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Matrix Modeling Methods for Spaceflight Campaign Logistics Analysis

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This paper proposes a matrix-based modeling approach for analyzing spaceflight campaign logistics. A campaign is considered to be a series of coordinated flights delivering cargo at a location or node. A matrix representation of the cargo carried by flights for consumption in different time periods (or missions) is formulated. The matrix adopts specific structures based on the nature of the campaign, thereby allowing a quick visualization of the campaign logistics properties. A logistics strategy index is proposed for quantifying manifesting strategies, and a flight criticality index is defined to help in identifying important flights from a cargo-delivery perspective and aid in assessing impact of flight cancellations, failures, and delays. The method is demonstrated on a lunar outpost establishment and is also applied in modeling the logistics of the International Space Station. A manifest (*M*) matrix and flight dependency (*D*) matrix is created for crew provisions cargo delivered to the ISS over a period of 10 years. It is found that the overall logistics strategy index for crew provisions has so far been 0.85 (meaning 85% of the crew provisions cargo is prepositioned on average for each mission) and that the prepositioning is for up to a maximum of four future missions at a time.

Nomenclature

b	=	width of lower triangular band diagonal of M
c_i	=	cargo capacity of flight i
D	=	dependency matrix
d_j	=	cargo demand of mission j
F	=	total number of flights in a campaign
f_i	=	flight i
M	=	manifest matrix
m_{ij}	=	cargo delivered by flight i for mission j
N_m^i	=	number of missions served by flight i
p	=	width of upper triangular band diagonal of M
T_i	=	time elapsed between arrival of flights i and $i+1$
δ_{ij}	=	(cargo) dependency of mission j on flight i

I. Introduction

MODELING the logistics of a long space exploration campaign, consisting of many flights over a period of several years, is nontrivial. Keeping track of flight activity, demand and delivery of different types of cargo, in addition to accounting for flight capacity constraints and inventory levels, can quickly become analytically complex [1]. An in-depth understanding of the logistics for a long space exploration campaign is, however, very desirable [2].

With NASA's new focus on sending humans back to the moon and ultimately to Mars [3], logistical considerations for supporting these missions have gained an increased importance. An important goal is to understand and then quantify how to optimally deliver what cargo and when (to a particular location) given future demand and consumption. In other words, it is important to understand how an optimal mix of prepositioning, carry along, and resupply manifesting strategies can be executed to ultimately maximize exploration.

It can be reasonably assumed that long-term exploration of the moon and Mars will employ several flights over the course of many years [3,4]. In these future missions, the flight cargo manifest strategies can play a key role in the overall success of the programs. One of the main challenges is that the cargo mass fractions in human spaceflight are significantly less than those of terrestrial vehicles where cargo often makes up more than 25% of the wet mass of a transportation vehicle. In the Apollo program, for example, "useful" cargo including the crew itself, scientific equipment, rovers, spacesuits and consumables accounted for only about 1500 kg whereas the entire launch stack weighed about 2,930,000 kg. This corresponds to a cargo mass fraction of about 0.05%, not including the dry mass of the vehicles themselves. It is therefore critical to carefully decide what cargo to manifest on what flight.

Unlike the Apollo program where individual missions were independent after launch, flights in future spaceflight campaigns may provide a gradual buildup of cargo and infrastructure. It is therefore necessary to consider the manifesting problem as a whole in which all the flights of the campaign are taken into account, instead of doing evaluations of only individual flights or missions. This study develops such a method in which all the flights in a campaign are analyzed in terms of their manifests, leading to the notion of a space supply chain.

Supply chain management and logistics is a well-researched field with an extensive body of available literature [5]. Interplanetary supply chain management, however, has only recently become a topic of keen interest ever since NASA has embarked on its new goal of exploring the moon and Mars through robotic and human

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missions. In recent years, there has been wide ranging research from definition of classes of supply for space exploration [6], to time-expanded network modeling of the flow of crew and cargo [1]. In addition to looking forward, there is plenty to harvest from the past [2]. The logistics lessons learned from the operation of Apollo, Skylab, Mir, and more recently the International Space Station (ISS), have been distilled into a set of recommendations for informing future system design [7]. The inventory-modeling problem has also been treated in detail with the ISS as an example in some cases [8]. Detailed studies on the logistics of lunar outpost establishment campaigns have been carried out with a focus on determining best strategies (prepositioning, carry along, and resupply) and evaluating campaign robustness to flight delays, cancellations, and stochastic demand [9].

This paper proposes a *matrix-based modeling approach* for analyzing campaign logistics. The key idea of the method is to construct a matrix representation of the cargo carried by flights for consumption in different time periods (or missions). Once such a representation is made, there are several modeling simplifications that can be achieved that allow for useful insights about the nature of the campaign from a logistics perspective. By organizing the manifest data in the proposed manner, an analyst can quickly visualize and determine certain properties of the campaign, and form a basis of comparison between different campaign architectures. This paper also proposes a few metrics that can be used to quantitatively define the delivery strategies of individual missions and whole campaigns. The quantitative characterization enables meaningful comparisons between different manifest strategies.

The application of the matrix modeling method and the associated metrics is illustrated through two different cases. The first is a detailed example of a future campaign for establishing a lunar outpost. The second is a historical analysis of ISS logistics. A complete modeling and analysis of the flow of crew and cargo over its multiyear history can serve to provide insights about how the logistics have worked for this program and be of practical relevance for future mission planning.

II. Matrix Modeling of Flight Manifest

It is assumed that in a spaceflight campaign there are several crewed and uncrewed flights, carrying both pressurized and unpressurized cargo to a specific location or node. A node could be an orbital node such as the ISS, or a surface node such as the lunar South Pole. A mission in this modeling approach will be defined as a period of time that is serviced by a particular flight. More specifically, it is the period of time that exists between the arrival of a flight and the arrival of the next incoming flight (or end of campaign). Because of this assumption, there is the same number of missions as there are incoming flights at the node. Figure 1 illustrates this notion.

The flights may deliver cargo in advance (preposition), or they may bring in cargo that is needed in the time period serviced by the flight (carry along). Any cargo that gets delivered after its need arises on the node is designated as "backordered." Such cargo may also be designated as "resupply." A flight may have a mix of prepositioned, carry along and backordered cargo for various missions.

A. M Matrix Definition

A set of F flights arriving at the same node at different times, carrying cargo that is to be consumed over various time periods, can be represented by a square matrix. This matrix referred to as the M (manifest) matrix is shown in Eq. (1). The element m_{ij} of the matrix

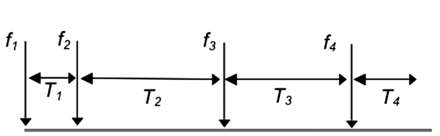

Fig. 1 Notional flight activity and mission definition for a single campaign. The vertical arrows show flight arrivals and the horizontal arrows show the mission durations (T_i).

represents the cargo mass brought by flight i for consumption in period (mission) j of the campaign.

$$M = \begin{bmatrix} m_{11} & \cdots & & m_{1F} \\ m_{21} & \ddots & & \\ \vdots & & m_{ij} & \\ m_{F1} & & & m_{FF} \end{bmatrix} \tag{1}$$

Thus, the ith row sum corresponds to the total cargo brought by flight i, whereas the jth column sum represents all cargo brought for mission j. It is assumed that consumption time periods (missions) start exactly with arrivals of individual flights at the node of interest.

This formulation of M reduces some of the modeling complexities by implicitly incorporating certain information (such as that of time) in the definition of the matrix itself. Additionally, the elements of the M matrix by virtue of their position allow for easy categorization of chunks of cargo as prepositioned, carry along, or backordered. For instance, m_{ij} will be prepositioned cargo if $i < j$, carry-along cargo if $i = j$ and backordered cargo if $i > j$.

It is interesting to note that with the above definition, the structure of the M matrix, can reveal certain properties of the campaign. For instance, if it is required to have no backordered cargo, all elements in which $i > j$ should be zero. This results in M being an upper triangular matrix [10] as shown in Eq. (2). The M matrix here represents a campaign in which all the cargo is either prepositioned or is brought as carry along by the flights.

$$M = \begin{bmatrix} m_{11} & \cdots & & m_{1F} \\ 0 & \ddots & & \\ \vdots & 0 & m_{ij} & \\ 0 & 0 & \cdots & m_{FF} \end{bmatrix} \tag{2}$$

Suppose a campaign has only carry along flights, that is, each flight brings cargo just for consumption during its own mission and no prepositioning or resupply is done. In such a case M will be a diagonal matrix.

$$M = \begin{bmatrix} m_{11} & \cdots & & 0 \\ & \ddots & 0 & \\ \vdots & 0 & m_{ij} & \\ 0 & & \cdots & m_{FF} \end{bmatrix} \tag{3}$$

Also note, that the trace (sum of diagonal elements of M) is the total amount of carry-along cargo brought in the campaign.

$$\mathrm{Tr}\,(M) = \sum_{i=1}^{F} m_{ii} = \mathrm{Mass}_{\text{carry along}} \tag{4}$$

