Launch Vehicle Production and Operations Cost Metrics

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Traditional Cost Metrics

• Cost per Mass
  – Assumes 100% payload mass capacity utilized
  – Must have a common reference orbit
    • Altitude and Inclination

  – Examples:
    • Delta IV Medium
      – (1030 kg, GEO: 0 deg at 35,786 km circular)
      – (4210 kg, GTO: 27.0 deg at 35,786 km x 185 km)
      – (9190 kg, LEO: 28.7 deg at 200 km circular)
      – (8510 kg, LEO ISS: 51.6 deg at 407 km circular)
      – (7690 kg, LEO Polar: 90 deg at 200 km circular)

    • Atlas V 501
      – (3780 kg, GTO: 27.0 deg at 35,786 km x 185 km)
      – (8210 kg, LEO: 28.7 deg at 200 km circular)
      – (7540 kg, LEO ISS: 51.6 deg at 407 km circular)
      – (6770 kg, LEO Polar: 90 deg at 200 km circular)

    • Falcon 9
      – $4296/kg ($56.5M/13,150 kg, 28.5 deg inclination to LEO)
      – $11,649/kg ($56.5M/4,850 kg, 27.0 deg inclination to GEO)
Work Breakdown Structure (WBS)

- Labor Cost View
  - Tasks across all vehicles
  - Manufacturing Base embedded
  - Unit Cost not visible

Product Breakdown Structure (PBS)

- Unit Cost View
  - Cost per unit
  - Manufacturing Base Separate
  - Labor tasks may span multiple products
Life Cycle Costs

- Add costs of Development Phase and Production and Operations Phase

- Advantages
  - Full life of the program view

- Limitations
  - Must assume program duration
    - P&O costs are weighted more heavily the longer the program duration extends after development
      - Shuttle anticipated 10 years of operations, achieved 30 years
      - B-52 projected to be operational for almost 100 years at end of life
      - Greatly skews results
  - Funding is done on annual basis, not on a lifetime basis
    - U.S. Government Space programs are funded annually
    - Corporations report annual earnings, not life cycle earnings
Cost Drivers

♦ Development Testing
  • Primary cost driver in the Development phase
  - Driven by prototype production
  - Test facility costs

♦ Manufacturing Base
  • Maintenance of
  - equipment and facilities
  - training and retention of the workforce
  - retained viability during any low launch periods

♦ Manufacturing processes
  • labor required to operate and maintain the equipment
  • Material costs are not generally substantial compared to labor cost
Cost Drivers

♦ Launch Site Base Operations
  • Maintenance of
    – servicing facilities
    – launch pad services
    – launch towers
    – consumables (i.e., fuel and oxidizer)
    – control center
  • 20 – 35% of the annual launch vehicle program costs

♦ Learning Curve
  • Reduction in production and launch site operation costs as experience gained in production, assembly, launch of launch vehicle

♦ Inflation Rate
  • Varies with economy
  • Significant over time
Cost Metrics

♦ Annual Production and Operations Cost
  • Provides the annual cost of all production costs and operations costs
  • Based on unit cost
    – Constant cost independent of payload mass or orbit achieved
  • Production
    – Manufacturing costs for each unit leading to unit delivery
  • Operations
    – Post manufacturing unit costs
      • Green run testing
      • Shipping
      • Assembly
      • Launch

• Learning curve sources are visible in production and operations
• Inflation rate is visible on P&O costs, manufacturing base, and launch site base operations
• Includes fixed costs (Manufacturing Base and Launch Site Base Operations)
  – Separately identifiable
  – Fixed costs are generally independent of flight rate with the follow exceptions
    • Flight rate << production/operations capacity leads to higher fixed costs to maintain unused facilities and equipment
      – Idle systems experience freeze up, lose calibration, increased corrosion, and soft goods expiration
      – Failures due to these cases are not often detected until manufacturing and operations restart
      – If capacity is leased out, the leased uses affect machine wear and life.
      – Low utilization of work force tends to lead to many continuous improvement ideas for production and operation performance
        – Increased cost of upgrade and modifications
    • Flight rate >> production/operations capacity leads to higher fixed costs to expand facilities and equipment to meet flight rate
      – Added production lines
      – Storage facilities to allow lower rate lines build ahead and store for higher flight rates
Manufacturing Base and Launch Operations maintenance costs provide partial unit cost capability

