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Efficiency Management in Spaceflight Systems

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Defining System Efficiency

Systems transform resource inputs into functional output.

- Spaceflight system resources:
  - payload,
  - launch vehicle,
  - ground-based launch operations.
- Functional output: successful spaceflight mission.

Process efficiency is maximized when the inputs used are the minimum required to create the maximum output, in this case mission success.

Three items are tracked to determine this efficiency:

- cost,
- schedule,
- technical feasibility.

Mathematical Modeling of Spaceflight Missions

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The dynamic of functional performance for a mission can be described as:

$$dF/dt = \delta * F + \alpha * I * R$$

- where δ, rate of function degradation, day^{-1};
- *F*, function provided by space system, function m^{-3} day^{-1} (for example life support, rate of materials consumption/recirculation, kg m^{-3} day^{-1});
- α, efficiency of resource support for considered system function, day^{-1};
- *I*, resource concentration/conversion infrastructure efficiency (such as efficiency of getting supplies from Earth), function kg^{-1} day^{-1};
- *R*, concentration of support resources (raw materials) in surrounding environment, kg m^{-3}.

Therefore the level of functional performance under steady state or long-term conditions becomes

$$F = \alpha * I * R/\delta$$

Mathematical Modeling of System Efficiency

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This gives us a mathematical definition of efficiency for spaceflight systems:

$$\alpha = \frac{F\delta}{IR}$$

Up to launch, δ=1 and R=1, so:

$$\alpha = \frac{F}{I}$$

Spaceflight missions (S) occur with a system of systems:

- Payload (P)
- Vehicle (V)
- Launch or Ground Operations (O)

So maximum efficiency requires optimized efficiency across these three systems:

$$\alpha_S = \alpha_O \alpha_P \alpha_V \quad \text{or} \quad \alpha_S = \frac{F_S}{I_S} = \frac{F_O}{I_O}\frac{F_P}{I_P}\frac{F_V}{I_V}$$

Functional Definitions

While functions may be moved among the systems, the flexibility of each operations group to trade functionality varies:

- Launch Operations: Changes to launch infrastructure are extremely expensive in schedule and funding, requires significant advanced planning.
- Payload: Tremendous flexibility in how it can accomplish its tasks once in orbit and generally has the shortest design schedule, but very limited in the functions it can do prior to launch.
- Launch vehicle: Ends up as the most flexible of the three operations groups. Can have a vehicle 'family' (multiple configurations from the same hardware) or variable staging/booster options. With a mid-length design schedule, the vehicle has the most places where changes can be made relatively quickly and with significant functional effect.

Functional Efficiency: Launch Operations

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Launch Operations Process Efficiency, F_O/I_O	How does it interact with other operations groups?	
	Associated Vehicle Resources, I_V	Associated Payload Resources, I_P
Processing/Integration	Number of segments at turnover from manufacturing	Number of segments at turnover from manufacturing
	Checkout process required	Checkout process required
	Number of propellants	Any propellants
	Hazards related to propellants	Pre-launch active stage
	Cryogenics	Cryogenics
	Number and type of consumables	Number and type of consumables
	Integrated transportation options	Number of external interfaces
Logistics	Number of spare parts to store	Storage prior to integration
	Pre-launch maintenance	Pre-launch maintenance
Launch Management/Control	Water suppression system	Shroud – ascent release
	Lightning protection	Pre-launch activation
	Shroud – launch release	Data management
	Data management (bandwidth and amount of sensor data)	On-pad consumables
	On-pad consumables	
Post-Launch Retrieval/Refurbishment	Number and type of segments to retrieve	NA
	Air or sea retrieval	
	Number and type of segments to refurbish	

Functional Efficiency: Payload

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Payload Functional Efficiencies, F_P/I_P		How does it affect other operations groups?	
		Associated Vehicle Resources, I_V	Associated Launch Operations Resources, I_O
Access to Orbit	Size	Mass-to-orbit capability	Integration
	Number	Mass-to-orbit capability	Number of launches
		Manufacturing rate	Flight availability
	Time Constraints	Manufacturing rate	Number of launches
		Integration time	Flight availability
Type	Cargo	Induced environments limitations	On-pad access
		Shroud – launch release	Shroud – launch release
			Pad-stay times
	Human	Abort system	Number of launch attempts
		Steering capability	Late-pad access
		Data system access	
		Induced environments limitations	
Activity Level		Pre-launch consumables	Pre-launch consumables
		Data management	Data management

Functional Efficiency: Vehicle

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Vehicle Functional Efficiency, F_V/I_V	How does it affect other operations groups?		
	Associated Launch Operations Resources, I_O		Associated Payload Resources, I_P
Propulsion	Engines	storage	Mass to orbit
		integration	
		hazards	
		number	
	Propellants	storage	Induced environments
		integration	
		hazards	
		number	
	Cryogenics		Trajectory
Configuration	Number of stages		Number of flights per mission
	Number of engines per stage		Induced environments
	Natural environments		Natural environments
Materials	Integration		Integration
	Checkout process		
	Transport		