For a purely carry along campaign, as shown in Eq. (3), the trace of M will also be the total cumulative mass delivered to the node. The total prepositioned mass and total backordered mass may be easily computed as follows:

$$\sum_{i=1}^{F-1} \sum_{j=i+1}^{F} m_{ij} = \mathrm{Mass}_{\text{prepositioned}} \tag{5}$$

$$\sum_{i=2}^{F} \sum_{j=1}^{i-1} m_{ij} = \mathrm{Mass}_{\text{backordered}} \tag{6}$$

Suppose there may be a requirement that a flight can deliver cargo for at most p time periods (or missions) in advance, for example due to shelf-life constraints or uncertainty as to whether some future missions may indeed occur (e.g., due to budgetary reasons). Then, assuming no backorders, M will be a band-diagonal matrix of width p above the diagonal. Equation (7) shows the structure of M for an example case with $p = 2$, that is, flights can preposition cargo for at most two future missions.

$$M = \begin{bmatrix} m_{11} & m_{12} & m_{13} & 0 & 0 \\ 0 & m_{22} & m_{23} & m_{24} & 0 \\ \vdots & \overset{b}{\longleftrightarrow} & \ddots & \overset{p}{\longleftrightarrow} & \\ & & & & \\ 0 & \cdots & & 0 & m_{FF} \end{bmatrix} \tag{7}$$

Similarly, there maybe a requirement that backorders may not extend to more than a certain number of missions. The width b measured from the main diagonal to the lower triangular portion will denote the extent of the backorders. Ideally, a campaign should be defined so that $b = 0$. For feasibility, b needs to be zero for critical and necessary supply items, but b could be greater than zero for noncritical supplies.

B. *M* Matrix: Square Versus Rectangular

It is important to note that the properties of the M matrix arise due to its square form resulting from an equal number of missions and flights. If the missions are arbitrarily defined and there is no longer a one-to-one correspondence with flights and missions (see Fig. 2), M can be rectangular. The elements m_{ij} of the rectangular M matrix can no longer be classified as prepositioned, carry along, or backordered based on the values of i and j alone. A separate and meticulous consideration of cargo arrival time and demand periods would have to be made to make that categorization. The properties of M as described in Eqs. (2–7) will no longer hold.

A square M matrix simplifies many equations that would be used in carrying out an optimization analysis when M is treated as an unknown. For instance, demand constraints can be written as follows:

$$\sum_{i=1}^{j} m_{ij} \geq d_j \tag{8}$$

Equation (8) shows that the sum of cargo brought by flights 1–j for consumption in mission j should be equal or greater to the demand, d_j, for mission j. This simple equation would not always be applicable if M was rectangular.

C. *D* Matrix Definition

Using the M matrix, a parameter δ_{ij} that captures the dependency of mission j on flight i can be defined as follows:

$$\delta_{ij} = \frac{m_{ij}}{\sum_{i=1}^{F} m_{ij}} \tag{9}$$

As shown in Eq. (9), δ_{ij} is the ratio of mass brought by flight i for mission j to the total mass brought in for mission j by all the F flights in the campaign. It thus defines the importance of a flight for a specific mission in terms of the fraction of mass that flight brings as compared with the total mass brought for that mission.

Note that, for a purely carry-along mission (i.e., one in which all the required cargo for the mission is brought entirely by its associated flight),

$$\delta_{ij} = 1 \qquad i = j, \qquad \delta_{ij} = 0 \qquad i \neq j \tag{10}$$

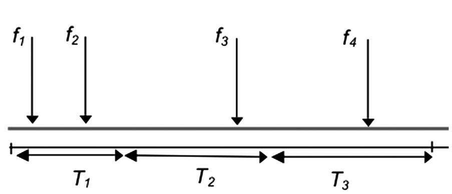

Fig. 2 Flight activity and arbitrary missions.

For a purely prepositioned mission (i.e., one in which all its required cargo has been delivered in advance by preceding flights),

$$\delta_{ij} = 0 \qquad i = j, \qquad \delta_{ij} \geq 0 \qquad i < j \tag{11}$$

If we define s_j to be the reciprocal of the total mass delivered for a mission j,

$$s_j = \frac{1}{\sum_{i=1}^{F} m_{ij}} \tag{12}$$

and define a diagonal matrix S,

$$S = \begin{bmatrix} s_1 & & & & 0 \\ & \ddots & & 0 & \\ & & s_j & & \\ & 0 & & \ddots & \\ 0 & & & & s_F \end{bmatrix} \tag{13}$$

then a matrix D can be written as follows:

$$D = MS \tag{14}$$

where

$$D = [\delta_{ij}]_{F \times F} \tag{15}$$

This D (dependency) matrix is a simple linear transformation of the M matrix. For a square M matrix, this transformation simply normalizes the entries in each column with respect to that column's sum. For a campaign with only carry along flights, the D matrix will be a diagonal matrix with ones on the diagonal:

$$D = \begin{bmatrix} 1 & \cdots & & 0 \\ & \ddots & & \\ \vdots & & 1 & \\ 0 & & \cdots & 1 \end{bmatrix} \tag{16}$$

III. Campaign Analysis

The M and D matrices form the basis of analyzing various mission and campaign level properties. Using elements of these matrices, a few quantitative measures are now defined for evaluating and comparing campaign logistics.

A. Flight Criticality for a Campaign

The parameter δ_{ij} defines the importance of a flight for a particular mission. This notion can be extended to the campaign level so that a flight's importance for the entire campaign may be quantified. Toward this goal, a flight criticality (FC) plot is proposed as a means of identifying critical flights. The FC plot is obtained by plotting

$$\sum_{j=1}^{F} \delta_{ij}$$

against the total number of missions served by each flight in the campaign. A mission j is said to be "served" by flight i if that flight delivers cargo for that mission, that is, $\delta_{ij} > 0$. The total number of missions served by flight i can be denoted as N_m^i and would be computed as follows:

$$N_m^i = \sum_{j=1}^{F} n_{ij} \qquad n_{ij} = 1 \quad \text{if } \delta_{ij} > 0 \qquad n_{ij} = 0 \quad \text{if } \delta_{ij} = 0 \tag{17}$$

Figure 3 shows a notional flight criticality plot for a campaign.

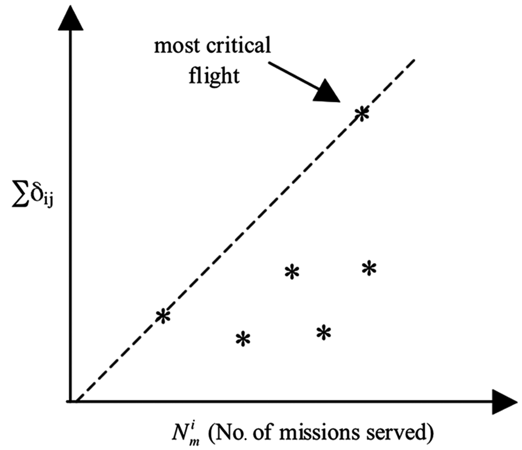

Fig. 3 Notional FC plot.

In general, if a flight serves n missions and

$$\sum_{j=1}^{F} \delta_{ij} = n$$

then it means that the flight is carrying all the required cargo for those missions (and has a δ_{ij} of 1 for each of them). This flight would be plotted on the (n, n) point in the FC plot (see Fig. 3, upper right corner). The 45 deg line thus serves as a reference to show the extent of cargo the flight is providing for the missions it is serving. The most important flight in the campaign (from a cargo-delivery perspective) would be one that lies farthest from the origin on the 45 deg line, because it would mean that it serves many missions (large N_m^i) and serves them solely (δ_{ij} of one for each).

The advantage of using an FC plot is that it keeps information easily discernible by showing both the breadth and extent of service of each cargo-carrying flight. It may, however, be advantageous to use a single quantitative value to rank or compare flights. For this purpose, a flight criticality index (FCI) can be defined as follows:

$$\text{FCI}_i = \sqrt{\left(\sum_{j=1}^{F} \delta_{ij}\right)^2 + (N_m^i)^2} \qquad (18)$$

This definition is the Euclidian distance from the origin to the point associated with flight i on the FC plot. This measure gives equal importance to both the breadth (N_m^i) and extent

$$\sum_{j=1}^{F} \delta_{ij}$$

of service provided by a flight. The FC chart can be used if these pieces of information are both of interest, whereas the FCI can be used as a means of scalar ranking between the flights.

B. Capacity Utilization Index

A capacity utilization index (CUI) can be defined as the ratio of total cargo mass carried by a flight and total flight cargo capacity. For flight i, with capacity c_i, its CUI_i will be

$$\text{CUI}_i = \frac{\sum_{j=1}^{F} m_{ij}}{c_i} \qquad (19)$$

It is assumed that the numerator has to be equal to or less than c_i. Based on this definition, the CUI will be a number between 0 (no cargo is brought by the flight) and 1 (the flight brings the maximum cargo allowed by its capacity).

