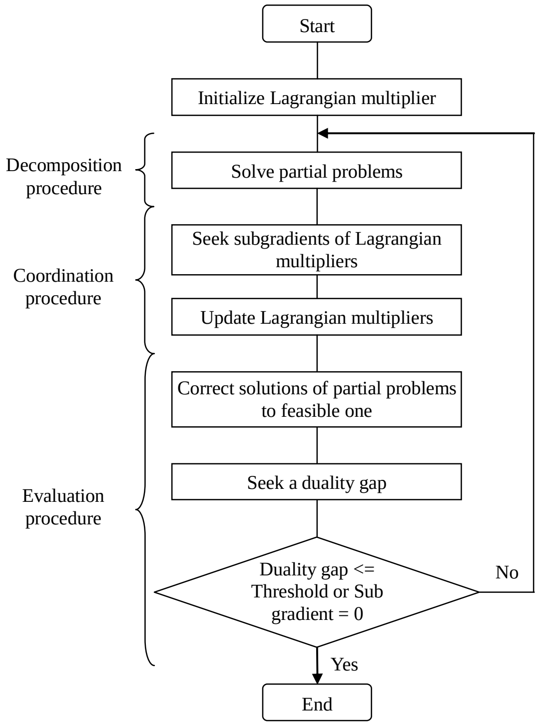


Figure 3 Lagrangian Decomposition and Coordination.

IV. Calculation Examples

E. Description of Logistics Carrier Operation

In this example, I solve an oxygen allocation problem with the oxygen supply system shown in Fig. 4 as an example of a confined logistics network in the lunar outpost. This logistics network consists of a Habitation Module, two Pressurized Rovers, and a Logistics Carrier. The oxygen supply system is expressed by Eqs. (12) to (23). Eqs. (12) to (16) are the Habitation Module, Eq. (17) is the Logistics Carrier, Eqs. (18) to (21) are the Pressurized Rovers, Eq. (22) is position of the Rovers and Logistics Carrier on lunar surface, and Eq. (23) is an amount of oxygen supply among the Rovers and Logistics Carrier. The supply system has five lines which are from the Habitation Module to Logistics Carrier (sw_1), Rovers 1 (sw_2) and 2 (sw_3), and from Logistics Carrier to Rovers 1 (sw_4) and 2 (sw_5). The supply system can operate when individual Habitation Module, Rovers, and the Logistics Carrier stay in place. The operation schedule of the Logistics Carrier is calculated considering both the rover positions and supply possibilities.

Table 1 shows the initial conditions used in this calculation. Here, operation schedules of Rovers 1 and 2 are given in advance, and the operation schedule of the Logistics Carrier is solved by the calculation. Table 1 (e) to (h) show the initial oxygen storage for the Rovers, Logistics Carrier, and Habitation Module. The switching cost of Table 1 (i) prevents Logistics Carrier from repeatedly going forward and back, and the supply cost of Table 1 (j) prevents the Logistics Carrier from remaining far from the Habitation Module when it has insufficient oxygen.