Functional Efficiency: Vehicle

Vehicle Functional Efficiency, F_V/I_V		How does it affect other operations groups? Associated Launch Operations Resources, I_O	Associated Payload Resources, I_P
Design Lifespan		Reusable/Refurbishable	Flight Rate
		Number and type of engines	Flight Availability
		Use of boosters	Planning time
		Additional DFI flights	Request upgrades
Optional	Ascent Only	NA	Additional bus capability
	Shroud	Launch release	Ascent release
	Steering	Data interface integration	Avionics integration Data management
	Abort Response	Abort systems checkout	Data management Recovery capability
	Trans-lunar Injection Trans-planetary Injection	NA	Simplified bus
	GTO+ Kick stage	NA	Additional bus capability
	Hold Attempt/ Launch Recycle	Consumables Pad stay time Transport	Consumables

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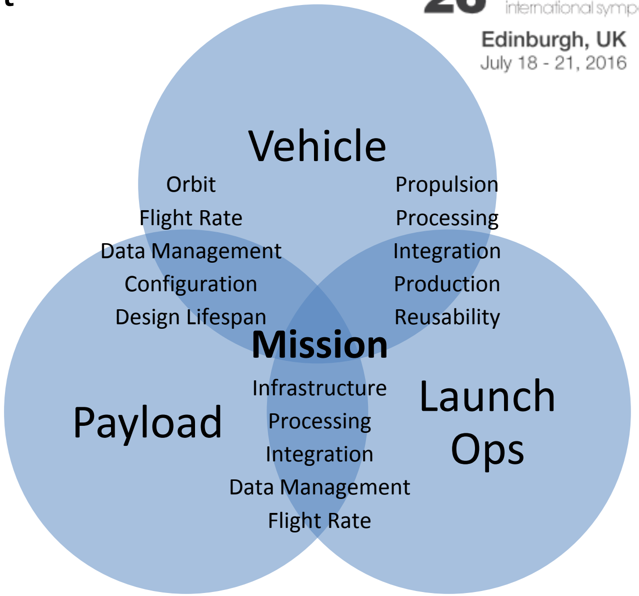
Conclusions

- Spaceflight mission systems must move towards a balance of cost, schedule and technical reliability. Spaceflight is a system of systems and balance occurs across the entirety of the system.
- Setting minimum functions required for the mission and understanding the working interfaces can be done for larger and more complex programs by optimizing among the principle operational groups and their functions.
- Efficiency in the overall mission system means moving away from an absolute focus on maximum technical performance of each subsystem in favor of mission success. Mission efficiency means opting for balanced functionality among the payload, vehicle, and launch operations systems. Spaceflight systems of the 21st century can and should move towards an operational efficiency that is both flexible and sustainable.



Backup

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Launch Ops: Tradeoffs

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Vehicle and Payload Resource Tradeoffs (I_V, I_P)		Launch Operations: Integration/Processing Efficiencies (F_O/I_O)
Interface reduction	Minimize interface points across stages and with payload and ground.	Reduces mating and checkout time, and personnel required. Reduces number of parts and types of tools. Simplifies tracking of parts and tools. Reduces transport infrastructure and processes. Reduces hazard mitigation processes and equipment.
	Minimize sections/stages integrated at launch site	
	Minimize types of gases and fuels required.	
	Minimize connector types.	
Incorporate computer-aided checkout in interface certification.		Reduces checkout time and personnel required. Reduces launch interval time.
Separation of vehicle and payload.		Provides timeline options: payload integration on the launch pad or integration on a different vehicle.
Provide launch stress and natural environments mitigation.		Simplifies pad refit post-launch. Reduces launch interval time.
Limit data downlink volume and type.		Reduces data infrastructure and storage needs.

Launch Ops: Tradeoffs

Vehicle and Payload Resource Tradeoffs (I_V, I_P)		Launch Operations: Management Efficiencies (F_O/I_O)
Interface reduction	Minimize information required for launch success.	Reduces number of computers, operators and bandwidth required.
	Minimize data to be downlinked during launch.	

Vehicle and Payload Resource Tradeoffs (I_V, I_P)		Launch Operations: Production/Recovery Efficiencies (F_O/I_O)
Interface reduction	Minimize sections/stages.	Reduces number of personnel required.
	Minimize on-site integration.	Simplifies inventory management: storage, tracking, integration processing, hazard management.
	Provide in-line replacement of bad parts.	Speeds up launch retry due to a malfunctioning part.
	Minimize connector types.	
Incorporate computer-aided checkout in interface certification.		Reduces checkout time and personnel required.
Minimize refurbishment requirements.		Reduces time and personnel required.
Design for recovery: transport requirements, storage and hazard mitigation, and checkout.		Reduces time and personnel required.