- Varies by manufacturing and launch site
- Overlap defined by comparing unit cost to base cost
  - Effort to produce unit assigned as part of unit cost
  - Effort to maintain facilities and equipment assigned to base cost
  - If a production lapse occurs, all costs revert to base case
    - Transition is accounted for as production stop and restart costs
Cost Metrics

♦ Unit Cost

• Advantages
  – Calculates cost of a single unit
  – Constant cost independent of payload mass or orbit achieved
  – Metric compares actual unit cost to planned unit cost
  – Includes all costs associated with vehicle production and launch
    • Production
      – Manufacturing costs for each unit leading to unit delivery
    • Operations
      – Post manufacturing unit costs
        – Green run testing
        – Shipping
        – Assembly
        – Launch

• Limitations
  – Manufacturing base and launch site base operations are not accounted
  – Can be amortized but varies greatly with launch rate fluxuations
    • Extreme low actual flight rates from planned flight rates eliminate this as a useful metric
      – Shuttle had early estimates of 50-150 flights per year, and averaged 5
  – Learning curve and Inflation causes unit cost to be a variable
    • Must be accommodated for when using unit cost
$/lb, $/Kg, (€/Kg) to orbit

• Traditional Metric

• Metric is an idealistic optimum
  – Rarely, if ever, do vehicles carry the maximum mass to orbit
  – Orbits very greatly with missions
    • GEO: 0 deg at 35,786 km circular
    • GTO: 27.0 deg at 35,786 km x 185 km
    • LEO: 28.7 deg at 200 km circular
    • LEO ISS: 51.6 deg at 407 km circular
    • LEO Polar: 90 deg at 200 km circular
    • Reference: ULA Atlas and Delta Product Card, March 2013

• Launch Vehicle costs vary directly with launch vehicle mass between launch vehicle classes and inversely within a specific class of launch vehicle
  – Simpler manufacturing costs, more economic materials, are generally higher mass solutions at lower cost
$/lb, $/Kg, (€/Kg) to orbit

- Manufacturing base, launch site base operations are amortized (over an assumed program duration and flight rate) and are very uncertain
- Learning curve and inflation rate are not visible (would need to be averaged over assumed program duration)
- Scaling in the cost/mass calculation lead to a sensitivity reduction of 4 or 5 magnitudes – Very small variations represent significant cost changes
- The large number of assumptions required make this metric very uncertain
## COST METRICS

### Options

<table>
<thead>
<tr>
<th>Options</th>
<th>1 Budget Baseline vs P&amp;O Cost Model</th>
<th>2 Unit Cost Goal vs Model Unit Cost</th>
<th>3 $/# to LEO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Learning Curve</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
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<tr>
<td>Inflation</td>
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<td>Learning Curve &amp; Inflation</td>
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<td>Mnfg/Ops Base</td>
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<td>w/o Mnfg/Ops Base</td>
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### Comparison Sensitivities

<table>
<thead>
<tr>
<th>Sensitive to all Cost Factors</th>
<th>Not Sensitive to - Budget Inflation - Mnfg/Ops Base</th>
<th>Based on Total Mass to Orbit Capability</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Not Sensitive to - Budget Inflation - Manufacturing/Oper.</td>
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<td>Weakly Sensitive - Learning Curve</td>
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<td>Big Changes on Cost Make Small Changes in Metric</td>
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WBS vs. PBS
- Both breakdown structures are useful to manage programs
- PBS provides basis for unit costs necessary in metrics

Life Cycle Costs
- Requires assumption on program duration

Cost Drivers
- Development Testing
  - Major cost during development relying on early P&O capabilities
- Manufacturing Base and Launch Site Base Operations
  - Significant costs during P&O
- Learning Curve
- Inflation Rate

Cost Metrics
- Cost/Mass to orbit
  - Traditional
  - Requires assumptions on flight rate, 100% payload mass, orbit, program duration
  - Inherent scaling makes metric weakly sensitive to major changes
  - Large uncertainty
- Unit Cost
  - Relative measure to planned cost
  - Insensitive to manufacturing base and launch site base operations costs
- Annual Production and Operation Costs
  - Direct measure of actual costs
  - Not dependent on program duration assumptions
  - Sensitive to all major cost drivers