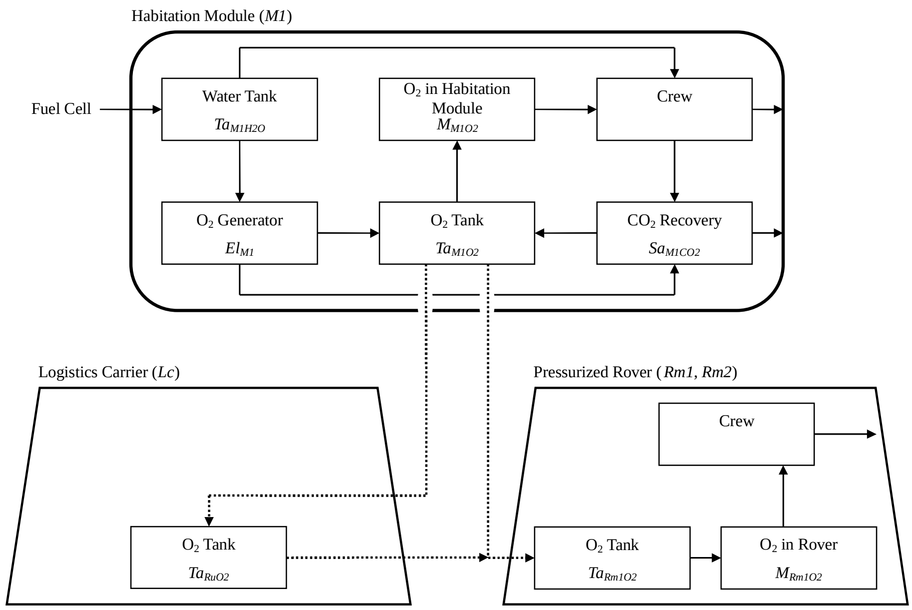


Figure 4 Oxygen Supply Systems in the Lunar Outpost.

Table 1 Initial Condition of Module, Rovers, and Logistics Carrier.

	Initial Conditions	Descriptions
(a)	Positions of Rover 1 [days]	-
	lx1 = {0,1,2,3,4,5,6,7,6,5,4,3,2,1,0}	(1) to (4)
(b)	Positions of Rover 2 [days]	-
	lx2 = {0,0,0,0,0,0,0,0,0,0,0,0,0,0,0}	(1)
	lx2 = {0,0,1,2,3,3,3,3,3,3,3,2,1,0,0}	(2) and (3)
	lx2 = {0,0,0,1,2,3,4,5,4,3,2,1,0,0,0}	(4)
(c)	Initial starting position of logistics carrier [days]	(2): 7 (1),(3) and (4): 0
(d)	Initial movement direction of Logistic Carrier [-]	$\delta = 0$
(e)	Oxygen in Rover 1 [CM-days]	14
(f)	Oxygen in Rover 2 [CM-days]	14
(g)	Oxygen in Logistics Carrier [CM-days]	28
(h)	Oxygen in Habitation Module 1[CM-days]	56
(i)	Switching cost *c* [-]	In Figure 5
(j)	Supply cost *h* [-]	In Figure 5

Oxygen Supply System Models
Habitation Module $i = 0$

$$M_{M1O2}(t+1) = M_{M1O2}(t) + rO_{2M1}(t) - Ch_{O2} \cdot N_{Mh} \tag{12}$$

$$Ta_{M1O2}(t+1) = Ta_{M1O2}(t) + pO_{2Sa}(t) + pO_{2El}(t) - rO_{2M1}(t) - sw_1 - sw_2 - sw_3 \tag{13}$$

$$Ta_{M1W}(t+1) = Ta_{M1W}(t) + Wfc(t) - rH_2O_{El}(t) - Wh(t) \cdot N_{Mh} \tag{14}$$

$$Sa_{M1}(t+1) = Sa_{M1}(t) - \left[pO_{2sa}(t) + pC_{sa}(t) \right] + Ch_{CO2} \cdot N_{Mh} \tag{15}$$

$$El_{M1}(t+1) = El_{M1}(t) + \left[rH_2O_{El}(t) - pO_{2El}(t) - pH_{2El}(t)\right] \tag{16}$$

Logistics Carrier $i = 1$

$$Ta_{LcO2}(t+1) = Ta_{LcO2}(t) + sw_3 - sw_4 - sw_5 \tag{17}$$

Pressurized Rover 1 $i = 2$

$$M_{Rm1O2}(t+1) = M_{Rm1O2}(t) + rO_{2Rm1}(t) - Ch_{O2} \cdot N_{Rh} \tag{18}$$

$$Ta_{Rm1O2}(t+1) = Ta_{Rm1O2}(t) - rO_{2Rm1}(t) + sw_2 + sw_4 \tag{19}$$

Pressurized Rover 2 $i = 3$

$$M_{Rm2O2}(t+1) = M_{Rm2O2}(t) + rO_{2Rm2}(t) - Ch_{O2} \cdot N_{Rh} \tag{20}$$

$$Ta_{Rm2O2}(t+1) = Ta_{Rm2O2}(t) - rO_{2Rm2}(t) + sw_3 + sw_5 \tag{21}$$

Position Models of Rovers and Logistics Carrier

$$\begin{aligned} &d_i = v_i t_{1i}\delta_i - v_i t_{2i}\delta_i \\ &t_{1i} + t_{2i} + t_{3i} = T_i \\ &t_{1i} \le t_{2i} \end{aligned} \tag{22}$$

