Space Exploration
Logistics Workshop

Project Overview

Prof. Olivier L. de Weck
deweck@mit.edu

Prof. David Simchi-Levi (MIT), Dr. Robert Shishko (JPL), Andy Evans (USA), Joe Parrish (PSI)

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Advanced Studies, Concepts and Technology
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COTR: Dr. Martin Steele, NASA

Interplanetary Supply Chain Management and Logistics Architectures
Previous Space Exploration Paradigms

• Apollo Program
  - 6 Lunar Surface Missions (1969-1972)
  - Each Mission self-contained (no space logistics network)
  - Carry-along all consumables & supplies
    • “backpack model”
  - Optimized for short-term lunar stays ~ 3 days

  “Carry-Along”

• Space Shuttle & ISS
  - Shuttle Operations 1981-
  - ISS is a single facility at LEO node (since 2000)
  - Logistics based on regular re-supply
    • Shuttle
    • Progress/Soyuz
    • Planned: ATV, HTV
  - Actual up and down mass capacity currently different than planned

  “Scheduled Resupply”
Simple Graphs

Apollo

ISS

VSE

KSC

ISS

LOP

MRS

LEO

RSA

KSC

RSA

ESA

JAX

KSC
Sustainable Space Exploration

Consider Interplanetary Exploration as a Supply Chain Problem!
What is an Interplanetary Supply Chain?

Three domains:
- Terrestrial
- In-Space
- Planetary Surfaces

Network of material and information flows to enable human/robotic space exploration:
- nodes, arcs, elements (vehicles/modules)
- crew, cargo
- probabilistic supply/demand
- pre-positioning, carry-along, re-supply
- effects of ISRU
- use of orbital & surface depots
Why is designing the ISCM challenging?

• Three domains
  – Earth, In-Space, Planetary Surfaces

• Network characteristics
  – Tradeoff between time-of-flight and mass (DV)
  – Time-varying arcs (mild for Moon, strong for Mars)
  – Discrete nature of mass flows/chunking of cargo
  – “small quantity logistics” (< 5 missions/year)
  – consumption rates uncertain, spares demand uncertain

• Multiple Levels of Nesting
  – Stacks
  – Elements (Modules)
  – Carriers
  – Cargo (Crew & Supplies)
# Nomenclature Challenge

- Pocket
- Container
- Carrier
- Module
- Segment
- Compartment
- Element
- Pallet
- Assembly
- Facility*  
- Node
- Vehicle

<table>
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<td>Platform</td>
<td>Payload Bay</td>
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* In-Space Facility (e.g., the European Technology Exposure Facility (EuTEF))

Source: Martin Steele
Project Goals

To help create a new discipline and field of study called “Interplanetary Supply Chain Management” as a critical enabler for sustainable space exploration

1. **By developing an integrated capability for guiding the development of the interplanetary supply chain**
   (nomenclature, methods & models, software tools, trade studies)

1. **By building of a community and the education of professionals skilled in the art and science of space logistics.**
   (workshop, executive course, web forum, course materials)
Impact

• **Network Level**
  – Help optimize crew & cargo flows for ISS/Moon/Mars campaigns based on technical/economic Measures of Effectiveness (MOE)
  – Provide quantitative analysis to help develop Exploration Systems Supportability Strategy

• **Operational Level**
  – Conceptualize information architecture for element, cargo asset and crew tracking
  – Suggest opportunities for commercial space logistics providers: help size market, example: fuel depot in LEO

• **Element Level**
  – Provide design recommendations for CEV (stowage, cargo capacity, internal arrangements) and CLV, HLLV
  – Quantify effects of parts commonality and reconfigurability on sparing requirements and functional availability of elements
Project Development Approach

Phase I Deliverables Year 1
- Report HMP 2005
- a-prototype software SpaceNet I
- Space Logistics evaluation of 11 CE&R architectures and ESAS Architecture
- Space Logistics Workshop I
  - SCM Short Course

Project Management
WBS 1.0

WBS 2.0
Terrestrial Supply Chain Analogies

WBS 3.0
Space Logistics Network Model

WBS 4.0
Exploration Supply & Demand Models

WBS 5.0
Interplanetary SCM Trade Studies

WBS 6.0
Public Education & Outreach

Phase II Deliverables Year 2
- b-version software = integrated space logistics modeling & simulation tool
  - SpaceNet II
- In-depth trade study results
- Workshop II
  - MIT OCW course

Civilian

Military

Space

Interplanetary Supply Chain Management and Logistics Architectures 10
HMP Expedition 2005

1. “Complete” Inventory of Research Base
2. Transportation Network Analysis
3. RFID Experiments (Agent and Asset Tracking)
4. EVA Logistics (mlogistics around camp)

- 56 researchers on site
- 683 crew days total
- 2300 items inventoried
- over 400 items tagged
- 8 EVA’s observed

Inventory: 20,717 kg
Processes and Objects of Exploration

Short Missions (< 14 days)
Medium Length Missions (14-180 days)
Long Term Missions (>180 days)
Terrestrial Simulation/Optimization Tool: LogicNet

**supply chain design:** place warehouses, consider potential w/h and manufacturing plants optimally, given customer distribution

**supply chain analysis:** estimate transportation costs, availability, shipping times, inventory levels…

Can we create a similarly sophisticated planning environment for space logistics?

Interplanetary Supply Chain Management and Logistics Architectures
Initial Condition: Spacecraft Starts at LEO, Final Condition: LOI
Can find a family of trajectories with different $\Delta V$ and flight time
Time dependency severe for Mars (26 month launch windows)
Developed concept of **Time-Expanded Networks** for Space Logistics

**Time Dependency: LEO - LLO**

- $\Delta V$ @ LEO around 3100 m/s
SpaceNet Block Diagram (simplified)

- **User Input GUI**
  - Batch Mode
  - Supply/Demand Models

- **Integrated Database**
  - Physical Nodes
  - Astrodynamic
  - Element Data
  - Crew Data
  - Supply/Demand Data
  - Scenario Data

- **Scenario Simulation**

- **Network Optimization Model**

- **NEXioM I/F**
  - SCM MoEs

- **Cost Model**
  - Tradespace Visualization
  - Simulation Visualization

**CoS = Classes of Supply**
SpaceNet Visualization

Interplanetary Supply Chain Management and Logistics Architectures
Accomplishments to date

• Completed MIT HMP 2005 Expedition
  – Gained real data and insights from field observation
  – Final report issued

• Space Logistics Lessons Learned
  – Extracted over 300 logistics lessons learned from past programs
  – Distilled down to top 7

• Network Modeling
  – Identified Time-Expanded Networks as key modeling concept

• Developed Integrated Space Logistics relational database
  – Based on functional Classes-of-Supply (COS)
  – Benchmarked against ISS & other organizations

• SpaceNet
  – Alpha prototype of space logistics discrete event network simulator
  – Provides visualization and output to assess Measures of Effectiveness (MOE) and Exploration Operations Cost Model input
Current/Future Work

• Further Develop Simulation Capability (SpaceNet)
  – Create a range of scenarios (ESAS focused)
  – “What-If” Trade Space Analyses

• Implement Logistics MOEs

• Demonstrate Optimization Capability
  – Network Optimization, Bin Packing, Launch Scheduling, Stack Formation working together

• Examine what are the key logistics strategies for NASA
  – Pre-positioning (where, what, how much?)
  – Carry-along, On-demand re-supply
  – Caching (orbital buffers/supplies – where, what, how much?)