C. Logistics Strategy Index

The logistics strategy index (LSI) is a ratio that indicates the amount of cargo that is prepositioned versus the amount of cargo that is brought in as carry along. This index can be defined at both the mission level and the campaign level. At the mission level, it can be denoted as mLSI_j (for a mission j) and is given as

$$\text{mLSI}_j = \frac{\sum_{i=1}^{j-1} m_{ij}}{\sum_{i=1}^{F} m_{ij}} \qquad (20)$$

The campaign-level logistics strategy index (cLSI) is simply the ratio of the total prepositioned cargo and total cargo delivered in the campaign:

$$\text{cLSI} = \frac{\sum_{j=1}^{F} \sum_{i=1}^{j-1} m_{ij}}{\sum_{j=1}^{F} \sum_{i=1}^{F} m_{ij}} \qquad (21)$$

The mLSI and cLSI are numbers between 1 and 0, with 0 being a mission (or campaign) in which no prepositioning is done and 1 being a mission (or campaign) in which everything is prepositioned. A limitation of this index is that it does not capture the presence of backordering in the campaign, and this will be addressed in future work.

The logistics strategy has implications for robustness and contingency situations. A prepositioning strategy may be more robust (such as in ensuring crew survivability and continued operability of infrastructure elements) in the presence of flight delays or cancellations. However, flight cargo capacity limits, shelf life, storage considerations, and many other factors limit the amount of prepositioning that can be done.

D. Class of Supply Based Analysis

The M and D matrix constructions, along with the metrics defined earlier, can be more meaningful if the cargo is differentiated on a class of supply (COS) [6] basis. For space logistics, there can be 10 functional COS that have been previously defined (see Fig. 4). There is not yet an internationally accepted standard for space logistics classes of supply. However, the COS classification in Fig. 4 will be used in this paper.

A detailed discussion about how the classification was achieved and validated, along with information regarding the subclasses that each of these 10 classes comprise, can be found in [6]. An M matrix for each COS can be constructed (and its associated D matrix found) using the same definitions as discussed in Sec. II. Overall cargo can then be obtained by superposition of these COS-specific M matrices.

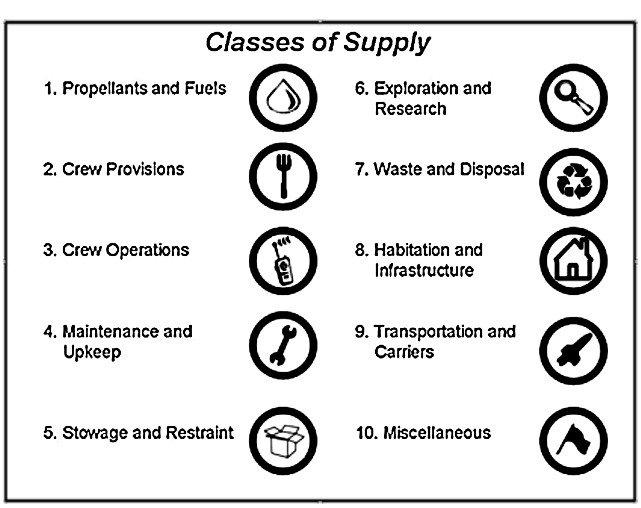

Fig. 4 Functional classes of supply for space exploration [6].

IV. Case I: Lunar Exploration Campaign Analysis

This section describes how the matrix-based modeling approach may be applied. The application is demonstrated through a detailed example of a future campaign for establishing a lunar outpost.

A. Lunar Exploration Campaign: Description

NASA's Lunar Architecture Team (LAT) proposed a plan for sustained lunar exploration in its LAT2 Option 2 report in 2007 [4]. The proposed lunar campaign serves to establish an outpost at a particular location on the moon with a series of manned and unmanned flights. The initial flights, in the "buildup phase" of the campaign, will deliver large infrastructure elements such as habitats, rovers, and power units, along with supply items and crew members. Once the necessary elements are in place, the campaign enters its "sustainment phase," which consists of logistics supply and crew rotation flights. The proposed campaign consists of 21 flights and spans a period from 2019 to 2029, with two flights, designated as A and B, each year. Figure 5 shows the nominal timeline of the lunar campaign.

A detailed description of the proposed flight activity, vehicles, infrastructure elements, and other relevant information can be found in [4]. Because this exploration campaign has been defined with enough fidelity, it is possible to model its missions' logistics and analyze various cargo manifest strategies.

B. Lunar Exploration Campaign: Modeling

The modeling of the LAT2 Option 2 campaign was done in SpaceNet 1.4, a MATLAB®-based interplanetary supply chain management and logistics planning and simulation software tool [11]. The tool allows the user to specify the origin and destinations of flights (in the Earth–moon–Mars system), number of crew in the missions, etc. Based on the given information, SpaceNet can estimate the demands that would result on a class of supply basis.

SpaceNet was particularly useful for this study because it provides detailed manifest information for each flight. It first produces an estimate for the classes of supply (COS 2, 3, 4, and 7, specifically) and then produces a list of supply items that have been packaged into appropriate shipping units (such as cargo transfer bags, etc). The total mass of the packaged items (including the tare mass) is then used for determining manifest feasibility in a given pressurized or unpressurized cargo-containing element. An automated manifesting algorithm in SpaceNet was used to obtain the results presented in the following section. The automanifesting process employs a "front-fill" algorithm, in which supply items are loaded onto flights starting with the first available one in the campaign. The LAT2 Option 2 campaign assumes that most flights will carry 500 kg of science and exploration items; however, for sake of simplicity (and for illustrative purposes), only supply items (COS 2, 3, 4, and 7) were modeled and manifested (in addition to the infrastructure elements). Because of the noninclusion of science items, there is overall excess capacity in the campaign.

C. Lunar Exploration Campaign: *M* Matrix Results

1. M Matrix:

Figure 6 shows the *M* matrix for a particular supply item manifest selected in SpaceNet for the lunar outpost campaign. The *M* matrix is a 21×21 square matrix due to the 21 flights in the campaign. It is also upper triangular, indicating that there are no backorders and that the campaign is feasible. The zeros in the matrix have not been explicitly shown, and those cells are simply left empty for visual clarity.

The *M* matrix can be interpreted in the following way. Row 1 shows that flight 2019-B delivers 1107 kg for consumption during its own associated mission (and is thus carry-along cargo). It also

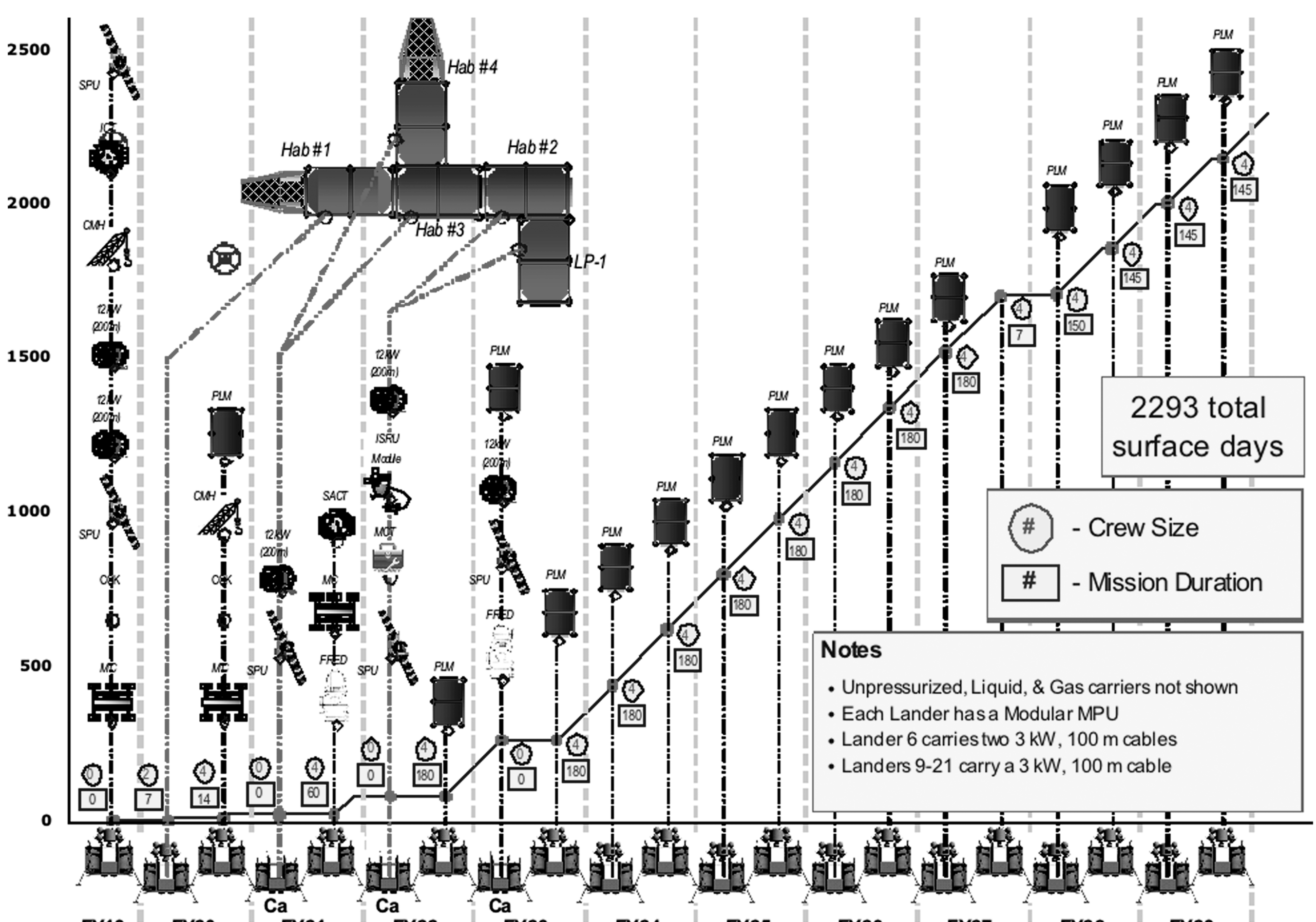

Fig. 5 LAT2 Option 2 campaign [4].