Supply Model among Rovers, Logistics Carrier and Habitation Module

$$sw_j = \begin{cases} if\,(d_1 = 0) & sw_1 = Ta_{LcO2\max} - Ta_{LcO2}(t) \\ if\,(d_2 = 0) & sw_2 = Ta_{Rm1O2\max} - Ta_{Rm1O2}(t) \\ if\,(d_3 = 0) & sw_3 = Ta_{Rm2O2\max} - Ta_{Rm2O2}(t) \\ if\,(d_1 = d_2) & sw_4 = Ta_{Rm1O2\max} - Ta_{Rm1O2}(t) \\ if\,(d_1 = d_3) & sw_5 = Ta_{Rm2O2\max} - Ta_{Rm2O2}(t) \end{cases} \tag{23}$$

F. Results of the Calculations

The calculations pertain to four operation schedule problems of the Logistics Carrier as follows:
(1) Only Rover 1 is used and initial positions of Rover 1 and Logistics Carrier are the same.
(2) Only Rover 1 is used and initial positions of Rover 1 and Logistics Carrier are different.
(3) Rovers 1 and 2 are used and the rovers are at a short separation distance.
(4) Rovers 1 and 2 are used and the rovers are at a long separation distance.

Calculations (1) and (2) demonstrate how simple operations can be solved in the case of easy conditions involving a single rover and the Logistics Carrier. Calculation (3) demonstrates similar simple solution in the case of easy conditions between two rovers and the Logistics Carrier. Calculation (4) demonstrates the more difficult condition involving two rovers and the Logistics Carrier.

The results are presented in Fig. 5 (1) to (4) where the graphs on the left show the positions of the vehicles, and graphs on the right show the amount of oxygen. The units of the position and the amount of oxygen are defined: 1 [day] as the distance of 1 day's movement, and 1 [CM-day] as the amount of oxygen consumed per crewmember in 1 day.

Calculation (1)

This operation schedule was solved when only Rover 1 is used and the initial positions of Rover 1 and Logistics Carrier are the same. Fig. 5, left (1) shows the position of Rover 1 (Lr1) and logistics Carrier (Lc). Fig. 5, right (1) shows the amount of oxygen in Rover 1 (Mr1) and Logistics Carrier (Mc). Logistics Carrier can follow Rover 1, supplying oxygen to Rover 1, and Rover 1 can go back to the Habitation Module without insufficient oxygen.

Calculation (2)

This operation schedule was solved when only Rover 1 is used and the initial positions of Rover 1 and Logistics Carrier are different.

(a) Fig. 5, left (2) shows the position of Rover 1 (Lr1) and Logistics Carrier (Lc). Fig. 5, right (2) shows the amount of oxygen in Rover 1 (Mr1) and Logistics Carrier (Mc). Fig. 5 demonstrates that the Logistics Carrier moved to Rover 1 from its starting position in 7 days and supplied oxygen to Rover 1 after which it remained with the Rover for the duration of the mission with the exception of day 7.

(b) The same operation schedule was solved when c was changed from 0.1 to 0.3. The logistics carrier stopped in the same position from the 2nd day to the 9th day at which time it supplied oxygen to Rover 1 remaining with the Rover thereafter. This demonstrates that by control of c we can prevent the Logistics Carrier from repeatedly making unnecessary trips forward and back.

