Space Logistics

Enabler of the final frontier
1960-2060

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1914-1916 Imperial Trans-Antarctic Expedition
Led by Sir Ernest Shackleton

Two separate parties (56 men):
Weddell Party (Endurance)
Ross Party (Aurora)

“Technology”
dogs, sleds, stoves

Key concept:
“Pre-Positioning” every 1 degree (60 nautical miles)

Failed due to:
-Poor logistics planning
-No communications
-Poor physical preparation

Source: Shackleton's Lost Men by Kelly Tyler
Impact of Technology and Logistics on Exploration

“More than any other, Antarctic science is dependent on logistics, on the ability to place and maintain scientist[s] and [their] equipment in the right place at the right time. Expeditions to Antarctica up to 1925 depended on techniques of transport, communication, survival, which remained largely unchanged for 100 years....after 1925 the development of mechanized transport, the airplane, radio and technology based on better understanding of human physiology, were to make access to the Antarctic, travel within it and survival in its hostile environment, much less difficult.”

Peter Beck
“The International Politics of Antarctica”, 1986, p.131
History of Antarctic Exploration

Cumulative Number of Antarctic Expeditions

- Initial Discovery Period
- "Heroic" Age
- Amundsen Reaches South Pole (1911)
- In-Depth Exploration enabled by Logistics and Technology
- International Geophysical Year (1957)
**Space Logistics ... enabling the final frontier**

- **Challenges of Space Logistics vs. Terrestrial Logistics**
  - Time-varying launch opportunities
  - Nested complexity and object hierarchy
  - Asset management in \( \mu \)-gravity

- **Contributions of MIT Research Group**
  - SpaceNet 2.5 – Discrete event simulation software
  - GMCNF and In-Situ Resource Utilization (ISRU) on the Moon

- **Recent and Future Work**
  - MOXIE on Mars

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**Timeline**

- **1957**
  - Sputnik

- **1960**
  - Apollo

- **1980**
  - Space Shuttle

- **2000**
  - ISS

- **2020**
  - Tiangong-1
  - Artemis
  - Lunar Village

- **2040**
  - ISS N+1

- **2060**
  - Mars Base

- **Today**
  - Mir
**Definition**

**Space logistics** is the theory and practice of driving space system design for operability, and of managing the flow of materiel, services, and information needed throughout the space system lifecycle.
Terrestrial Supply Chains are designed and optimized

Supply Chain Network Design: place warehouses, consider potential w/h and manufacturing plants optimally, given customer distribution

Supply Chain Analysis: optimize for transportation costs, availability, shipping times, inventory levels…

LogicNet now part of Llamasoft

Can we create a similar planning environment for space logistics?

https://llamasoft.com/llamasoft-acquires-ibms-logictools-supply-chain-applications-business-unit/
# Terrestrial vs. Space Logistics

## Concept 1: Networks

<table>
<thead>
<tr>
<th></th>
<th><strong>Terrestrial Commercial</strong></th>
<th><strong>Space Exploration</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nodes</strong></td>
<td>Suppliers, Manufacturers, Distributors, Retailers</td>
<td>Launch Sites, Orbital Nodes/Depots, Surface Ops</td>
</tr>
<tr>
<td><strong>ArCs</strong></td>
<td>Transportation Links: Truck, Rail, Air, Barge, Cargo Ship</td>
<td>Chemical or Electric Propulsion Trajectories</td>
</tr>
</tbody>
</table>

## Concept 2: Push-Pull

<table>
<thead>
<tr>
<th></th>
<th><strong>Terrestrial Commercial</strong></th>
<th><strong>Space Exploration</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Supply Items</strong></td>
<td>SKUs</td>
<td>COSs: Consumables, Spares, Exploration items, …</td>
</tr>
<tr>
<td><strong>Demand</strong></td>
<td>Generated by Customers (online &amp; retail stores)</td>
<td>During in-space transit, While exploring on surface</td>
</tr>
</tbody>
</table>

## Concept 3: Lean Design

<table>
<thead>
<tr>
<th></th>
<th><strong>Terrestrial Commercial</strong></th>
<th><strong>Space Exploration</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Elements</strong></td>
<td>Modular, easily upgradeable products</td>
<td>Modular, easily maintainable vehicles</td>
</tr>
</tbody>
</table>

While the specific details differ significantly (# of SKUs, # missions/year,…), some of the fundamental concepts and modeling approaches remain valid.
Earth \rightarrow Mars: Time-varying Launch Opportunities

Can only launch missions every ~ 26 months = time-expanded transportation.