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	2019-B	1107	548	86	550																	
2	2020-A		242	23																		
3	2020-B			388		1746		218											54			
4	2021-A					1245	885	3950	1143	152												
5	2021-B									689	218									44		
6	2022-A									3063	2273	1693	617	1113	884	218					44	
7	2022-B										1538	509			316	83						44
8	2023-A											2048				1415	872	1588	1054	1004	1085	416
9	2023-B											594	1453									
10	2024-A												1337	711								
11	2024-B													1968	77	2						
12	2025-A													291	1751	4	2					
13	2025-B														1327	716	4					
14	2026-A															1957	89	2				
15	2026-B															111	1932	4				
16	2027-A																772	315	960			
17	2027-B																		1024			
18	2028-A																		858	1188		
19	2028-B																			1149	897	
20	2029-A																				1603	444
21	2029-B																					1640

Fig. 6 ***M*** **matrix for a lunar exploration campaign, in kilograms.**

prepositions 548 kg for the future mission associated with flight 2020-A, 86 kg for 2020-B, and 550 kg for 2021-A. The total cargo (of packaged supply items) delivered by flight 2019-B will simply be the sum of row 1 and is 2291 kg in this case. It is clear to see that, with the front-fill approach (and excess capacity), we have a campaign in which most flights are prepositioning cargo for later missions. The elements on the main diagonal of M are mostly zero, except for the first few and last few flights, which also have to bring carry-along cargo.

2. *D Matrix*

Figure 7 shows the D matrix that corresponds to the M matrix in Fig. 6 and is based on Eq. (9) and (15). Values greater than 0.5 for δ_{ij} have been highlighted.

Recall that the construction of the D matrix is to aid in understanding the interdependencies of the flights and missions. Thus, for instance, row 1 in Fig. 7 shows that flight 2019-B delivers all the supplies for missions 2019-B and 2021-A (note the ones under columns 1 and 4, corresponding to flights 2019-B and 2021-A). Similarly, row 4 shows that flight 2021-A is prepositioning all the supplies for future missions 2022-A and 2023-A. A potential failure/delay of 2021-A is thus going to especially impact the cargo delivery of these particular missions.

As in the case of the M matrix, a D matrix for each COS can serve to provide insights and perhaps aid in generating cargo manifests that increase robustness and reduce various risks. Figure 8 shows the D matrix for COS 2 (crew provisions) as an illustrative example.

It is interesting to note that the crew provisions are prepositioned to a greater extent (see the zeros in the main diagonal for 2026-B, 2027-A, and 2028-A) compared with the total cargo case shown in Fig. 7. Note that, in this specific manifest, 89% of the crew provisions for the 2021-B mission are prepositioned by flight 2020-B and 90% of the crew provisions for the 2022-B mission are prepositioned by flight 2021-A. The values of δ_{ij}, however, do get more spread out for later missions in the campaign. This is to be expected (given the definition of δ_{ij}); for the earlier missions, there are fewer flights that have occurred that can preposition cargo. The relative importance of those earlier flights will therefore be higher, because those few flights have to bring all the cargo. For later missions, there would have been many preceding flights, thereby allowing the cargo to be distributed among them and thus reducing the typical values of δ_{ij}. This effect is the clearest in Fig. 8, in which the ones can be seen in the top part of the total cargo D matrix, whereas in the bottom part the values are lower.

3. *Flight Criticality*

The flight criticality plot for the total cargo and for each class of supply was obtained as described in Sec. III. Figure 9 shows the FC plot for total cargo. A few flights stand out from the others in the campaign.

Flight 2021-A serves five missions (or almost a quarter of the missions in the campaign) and is also close to the 45 deg line, meaning that the extent of service is also high. Thus, 2021-A is one of the most critical flights of the campaign from a total cargo-delivery

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	2019-B	1.00	0.69	0.17	1.00																	
2	2020-A		0.31	0.05																		
3	2020-B			0.78		0.58		0.05											0.01			
4	2021-A					0.42	1.00	0.95	1.00	0.04												
5	2021-B									0.18	0.05									0.01		
6	2022-A									0.78	0.56	0.35	0.18	0.27	0.20	0.05					0.01	
7	2022-B										0.38	0.11			0.07	0.02						0.02
8	2023-A											0.42				0.31	0.24	0.83	0.27	0.30	0.30	0.16
9	2023-B											0.12	0.43									
10	2024-A												0.39	0.17								
11	2024-B													0.48	0.02	0.00						
12	2025-A													0.07	0.40	0.00	0.00					
13	2025-B														0.30	0.16	0.00					
14	2026-A															0.43	0.02	0.00				
15	2026-B															0.02	0.53	0.00				
16	2027-A																0.21	0.17	0.24			
17	2027-B																		0.26			
18	2028-A																		0.22	0.35		
19	2028-B																			0.34	0.25	
20	2029-A																				0.44	0.17
21	2029-B																					0.65

Fig. 7 ***D*** **matrix of total cargo delivered for a lunar exploration campaign.**

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	2019-B		0.71	0.2																		
2	2020-A		0.29	0.1																		
3	2020-B			0.7		0.9		0.1											0.02			
4	2021-A					0.1		0.9		0.1												
5	2021-B									0.2	0.1									0		
6	2022-A									0.8	0.6	0.2	0.1	0.2	0.1	0.1					0	
7	2022-B										0.3	0.2			0	0						0.02
8	2023-A											0.6				0.1	0.1	0.3	0.21	0.1	0.1	0.12
9	2023-B											0	0.7									
10	2024-A												0.2	0.3								
11	2024-B													0.5	0	0						
12	2025-A													0	0.8	0	0					
13	2025-B														0	0.3	0					
14	2026-A															0.5	0	0				
15	2026-B															0	0.8	0				
16	2027-A																0	0.7	0.45			
17	2027-B																		0.31			
18	2028-A																		0	0.6		
19	2028-B																			0.2	0.5	
20	2029-A																				0.4	0.24
21	2029-B																					0.62

Fig. 8 ***D*** **matrix for COS 2 (crew provisions).**

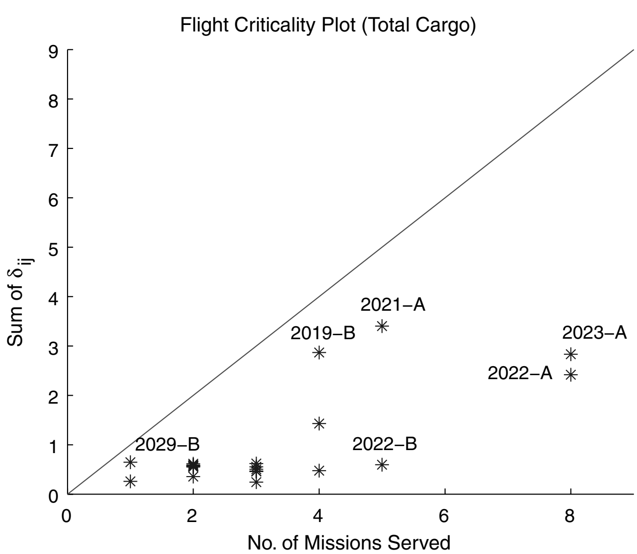

Fig. 9 Flight criticality chart (total cargo).

perspective. The first flight, 2019-B, also appears to be important in this chart (serving four missions and lying close to the 45 deg line). Flights 2022-A and 2023-A each serve eight missions, or more than a third of the missions in the campaign. However, their data points are far away from the 45 deg line, indicating that the dependency of their service is not very high on average.