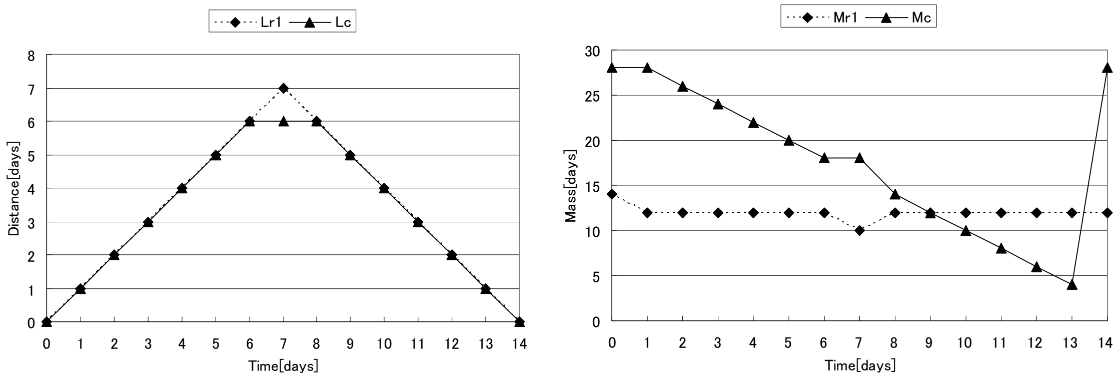
Calculation (3)

This operation schedule called for both Rovers 1 and 2 to be used and to be separated by two days distance, the Logistics Carrier initially positioned with Rover 1. Fig. 5, left (3) shows the positions of Rover 1 (Lr1), Rover 2 (Lr2), and Logistics Carrier (Lc). Fig. 5, right (3) shows the amount of oxygen in Rover 1 (Mr1), Rover 2 (Mr2), and Logistics Carrier (Mc). Rover 1 moves out on day 0 and Rover 2 remains at rest until day 2. The Logistics Carrier moves with Rovers 1 supplying it with oxygen until day 5 when it moves to Rover 2 and replenishes its supply. On day 8 it returns to Rovers 1 and both Rovers return to the Habitation Module with sufficient oxygen.

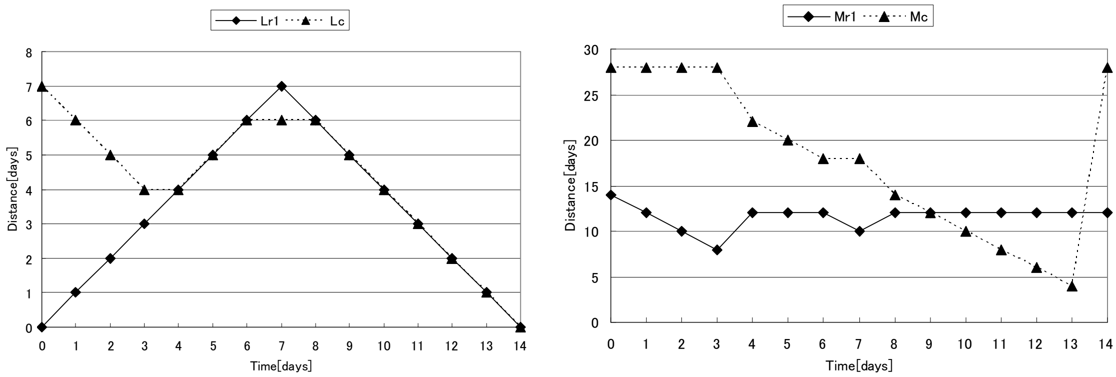
Calculation (4)

This operation schedules a large separation between Rovers 1 and 2. Fig. 5, left (4) shows the positions of Rover 1 (Lr1), Rover 2 (Lr2), and Logistics Carrier (Lc). Initially the rovers travel together, the Logistics Carrier traveling with Rover 1. On day 5 the carrier moves to Rover 2 and replenishes it after which the rovers begin to separate when Rover 2 stops and the Logistics Carrier maintains a position between them. As Rover 1 continues the separation grows, the Logistics Carrier maintaining itself between the two rovers until day 8 when it rejoins Rover 1. The separation distance now diminishing, the Logistics Carrier remains with Rover 1 to the end of the mission. Fig. 5, right (4) shows the amount of oxygen in Rover 1 (Mr1), Rover 2 (Mr2), and Logistics Carrier (Mc). This reveals that (a) Rover 1 reaches the Habitation Module with more than enough oxygen and (b) both Rover 2 and the Logistics Carrier run out of oxygen at 12th day. Evidently if the Logistics Carrier had transferred too much oxygen to Rover 1 on day 8 and should have retained some for Rover 2.