### Nested Complexity and Object Hierarchy

<table>
<thead>
<tr>
<th>Supply Items</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pocket</td>
<td>Item</td>
</tr>
<tr>
<td>Container</td>
<td>Component</td>
</tr>
<tr>
<td>Carrier</td>
<td>Subsystem</td>
</tr>
<tr>
<td>Module</td>
<td>System</td>
</tr>
<tr>
<td>Segment</td>
<td>SRU</td>
</tr>
<tr>
<td>Compartment</td>
<td>LRU</td>
</tr>
<tr>
<td>Element</td>
<td>ORU</td>
</tr>
<tr>
<td>Pallet</td>
<td>CTB</td>
</tr>
<tr>
<td>Assembly</td>
<td>M-01</td>
</tr>
<tr>
<td>Facility*</td>
<td>M-02</td>
</tr>
<tr>
<td>Node</td>
<td>M-03</td>
</tr>
<tr>
<td>Vehicle</td>
<td></td>
</tr>
</tbody>
</table>

*In-Space Facility (e.g., the European Technology Exposure Facility (EuTEF))

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Net cargo mass fractions are very low (<1% of launch mass). Tare mass matters.

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Asset Management in \( \mu \)-gravity

Tracking ~ 20,000 items
Manual bar-code based system
Relatively accurate system, but still ~ 3% of items are tagged as lost
Requires substantial manual labor in space and on the ground (\( \geq 20'/\text{day/crew} \))

Russian/NASA Inventory Management System (IMS)

Automate real-time asset management.
Track parent-child relationships.


Challenges of Space Logistics
SpaceNet 2.5 Modeling and Simulation

A computational environment for

• **Modeling** space exploration from a **logistics perspective**
• **Discrete event simulation**
  • at the individual mission level (sortie, pre-deploy, re-supply,...)
  • at the **campaign** (=set of missions) level
• **Evaluation** of manually generated exploration scenarios with respect to feasibility and measures of effectiveness
• **Visualization** of the flow of elements, agents and supply items through the “interplanetary” supply chain
• **Optimization** of scenarios according to selected MOEs
• Provide software tool for users (= logisticians, mission architects) to support **trade studies** and architecture analyses.

Open Source Release 2.5.1 Oct 2009
Under GNU General Public License

http://spacenet.mit.edu

Building Blocks of SpaceNet

- **Nodes**
  - Surface, Orbital, Lagrange

- **Objects**
  - Supply Items, Elements, Crew (Agents)

- **Network (Time-Expanded)**
  - Time-dependent Edges
  - Surface, Trajectory, Flight

- **Events**
  - Create, Transfer, Remove, Reconfigure, Demand
  - Higher-level Processes (Transport, Exploration)

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**Classes of Supply**

1. Propellants and Fuels
3. Crew Operations
4. Maintenance and Upkeep
5. Stowage and Restraint
6. Exploration and Research
7. Waste and Disposal
8. Habitation and Infrastructure
9. Transportation and Carriers
10. Miscellaneous

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**Domain**

- Nodes, Edges
- Elements, Supplies

**Simulator**

- time = 4.2
- MOE₁ = 39.294
- MOE₂ = 198.339

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Exploration Capability Figures of Merit

• Exploration Capability [kg • crew-days]
  Dot product of crew days and exploration mass over all explored nodes for entire scenario

\[ EC_{tot} = \Delta T \sum_{i=1}^{T} \sum_{j=1}^{S} (1 - \alpha_{ij}) N_{crew,i,j} [m_{COS6,i,j} + m_{COS8,i,j}] \]

• Relative Exploration Capability [0, ∞)
  • exploration productivity relative to Apollo 17

\[ REC_b = \frac{EC_{tot}^b}{EC_{tot}^{a17}} \prod_k \left( \frac{m_{COSk}^b}{m_{COSk}^{a17}} \right)^{\beta_k} \]

\[ \beta_k = \frac{1}{2} \left( \omega_k^{a17} + \omega_k^b \right) \]

Divisia Index

\[ \omega_k^b = \text{mass fraction for class of supply } k \text{ in scenario (campaign) } b \]

Apollo 17 Normalization (1972)

Space Logistics Trade Space Results

Exploration Capability EC [man-day-kg]

Total Launch Mass TLM [MT]

- Constellation Lunar Outpost
- Constellation Campaign (4 Sorties)
- Apollo Campaign (6 Landings)
- Single Sortie Missions
- Campaign of Sortie Missions
- Constellation Sortie 1
- Apollo 17
- Apollo 11

REC=1
REC=0.2
REC=10
REC=200
Paradigm shift in human space exploration is underway ...

**Apollo**
1960-70s: carry-along

11 12 14 15 16 17

**ISS (early)**
1990-2010’s: resupply

ISS

KSC

RSA

KSC

**ISS (late)**

Future
2020-2060’s: mixed, incl. ISRU?

S1

LOP

S2

LLO

ISS

LEO

ISS

MARS

RSA

ESA

JAX

USA

PAC

What is the preferred mode for campaign logistics (carry-along, resupply, prepositioning, mixed) for future human exploration beyond LEO after 2024?

What are the demand drivers for human crews in terms of classes of supply?

What ECLSS / ISRU / propulsion technologies are the most critical?