The FC plot provides a birds-eye view of how the flights in the campaign measure up in importance from a cargo-delivery perspective. This can be especially helpful if there are many flights in a long, drawn-out campaign. Table 1 shows the top five flights in terms of their FCI. Flight 8 (2023-A) has the highest FCI, followed closely by flight 6 (2022-A), whereas flight 4 (2021-A) is ranked third. The table also shows a sorted list of flights and their cargo in

Table 1 FCI and total cargo comparison

	FCI ranking		Total cargo ranking	
Rank	Flight no.	FCI	Flight no.	Total cargo, kg
1	8	8.49	6	9905
2	6	8.36	8	9481
3	4	6.05	4	7374
4	7	5.04	7	2489
5	1	4.92	3	2406

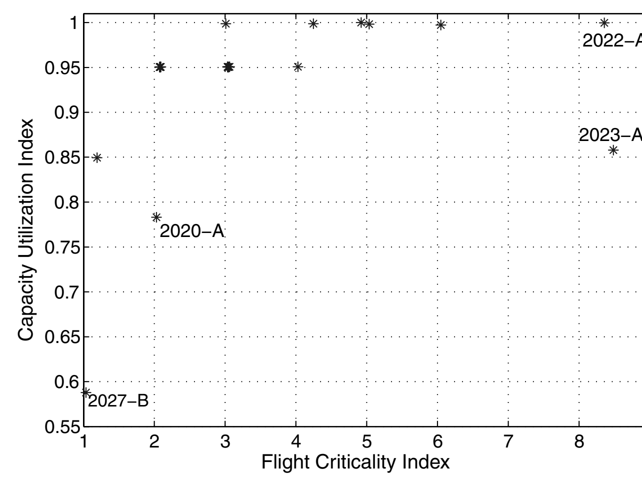

Fig. 10 Capacity utilization vs flight criticality.

descending order. The purpose is to illustrate that the ranking of the flights based on their FCI is not a simple ranking of their total cargo alone. Rather, FCI is a more sophisticated measure that takes into account the breadth and extent of service. Thus, although flight 6 delivers more cargo than flight 8, its rank turns out to be second. This is because both flights 6 and 8 (2023-A and 2022-A) serve eight missions each; however, the total delta of flight 8 is higher than that of 6, which gives it a higher FCI value.

Figure 10 compares the capacity utilization and criticality for each flight. It can be seen that most of the flights have a utilization of greater than 95%. There are two flights, 2020-A and 2027-B, that have less than 80% utilization (however, their criticality is also low). This indicates where extra cargo, for example, for science equipment, could be manifested.

4. Logistics Strategy Index

The LSI was computed both for the individual missions and the entire campaign. Figure 11 shows the mLSI for total cargo. It should be noted that the curve profile follows the structure of the *M* (and *D*) matrices. The missions in the middle of the campaign have an mLSI of 1, meaning that these missions are fully prepositioned in terms of their required cargo (as was seen through the zero diagonal entries in the *M* and *D* matrices in Figs. 6 and 7). The missions at the beginning and end of the campaign have a mix of prepositioning and carry-along cargo. The only fully carry-along mission is the first one (associated with flight 2019-B) in the campaign.

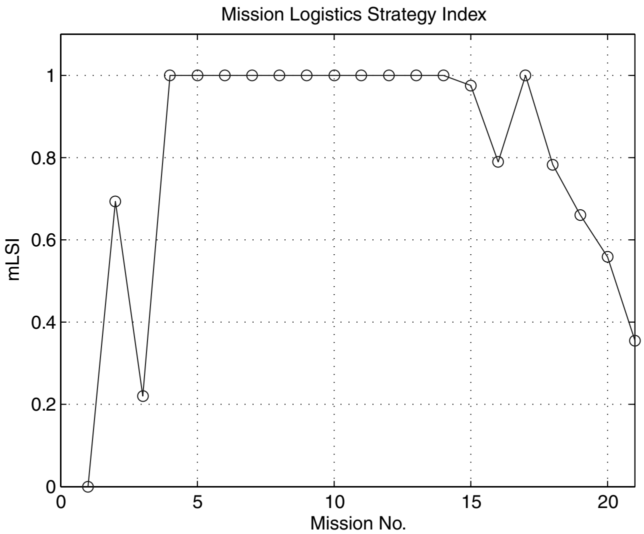

Fig. 11 Mission logistics strategy index for lunar campaign: mLSI=0 indicates full carry along, whereas mLSI=1 indicates 100% prepositioning.

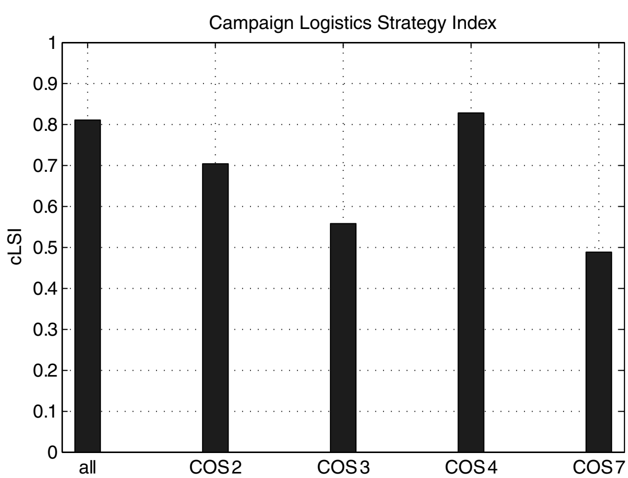

Fig. 12 cLSI.

The overall LSI at the campaign level was computed for the total cargo and for the COS cases and is shown in Fig. 12. The cLSI for this campaign, based on the cargo manifest that was chosen in SpaceNet, is 0.81. In other words, 81% of the cargo needed for the missions in the campaign is prepositioned by the flights, whereas 19% is brought in as carry along.

In general, having a high LSI may be desirable; however, it may not always be possible due to capacity limitations, shelf-life considerations, and so on. The LSI can be used for comparing against different manifest rules (for a given transportation architecture) or may be used to compare a specific set of manifest rules against different transportation architectures in a campaign.

V. Case II: International Space Station Logistics Modeling

This section describes how a historical campaign, the past ISS logistics flights, can be modeled using this approach. The following discussion provides details on how the ISS flight activity, cargo delivery, and manifest matrix were modeled and what implications can be observed from the associated results.

First, the *M* matrix for the ISS was constructed for which all the relevant data had to be collected. From the beginning of the assembly of the ISS in December 1998 until June 2008, there have been a total of 75 manned and unmanned flights to the station. These include assembly missions, crew rotation flights, and resupply missions.¶ This study focused on understanding the logistics of supply items related to crew sustenance (such as food, water, and hygiene items) and infrastructure operability (such as spares). Because of the difficulty in obtaining data regarding the amount of cargo delivered on each flight on a COS basis, only COS 2 (crew provisions) was selected for constructing its associated *M* matrix. Subclasses 201 (water and support equipment) and 202 (food and support equipment) were included in this analysis [11].

The bulk of the crew provisions cargo delivered to the ISS is brought by the Progress (and now also the automated transfer vehicle, or ATV) spacecraft. The manifest of the shuttle flights can vary significantly from one mission to the next; however, there are some missions that also deliver sizeable amounts of crew provisions cargo. Because the study was focused only on supply items (within COS 2), only missions designated as "resupply" were included in the analysis. Note that resupply here is not backordered cargo; rather, it refers to supplying provisions to ongoing ISS expeditions. From the total of 75 flights, there were 36 resupply flights between August 2000 and March 2008. The data, with flight and total cargo information, are provided in Fig. 13.** As discussed previously, an *M* matrix on a class of supply basis is more meaningful. The breakdown of the total cargo delivered to the ISS on a COS basis was, however, not readily available. Information from NASA regarding some of the Progress flights, however, provided information regarding the amount of propellants, food and water, and "dry cargo." Table 2 shows the specific data for four Progress missions.¶

The double dashes in Table 2 signify that the actual data for those categories were not specifically listed in the data source. To obtain mass estimates for food supplies (such as the 112 days of food for two crew listed for flight 16P), SpaceNet 1.3 was employed. Table 3 shows how the missing data were populated using results from SpaceNet and the information given in Fig. 13.

Based on the data shown in Table 3, the average ratio for estimating cargo for COS 1 (propellants), COS 201 and 202 (food and water), and the rest was found as shown in Table 4. The data for the space shuttle were estimated based on manual calculations of a sample of typical shuttle manifests available to the authors.

Using the gross ratios for estimating the COS breakdown from total cargo delivered by the Progress and shuttle flights, the actual cargo delivered for COS 2 was computed (shown in Table 5).

The *M* matrix, as described in Sec. II.A, is a square matrix in which each flight delivering cargo to a node has an associated "mission" whose duration is defined by the time interval between the preceding and the next incoming flight. This time interval for each flight or mission was computed using the data in Fig. 13 and is shown in Table 5 in the column titled "Days." For instance, the first flight, 1P, is assigned a 33-day mission because this is the number of days between the launch of flight 1P and the launch of the next flight, 2A. The number of crew is assumed to be the permanent number of crew in the station and not the crew that may briefly visit the station during a shuttle mission. Those shuttle missions have carry-along cargo for consumption during the time the extra crew is onboard the station; thus, that cargo can be reasonably excluded for this study. The supply mass in Table 5 is the mass of cargo delivered to the station and excludes any carrier mass, such as that of the multipurpose logistics module (MPLM) used by the shuttle. Therefore, for instance, whereas the cargo up mass for flight 2A (a Space Shuttle Atlantis flight) is 14 tons, the supply mass is taken to be 9.5 tons after subtracting the 4.5 tons of the MPLM. Using the data for the number of crew and number of days for each mission, SpaceNet 1.3 was used

¶Data available online at http://www.nasa.gov/mission_pages/station/expeditions/index.html [cited August 28, 2008].