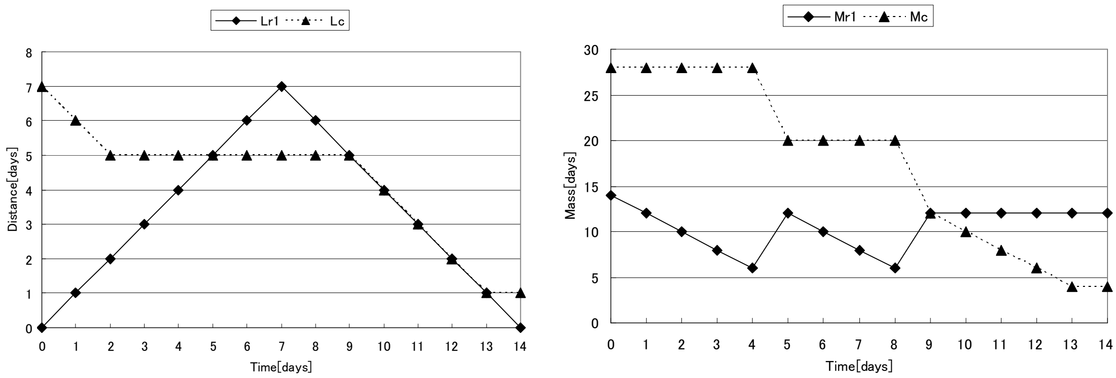
In the second test of large separation I increase c to 0.2. Both Rovers follow the same paths as before. The Logistics Carrier remains with Rover 1 until day 3 after which it joins Rover 2, there remaining until day 9 when it rejoins Rover 1, exhausts its oxygen supply and returns to the Habitation Module with that vehicle. This time the oxygen supply graphs show that Rover 1 oxygen reaches a minimum on day 8 and Rover 2 reaches its minimum on day 12 but in neither case is the supply insufficient. The control of c has more effectively managed this difficult condition.



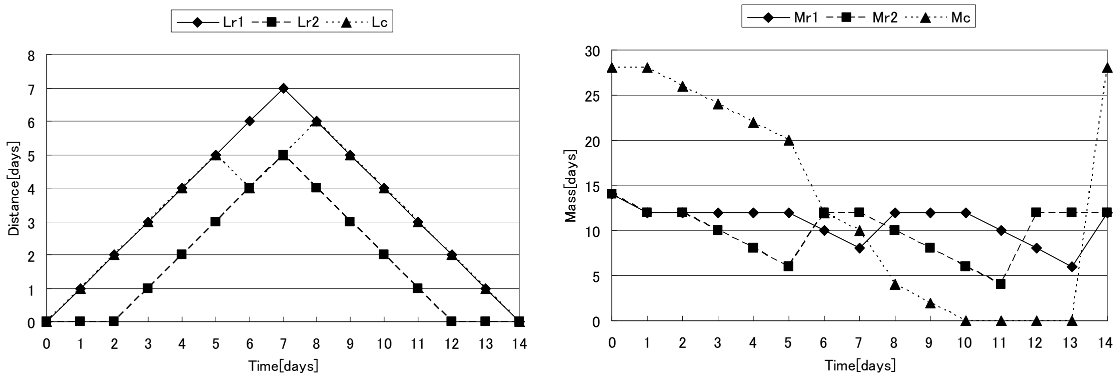
(1) Only Rover 1 is used and initial positions of Rover 1 and Logistics Carrier are the same *h* = 1, *c* = 0.1