How do the key decisions in a human space exploration strategic planning interact?
SpaceNet – sample scenarios analyzed

- ISS Resupply
- Mars Campaign with Robotic Pre-cursors
- Lunar Outpost (South Pole)
- Lunar Global Exploration (Nomadic)
## SpaceNet 2.5: What have we learned?

<table>
<thead>
<tr>
<th></th>
<th>ISS Resupply</th>
<th>Lunar Outpost</th>
<th>NEO Sortie</th>
<th>Mars Exploration Campaign</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodes</td>
<td>9</td>
<td>5</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Edges</td>
<td>13</td>
<td>6</td>
<td>3</td>
<td>23</td>
</tr>
<tr>
<td>Missions</td>
<td>78</td>
<td>17</td>
<td>1</td>
<td>21</td>
</tr>
<tr>
<td>Events</td>
<td>271</td>
<td>156</td>
<td>6</td>
<td>337</td>
</tr>
<tr>
<td>Elements Types</td>
<td>14</td>
<td>30</td>
<td>11</td>
<td>32</td>
</tr>
<tr>
<td>Elements</td>
<td>90</td>
<td>140</td>
<td>12</td>
<td>234</td>
</tr>
<tr>
<td>Duration (days)</td>
<td>1,920</td>
<td>2,628</td>
<td>148</td>
<td>6,911</td>
</tr>
</tbody>
</table>

- Campaigns involve 100’s of events and vehicles over 1000’s of days
- Bringing everything from Earth is **not** sustainable
- We need to start thinking of it as a supply chain network in space

How do we select an optimal logistics network?

Note: in SpaceNet 2.5 the network needs to be defined apriori.
Graph-theoretic modeling framework to evaluate/optimize space exploration logistics with optional ISRU from a network perspective.

Generalized Multi-Commodity Network Flow (GMCNF)

Minimize (or maximize):

$$J = \sum_{(i,j) \in \mathcal{A}} (c_{ij}^+ x_{ij}^+ + c_{ij}^- x_{ij}^-)$$

subject to:

$$\sum_{j : (i,j) \in \mathcal{A}} A_{ij}^+ x_{ij}^+ - \sum_{j : (j,i) \in \mathcal{A}} A_{ji}^- x_{ji}^- \leq b_i \quad \forall \, i \in \mathcal{N}$$

- **Mass balance**

$$x_{ij}^- = B_{ij}^- x_{ij}^+ \quad \forall \, (i,j) \in \mathcal{A}$$

- **Flow Transformation**

$$C_{ij}^+ x_{ij}^+ \leq d_{ij}^+ \quad \text{and} \quad C_{ij}^- x_{ij}^- \leq d_{ij}^- \quad \forall \, (i,j) \in \mathcal{A}$$

- **Flow Concurrency**

$$l_{ij}^+ \leq x_{ij}^+ \leq u_{ij}^+ \quad \text{and} \quad l_{ij}^- \leq x_{ij}^- \leq u_{ij}^- \quad \forall \, (i,j) \in \mathcal{A}$$

- **Flow bound**

**Multigraph:**

- Allowing multiple (parallel) arcs between the same end nodes
  - Propulsion system
  - Aerobraking option
  - TOF and $\Delta V$

Each arc has a different set of $ABC$ matrices.
**Key Results:**

- Taking full advantage of ISRU could **save up to 68.0% of IMLEO** vs. Mars DRA 5.0
- **LOX/LH2 is preferred** to NTR because of compatibility with ISRU
- **Lunar ISRU water production** and the use of aerocapture play an important role in Lunar/Mars ISRU becoming beneficial at the threshold values of production rate between 0.5 and 3.5 kg/year/kg of plant mass in the context of human exploration of Mars

MOXIE onboard Perseverance arrived on Mars on Thursday at 3:55 p.m. EST (2055 GMT)!

MOXIE – First ever $O_2$ production on Mars!
Space Logistics: Key Points to remember

• There is a paradigm shift underway from mission-centric thinking to a **network-centric approach** in space (not just for communications such as TDRSS, DSN, but mass and energy as well)

• Pioneering space with humans will rely on
  i. Combination of “traditional” but more efficient technologies (e.g. LOX/LH2)
  ii. New Technologies such as extensive ISRU, ISFR, advanced ECLSS …
  iii. Possibly Nuclear Thermal Rockets (NTR) as propulsion of “first frontier”

• Lunar + Mars ISRU has the potential to save up to 68% of IMLEO relative to a DRA 5.0 mission in steady state

• **More research and development** is needed, e.g.
  i. ISRU technology sensitivity and thresholds analysis by resource and location type
  ii. Role of Solar-Electric Propulsion (SEP) for cargo only
  iii. What happens if launch costs from Earth [$/kg] fall dramatically?
  iv. Technology covariance matrix → technology portfolio analysis
  v. ISRU remote sensing science missions and technology demonstrators
  vi. Clarifying international legal frameworks
Questions?

http://spacelogistics.mit.edu