JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 46, No. 5, September–October 2009

Matrix Modeling Methods for Spaceflight Campaign Logistics Analysis

Afreen Siddiqi* and Olivier L. de Weck†
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
Gene Y. Lee‡
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109
and
Sarah A. Shull§
NASA Johnson Space Center, Houston, Texas 77058

DOI: 10.2514/1.43319

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

Presented as Paper 7749 at the AIAA Space 2008 Conference and Exposition, San Diego, CA, 8–12 September 2008; received 19 January 2009; revision received 6 March 2009; accepted for publication 6 March 2009.

*Postdoctoral Research Associate, Department of Aeronautics and Astronautics, 33-410; siddiqi@mit.edu. Member AIAA.

†Associate Professor, Department of Aeronautics and Astronautics and Engineering Systems, E40-261; deweck@mit.edu. Associate Fellow AIAA.

‡Staff Engineer, Mission Systems Concepts Section 312, 301-180; gene.y.lee@jpl.nasa.gov. Member AIAA.

§Flight Controller, DO5/Cargo Integration and Operations Branch, Mission Operations Directorate; sarah.a.shull@nasa.gov. Member AIAA.