**Data available online at http://www.nasa.gov/mission_pages/station/expeditions/index.html [cited August 20, 2008], http://www.astronautix.com/craft/intation.htm [retrieved August 20, 2008], http://en.wikipedia.org/wiki/International_Space_Station [retrieved August 20, 2008], and http://www.hq.nasa.gov/osf/station/assembly/ISSProgress.html [retrieved August 28, 2008].

Table 2 Cargo breakdown for selected progress flights

Progress M	Total, kg	Propellant, kg	Air, kg	Water, kg	Dry cargo, kg	Notes
16P (Dec.2004)	——	561.4	50	420.9	——	112 days of food for two crew
17P (March 2005)	——	175.4	110	486.8	——	1333 kg of spares, science, and 6 months of food
19P (Sept. 2005)	2352.2	800	110	187.2	1227.3	
25P (May 2007)	2329.5	477.27	45.45	420.45	1382.7	

Table 3 Cargo breakdown for progress flights: completed data

Progress M	Total, kg	Propellant, kg	Air, kg	Water, kg	Food, kg	Other cargo
16P (Dec. 2004)	2350	561.4	50	420.9	619.5	698.3
17P (March 2005)	2350	175.4	110	486.8	244.73	1333
19P (Sept. 2005)	2352.2	800	110	187.2		1227.3
25P (May 2007)	2329.5	477.27	45.45	420.45		1382.7

Table 4 COS ratios from total cargo

Spacecraft	COS 1	COS 2 (201, 202)	Other COS
Progress M	0.21	0.38	0.41
Space shuttle	0	0.2	0.8

to estimate the required amount of cargo for COS 201 and 202 (food and water). The results are shown in the last column of Table 5.

It should be noted that, although there are 36 resupply flights (see Fig. 13), only 35 have been included in Table 5. This is because the authors did not have data to estimate the cargo manifest for the ATV. Therefore, only the top 35 flights involving the shuttle and Progress missions have been used in the analysis.

From Table 5 it can also be observed that the actual mass delivered for COS 201 and 202 (38.2 t as estimated from the average COS ratios) and the estimated mass needed (37.76 t as computed from SpaceNet 1.3) have a difference of only 1.2%.

Figure 14 shows the number of days between consecutive resupply flights (including the Progress and shuttle flights), as shown in the Days column of Table 5. The seven resupply shuttle missions have been labeled on the plot. It is interesting to note the saw tooth pattern, which had a pronounced upward shift between flights 13–25. Note that this was the period of time when the shuttle had been grounded (after the Columbia accident in 2003), and this perhaps led to higher average days between resupply missions.

The M matrix can be constructed using data on cargo delivered and cargo demand. The algorithm for finding the value of each m_{ij} (cargo

Table 5 ISS resupply flight data

	Flight	Spacecraft	Days	Crew	Supply mass, kg	COS 201, 202 delivered, kg	COS 201, 202 required, kg
1	1P	Progress M1-3, 251	33	3	2230	840.74	556.52
2	2A.2b	Shuttle Atlantis	68	3	9500	1900	1089.57
3	2P	Progress M1-4, 253	103	3	2230	840.74	1622.63
4	3P	Progress M-44, 244	10	3	2350	885.98	206.23
5	5A.1	Shuttle Discovery	42	3	9500	1900	693.59
6	6A	Shuttle Endeavour	31	3	9244	1848.8	526.06
7	4P	Progress-M1-6, 255	93	3	2230	840.74	1470.33
8	5P	Progress-M45, 245	97	3	2350	885.98	1531.25
9	6P	Progress-M1-7, 256	9	3	2230	840.74	191
10	UF-1	Shuttle Endeavour	105	3	9500	1900	1653.09
11	7P	Progress-M1-8, 257	77	3	2230	840.74	1226.64
12	UF-2	Shuttle Endeavour	21	3	10,122	2024.4	373.76
13	8P	Progress-M46, 246	92	3	2350	885.98	1455.1
14	9P	Progress-M1-9, 258	128	3	2230	840.74	2003.38
15	10P	Progress M-47, 247	127	2	2350	885.98	1343.41
16	11P	Progress M1-10, 259	80	2	2230	840.74	866.2
17	12P	Progress M-48, 248	154	2	2350	885.98	1617.55
18	13P	Progress M1-11, 260	117	2	2230	840.74	1241.87
19	14P	Progress M-49, 249	79	2	2350	885.98	856.05
20	15P	Progress M-50, 350	133	2	2350	885.98	1404.33
21	16P	Progress M-51, 351	68	2	2350	885.98	744.36
22	17P	Progress M-52, 352	107	2	2350	885.98	1140.34
23	18P	Progress M-53, 353	41	2	2350	885.98	470.22
24	LF-1	Shuttle Discovery	43	2	10,500	2100	490.53
25	19P	Progress M-54, 354	105	2	2350	885.98	1120.03
26	20P	Progress M-55, 355	123	2	2350	885.98	1302.79
27	21P	Progress M-56 365	62	2	2350	885.98	683.44
28	22P	Progress M-57 366	10	2	2350	885.98	155.46
29	ULF1.1	Shuttle Discovery ULF1.1	111	3	10,500	2100	1744.47
30	23P	Progress M-58	87	3	2350	885.98	1378.95
31	24P	Progress M-59	114	3	2350	885.98	1790.16
32	25P	Progress M-60	82	3	2350	885.98	1302.79
33	26P	Progress M-61	143	3	2350	885.98	2231.83
34	27P	Progress M-62	44	3	2350	885.98	724.05
35	28P	Progress M-63	33	3	2350	885.98	556.52
				Total Mass	*133,706*	*38,218.6*	*37,764.5*

	Flight	Vehicle	Launch Date	Undock Date	Number of Crew	Cargo Up Mass [kg]	Cargo Down Mass Kg]	Notes	Permanent Crew
1	1P	Progress M1-3, #251	8/6/00	10/31/00	0	2230	1000	Resupply	
2	2A.2b	Shuttle - Atlantis	9/8/00	9/18/00	7	14000	0	Supply and Maintenance	3
3	2P	Progress M1-4, #253	11/15/00	2/8/01	0	2230	1000	Resupply	3
4	3P	Progress M-44, #244	2/26/01	4/15/01	0	2350	1000	Resupply	3
5	5A.1	Shuttle - Discovery	3/8/01	3/19/01	7	14000	12500	(Leonardo), Crew Rotation (E2 up)	3
6	6A	Shuttle - Endeavour	4/19/01	4/29/01	7	13744	12500	(Raffaello), Launch of Canadarm2	3
7	4P	Progress-M1-6, #255	5/20/01	8/22/01	0	2230	1000	Resupply	3
8	5P	Progress-M45, #245	8/21/01	11/22/01	0	2350	1000	Resupply	3
9	6P	Progress-M1-7, #256	11/26/01	3/19/02	0	2230	1000	Resupply	3
10	UF-1	Shuttle - Endeavour	12/5/01	12/15/01	7	14000	12500	Resupply Mission - MPLM. Crew Rotation (E4 Up)	3
11	7P	Progress-M1-8, #257	3/20/02	6/25/02	0	2230	1000	Resupply	3
12	UF-2	Shuttle - Endeavour	6/5/02	6/15/02	7	14622	12500	Resupply Mission - MPLM. Crew Rotation (E5 Up)	3
13	8P	Progress-M46, #246	6/26/02	9/24/02	0	2350	1000	Resupply	3
14	9P	Progress-M1-9, #258	9/26/02	2/1/03	0	2230	1000	Resupply	3
15	10P	Progress M-47, #247	2/1/03	8/27/03	0	2350	1000	Resupply	2
16	11P	Progress M1-10, #259	6/8/03	9/4/03	0	2230	1000	Resupply	2
17	12P	Progress M-48, #248	8/27/03	1/28/04	0	2350	1000	Resupply	2
18	13P	Progress M1-11, #260	1/28/04	5/24/04	0	2230	1000	Resupply	2
19	14P	Progress M-49, #249	5/24/04	7/30/04	0	2350	1000	Resupply	2
20	15P	Progress M-50, #350	8/11/04	12/22/04	0	2350	1000	Resupply	2
21	16P	Progress M-51, #351	12/22/04	2/27/05	0	2350	1000	Resupply	2
22	17P	Progress M-52, #352	2/28/05	6/15/05	0	2350	1000	Resupply	2
23	18P	Progress M-53, #353	6/15/05	9/7/05	0	2350	1000	Resupply	2
24	LF-1	Shuttle - Discovery	7/26/05	8/6/05	7	15000	15000	Resupply mission - MPLM	2
25	19P	Progress M-54, #354	9/7/05	3/3/06	0	2350	1000	Resupply	2
26	20P	Progress M-55, #355	12/21/05	6/19/06	0	2350	1000	Resupply	2
27	21P	Progress M-56 #365	4/23/06	9/19/06	0	2350	1000	Resupply	2
28	22P	Progress M-57 #366	6/24/06	1/16/07	0	2350	1000	Resupply	2
29	ULF1.1	Shuttle - Discovery ULF1.1	7/4/06	7/14/06	7	15000	15000	Resupply Mission - MPLM	3
30	23P	Progress M-58	10/23/06	3/27/07	0	2350	1000	Resupply	3
31	24P	Progress M-59	1/18/07	8/1/07	0	2350	1000	Resupply	3
32	25P	Progress M-60	5/12/07	9/19/07	0	2350	1000	Resupply	3
33	26P	Progress M-61	8/2/07	12/22/07	0	2350	1000	Resupply	3
34	27P	Progress M-62	12/23/07	3/4/08	0	2350	1000	Resupply	3
35	28P	Progress M-63	2/5/08	4/7/08	0	2350	1000	Resupply	3
36	ATV-1	ATV-1	3/9/08		0	7667		Resupply --- Still at ISS	3