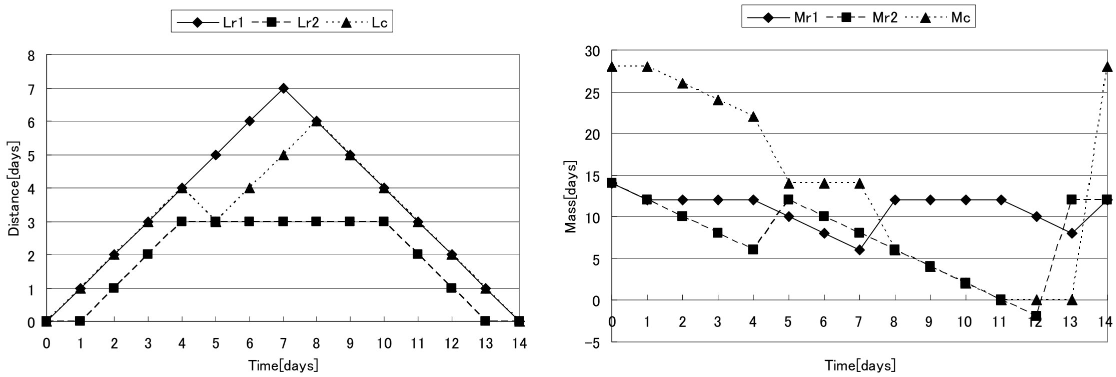
(2) – (a) Only Rover 1 is used and initial position of Rover 1 and Logistics Carrier are different *h* = 1, *c* = 0.1



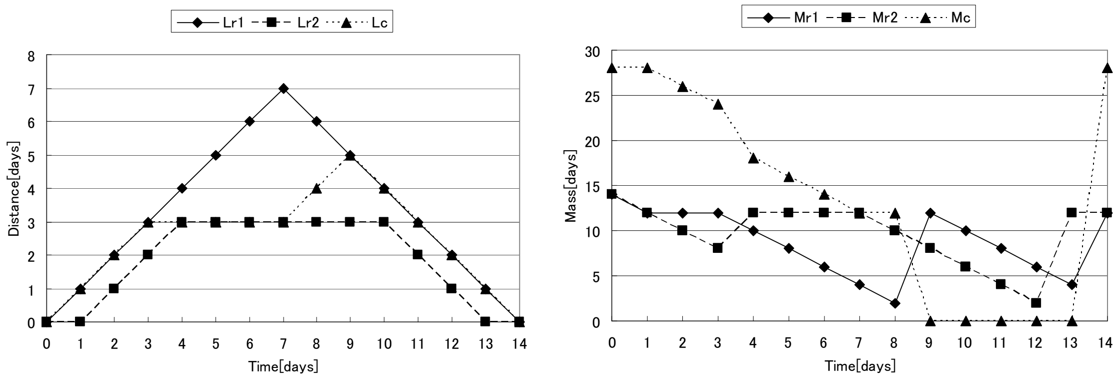
(2) - (b) Only Rover 1 is used and initial position of Rover 1 and Logistics Carrier are different *h* = 1, *c* = 0.3



(3) Rovers 1 and 2 are used and the rovers are at a short distance away *h* = 1, *c* = 0.1



(4) – (a) Rovers 1 and 2 are used and the rovers are at a long distance away *h* = 1, *c* = 0.1



(4) – (b) Rovers 1 and 2 are used and the rovers are at a long distance away *h* = 1, *c* = 0.2

Figure 5 Changes of positions of the vehicles and the amount of oxygen.
The graphs on the left show the positions of the vehicles, and graphs on the right show the amount of oxygen in Fig. 5 (1) to (4).

V. Conclusion

The proposed logistics network for manned wide area exploration on the lunar surface was formulated and tested by means of a Logistics Carrier operation problem using LDC. The results demonstrate that this method can solve operation schedule problems that consist of two Rovers and Logistics Carrier which is modeled in limited axial movement. This method guarantees the computational accuracy of partial problems because of the use of Dynamic

Programming (DP) to solve them. This method can apply to large scale problems because the method is a decomposition method. As the evaluation function of this method can be expanded to include movement in a network, it is planned to extend its application to large scale problems in complex networks in the future.

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