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Payload: Tradeoffs

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<table>
<tr><th colspan="2">Vehicle and Launch Ops Resource Tradeoffs (I_V, I_O)</th><th>Payload: Orbit Efficiencies (F_P/I_P)</th></tr>
<tr><td colspan="2">Increase orbit reached at launch.</td><td>Reduces number of transport systems and fuel required.</td></tr>
<tr><td colspan="2">Optimize launch site.</td><td>Reduces fuel required to reach orbit.</td></tr>
<tr><td rowspan="4">Optimize facilities capabilities and accommodations.</td><td>Various sizes of vehicle and payload</td><td rowspan="4">Increases mission options.</td></tr>
<tr><td>Propellant types</td></tr>
<tr><td>Abort requirements</td></tr>
<tr><td>Integration requirements</td></tr>
<tr><td colspan="2">Maximize orbits from location.</td><td>Reduces energy to orbit.</td></tr>
</table>

Vehicle and Launch Ops Resource Tradeoffs (I_V, I_O)	Payload: Flight Rate Efficiencies (F_P/I_P)
Reduce vehicle inspection/checkout time.	Reduces time between launch attempts.
Minimize effect of natural environments.	Reduces need for non-mission systems (such as shroud).
Increase vehicle availability.	Improves flight availability.
Increase pad availability.	Adds schedule flexibility.
Increase infrastructure for vehicle refit (transport, storage, assembly structure).	Improves flight availability. Reduces time between launch attempts.

Vehicle and Launch Ops Resource Tradeoffs (I_V, I_O)	Payload: Data Management Efficiencies (F_P/I_P)
Limit data required from payload.	Reduces power and bandwidth usage.

Vehicle: Tradeoffs

Payload and Launch Ops Resource Tradeoffs (I_P, I_O)		Vehicle: Propulsion Efficiencies (F_V/I_V)
Minimize I_{SP} required.		Reduces number and size of engines required.
Minimize engine requirements.	Type(s)	Reduces interface points.
	Fuel used.	
	Number of stages.	
Provide for various propellant types.		Increases mission options.

Payload and Launch Ops Resource Tradeoffs (I_P, I_O)		Vehicle: Configuration Efficiencies (F_V/I_V)
Minimize trajectory/orbit required.		Reduces required vehicle robustness.
Minimize interfaces.	Internal systems	Reduces interface points, simplifying integration requirements. Minimizes effects of internal and external systems on vehicle, improving reliability and mitigation requirements.
	Induced environments	
	Natural environments	
	Software.	
	Stages.	
	Operations groups.	
Provide orbital stage.		Reduces propellant and stages required.

Vehicle: Tradeoffs

Payload and Launch Ops Resource Tradeoffs (I_P, I_O)		Vehicle: Natural Environments Efficiencies (F_V/I_V)
Minimize exposure.	Limit rollout time.	Reduces required vehicle robustness, improves reliability.
	Limit pad-stay time.	
	Electrically isolate payload.	
Mitigate natural environments effects.	Lightning protection systems	Reduces vehicle exposure to specific natural environments.
	Precipitation shield	
	Fauna shield	
	Neutral gas purges	

Payload and Launch Ops Resource Tradeoffs (I_P, I_O)		Vehicle: Avionics Efficiencies (F_V/I_V)
Minimize vehicle data bandwidth.	Amount of data.	Reduces number of transmitting systems, including video, system health, and vehicle-to-payload. Reduces required bandwidth and storage space.
	Type of data.	
	Data routing.	

Vehicle: Tradeoffs

Payload and Launch Ops Resource Tradeoffs (I_P, I_O)	Vehicle: Lifespan Efficiencies (F_V/I_V)
Optimize infrastructure for propulsion and configuration set. Increase flexibility in payload deployment.	Create family of vehicles using the same engines and initial stages, and/or boosters.
Extend mission planning time.	Provide block upgrade options for existing vehicles. Extend cost and schedule options. Incorporate required upgrades earlier in planning.

Optional Functionality	Efficiency
Ascent only (not orbit insertion)	Reduces I_{SP} required, vehicle stages, and fuel.
Shroud	Reduces vehicle and launch operations mitigation of natural environments.
Steering	Reduces vehicle avionics requirements. Provides for human-guided abort.
Abort response	Provides for recovery of payload.
Trans-lunar/-planetary injection Geostationary Transitional Orbit kick	Additional stage on vehicle. Reduces boost system and fuel required on payload.
Hold and launch recycle	Minimize consumable usage prior to launch. Minimize pad damage prior to launch. Minimize hazard mitigation to transport off the pad.