Fig. 13 Resupply flight log for ISS used for creating the *M* matrix.

brought by flight i for mission j) was as follows. Consider a three-flight scenario in which the demand for mission 1 is 100 kg, for mission 2 is 200 kg, and for mission 3 is 300 kg. The actual cargo delivered for that COS in mission 1 is 150 kg. Then, of the 150 kg delivered, 100 kg will be assigned to mission 1 (as carry along) and the remaining 50 kg will get allocated for mission 2 (as prepositioned mass). Thus $m_{11} = 100$, $m_{12} = 50$, and $m_{13} = 0$. Now suppose that flight 2 brings in 50 kg of cargo. This cargo will be assigned for consumption in mission 2 (carry along). Thus, $m_{21} = 0$, $m_{22} = 50$, and $m_{23} = 0$. Note that the total cargo delivered for mission 2 would only be 100 kg by that time, whereas the demand for mission 2 was 200 kg. There would thus be a backorder of 100 kg. Now suppose flight 3 delivers 400 kg. The cargo of flight 3 would then be divided up as 100 kg for the backordered cargo of the previous mission and the remaining 300 for consumption in mission 3 (carry along). Thus, $m_{31} = 0$, $m_{32} = 100$, and $m_{33} = 300$. In summary, for a cargo demand vector of [100 200 300] and a cargo-delivery vector of [150 50 400], the resulting M matrix would be

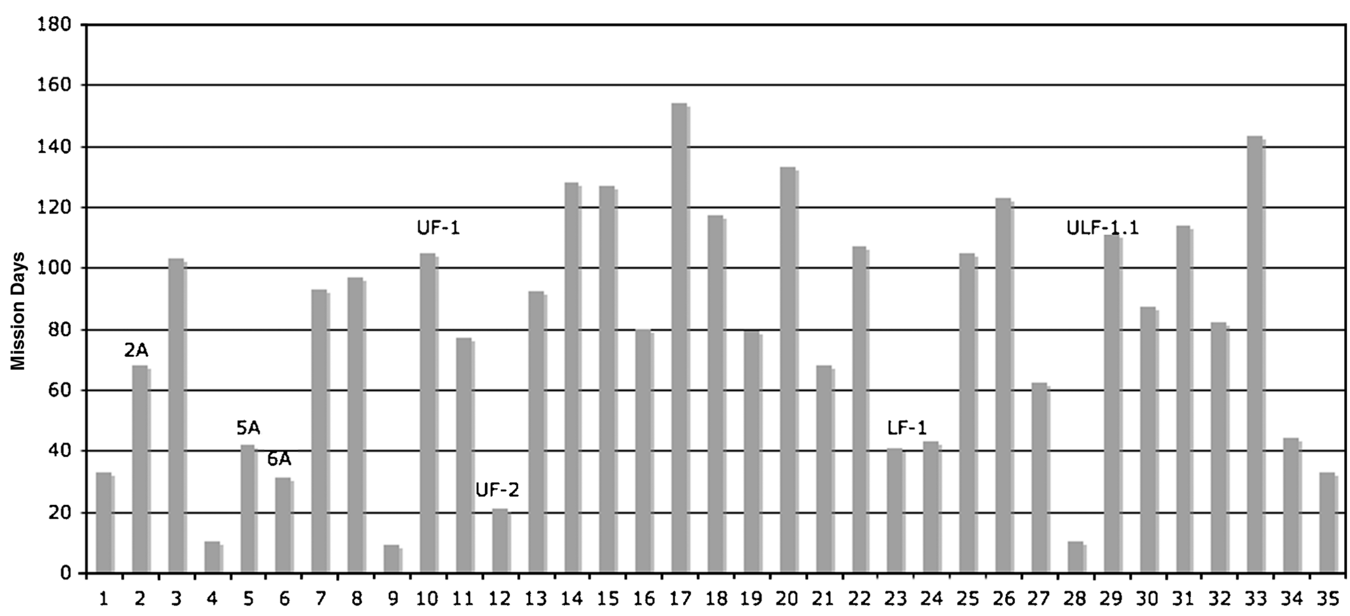

Fig. 14 Time intervals between consecutive resupply missions to the ISS.

$$M = \begin{bmatrix} 100 & 50 & 0 \\ 0 & 50 & 0 \\ & 100 & 300 \end{bmatrix} \tag{22}$$

Note that the sum of elements in each column of M yield the demand vector [100 200 300], indicating that all the demands are satisfied.

VI. Matrix-Based International Space Station Logistics Analysis Results

The data shown in the last two columns of Table 5 were used to find the associated M (for COS 201 and 202) for the ISS using the algorithm described in the previous section. Figure 15 shows the results. A few observations can be made from looking at the structure of the M matrix. First, the matrix is mostly upper triangular (except for one small nonzero entry below the diagonal on row 34, indicating a small backorder). Second, the diagonal entries are mostly zero, indicating that crew provisions are primarily prepositioned. Third, the width of the upper band over the diagonal, p, is 4. As described in Eq. (7), this means that some amount of cargo for up to a maximum of four future missions is prepositioned (as in the case of flights 6, 10, and 25). In most of the flights, the prepositioning is primarily for one or two missions.

The M matrix data were then used to generate the associated D matrix. The data from the D matrix are summarized by a flight criticality plot, shown in Fig. 16.

Some of the key flights, such as flight 6 (6A), 10 (UF1), and 4 (3P), are labeled to show how the importance of each flight can be viewed through such a graph. The figure shows that flights 6 and 10 are among the most critical ones, as they served three missions each with

$$\sum_{j=1}^{F} \delta_{ij}$$

of 1.99 and 1.97, respectively. It is interesting to note that most of the data points lie in the two-mission column, indicating that most of the flights serviced more than one mission in terms of crew provisions. This observation can also be made directly from the band-diagonal structure of the M matrix as well. Table 6 shows the top ten flights with the highest FCI among the 35 flights modeled in the study. From the top five flights (6, 10, 25, 24, and 5), four are shuttle missions (6, 10, 24, 5), indicating that the shuttle has served a critical logistical role from a supply-delivery perspective in addition to transporting crew and other cargo.

The mLSI for each flight/mission, computed using Eq. (20), is shown in Fig. 17. It can be seen that the mLSI for crew provisions has been largely 1 (pure prepositioning), except for the first few initial flights, an intermediate period between flights 15–24, and at the end. It is interesting to note that the period between flights 16–24 (2003–2005) in Fig. 17 corresponds to the time after the Shuttle Columbia accident (1 February 2003), when only Progress flights, with a limited cargo capacity relative to the shuttle, were available for resupply of the ISS. We hypothesize that, due to the limited cargo capacity during this period, less prepositioning was possible. The

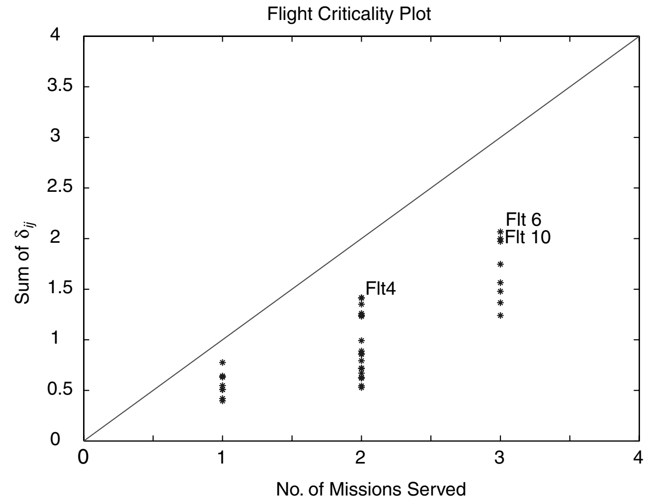

Fig. 16 Flight criticality plot for COS 201 and 202 for historical ISS resupply.

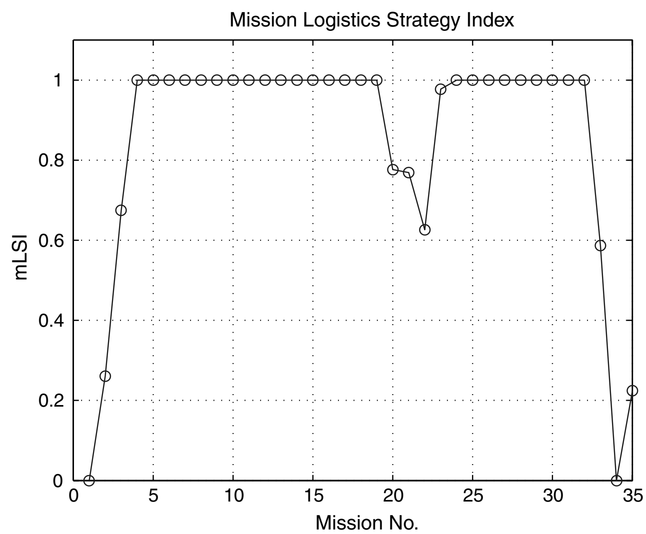

Fig. 17 mLSI for ISS resupply flights.

overall LSI across all the flights (i.e., the ratio of total COS 201 and 202 cargo prepositioned versus total COS 201 and 202 cargo delivered) is found to be 0.85. This means that, on average, 85% of crew provisions cargo is prepositioned in the ISS.

In summary, this analysis shows how matrix-based analysis methods can be applied toward understanding ISS logistics. An analysis of the historical cargo-delivery data for the ISS can give important insights about how the program functioned and possibly provide guidance for future mission planning. The results presented in this section are a different way to think of ISS manifesting.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
1	556.5	284.2	0.0	0.0	0.0	0.0																													
2		805.4	1094.6	0.0	0.0	0.0																													
3			528.0	206.2	106.5	0.0																													
4				0.0	587.1	298.9																													
5					0.0	227.2	1470.3	202.5																											
6						0.0	0.0	1328.7	191.0	329.1																									
7							0.0	0.0	0.0	840.7																									
8								0.0	0.0	483.3	402.7																								
9									0.0	0.0	823.9	16.8																							
10										0.0	0.0	357.0	1455.1	87.9																					
11											0.0	0.0	0.0	840.7																					
12												0.0	0.0	1074.7	949.7																				
13													0.0	0.0	393.7	492.3																			
14														0.0	0.0	373.9	466.8																		
15															0.0	0.0	886.0																		
16																0.0	264.8	576.0																	
17																	0.0	665.9	220.1																
18																		0.0	636.0	204.7															
19																			0.0	886.0															
20																				313.6	572.4														
21																					172.0	714.0													
22																						426.3	459.6												
23																							10.6	490.5	384.9										
24																								0.0	735.2	1302.8	62.0								
25																									0.0	0.0	621.4	155.5	109.1						
26																										0.0	0.0	0.0	886.0						
27																											0.0	0.0	749.4	136.6					
28																												0.0	0.0	886.0					
29																													0.0	356.4	1743.6				
30																														0.0	46.5	839.4			
31																															0.0	463.3	422.6		
32																																0.0	886.0		
33																																	886.0		
34																																	37.2	724.1	124.7
35																																			431.8

Fig. 15 *M* matrix of ISS for COS 201 and 202.

Table 6 Flight criticality index for ISS flights

Rank	1	2	3	4	5	6	7	8	9	10
Flight No.	6	10	25	24	5	3	23	34	4	2
FCI	3.64	3.60	3.59	3.47	3.38	3.34	3.30	3.25	2.45	2.45

Traditionally, it has been rare to consider the integrated Progress and shuttle cargo complement. Typically, the Progress is viewed as flying mostly Russian supplies with a small amount of U.S. items and the shuttle is largely U.S. items with an occasional high-priority Russian item. The flight schedule of each vehicle is relatively independent of the other vehicle; the Progress flies consistently every few months, whereas the shuttle schedule is unpredictable and highly varied. It should be noted that, because the food for the crew is 50/50 United States/Russian and flies on both vehicles, it is accurate to look at the entire complement for COS 2 as has been done in this work.

The data sources used in this work have to be treated with some caution; therefore, the results obtained in the previous section should be treated as approximate. This approach, however, can be easily applied to more accurate data for the ISS, and a more inclusive study involving other classes of supply can be beneficial for informing logistical decisions for other spaceflight programs.

VII. Conclusions

This paper has presented an approach to simplify the representation of flight cargo manifests for campaigns involving many flights and missions. Using a matrix representation of cargo delivered by flights for consumption in different missions, matrices of specific properties and structures can be obtained. The formulation is then amenable to high-level analysis of the missions and the campaign from a cargo-delivery standpoint. An important benefit of formulating the *M* matrix as proposed in this paper is that it simplifies the formulation of optimization problems for determining campaign architectures that are feasible and robust from a cargo-delivery perspective.

In the present analysis, *M* and *D* matrices were based on cargo mass; however, these matrices can also be constructed for volume or for pressurized and unpressurized cargo. In this work, *M* was a known quantity (determined by SpaceNet or historical data) for a specific campaign architecture. In general, for future campaigns, the *M* matrix is unknown and is an important variable that needs to be optimized.

In a future continuation of this work, the elements of the *M* matrix (m_{ij}) will be treated as variables that are to be optimized subject to flight capacity and demand constraints. One may, for example, choose to optimize *M* such that the campaign is feasible, while minimizing the largest value of δ_{ij} in the matrix (mini-max problem) to evenly distribute the risk due to flight cancellation, failure, or delay. Another optimization approach may be to maximize the CUI for each flight. As discussed earlier, the formulation of the *M* matrix in its proposed form simplifies many demand and other constraint equations. It allows for easily specifying constraints on shelf life and storage (limiting the amount of prepositioning) and specifying the criticality of cargo for a given flight/mission (defining the amount of carry-along cargo). The important thing to note is that the problem can be posed as a linear optimization problem with linear inequality constraints. This would thus allow for using well-understood linear optimization techniques that can be readily employed for finding the "optimal" *M* matrix. Furthermore, the *M* and *D* matrices may be allowed to vary so that, depending on delays and failures/cancellations of flights, the *M* matrix can be optimally replanned for the future remaining flights.

Additionally, with regard to future work on evaluating ISS logistics, we will analyze the impact of safety stock levels for each COS on the structure of the *M* matrix. In other words, the backorder levels and resupply cargo could be positioned in the lower-left triangular *M* matrix depending on varying safety stock levels. Also, we are planning to analyze the ISS logistics strategy in a forward-looking manner by generating different versions of the *M* matrix depending on the timing and capacity of future flights. Specifically, after the proposed retirement of the space shuttle fleet in 2010, we expect that ISS logistics will require at least four different types of vehicles, such as the Progress, Soyuz, ATV (Europe), H-II transfer vehicle (Japan), and, eventually, the Orion (Unites States). In the long term, commercial transportation services to ISS are also expected to deliver cargo.[††] Assuming a total cargo requirement on the order of 30 t per year with a permanent crew of six, this will require on the order of 10–15 different flights per year. Carefully coordinating such a complex logistics enterprise is not trivial, and matrix-based planning methods such as the ones presented here may be helpful in this respect.

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References

[1] Taylor, C., Song, M., Klabjan, D., de Weck, O., and Simchi-Levi, D., "Modeling Interplanetary Logistics: A Mathematical Model for Mission Planning," AIAA Paper 2006-5735, June 2006.

[2] Watson, J. K., Dempsey, C., and Butina, A., "The Logistics Path Beyond the International Space Station," *Logistics Spectrum*, Jan.–March 2005.

[3] Stanley, D., Cook, S., and Connolly, J., "NASA's Exploration Systems Architecture Study," NASA TM-2005-214062, 2005.

[4] Cirillo, W., Stromgen, C., Andraschko, M., Reeves, J. D., Green, J., Goodliff, K., Earle, K., Merrill, G., and Cates, G., *Architecture Reference Document (ARD) LAT Phase 2 Option 2 Version 3.0*, NASA Campaign Development and Analysis Team, 2007.

[5] Simchi-Levi, D., Kaminsky, P., and Simchi-Levi, E., *Designing and Managing the Supply Chain: Concepts, Strategies and Case Studies*, 2nd ed., McGraw–Hill, New York, 2003.

[6] Shull, S., Gralla, E., de Weck, O., Siddiqi, A., and Shishko, R., "The Future of Asset Management for Human Space Exploration," AIAA Paper 2006-7232, Sept. 2006.

[7] Evans, W., de Weck, O., Laufer, D., and Shull, S., "Logistics Lessons Learned in NASA Space Flight," NASA TP-2006-214203, May 2006.

[8] Sherbrooke, C. C., *Optimal Inventory Modeling of Systems: Multi-Echelon Techniques*, 2nd ed., Kluwer Academic, Norwell, MA, 2004.

[9] Shull, S., "Integrated Modeling and Simulation of Lunar Exploration Campaign Logistics," M.S. Thesis, Dept. of Aeronautics and Astronautics, Massachusetts Inst. of Technology, Cambridge, MA, 2007.

[10] Strang, G., *Introduction to Applied Mathematics*, Wellesley Cambridge Press, Wellesley, MA, 1986.

[11] de Weck, O. L., Simchi-Levi, D., Shishko, R., Ahn, J., Gralla, E., Klabjan, D., Mellein, J., Shull, A., Siddiqi, A., Bairstow, B., and Lee, G., "SpaceNet v1.3 User's Guide," NASA TP-2007-214725, 2007.

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[††] Data about NASA Awards Space Station Commercial Resupply Services Contracts available online at http://www.nasa.gov/home/hqnews/2008/dec/HQ_C08-069_ISS_Resupply.html [retrieved January 11, 2009].