Efficiency Management in Spaceflight Systems

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Abstract. Efficiency in spaceflight is often approached as "faster, better, cheaper – pick two". The high levels of performance and reliability required for each mission suggest that planners can only control for two of the three. True efficiency comes by optimizing a system across all three parameters. The functional processes of spaceflight become technical requirements on three operational groups during mission planning: payload, vehicle, and launch operations. Given the interrelationships among the functions performed by the operational groups, optimizing function resources from one operational group to the others affects the efficiency of those groups and therefore the mission overall. This paper helps outline this framework and creates a context in which to understand the effects of resource trades on the overall system, improving the efficiency of the operational groups and the mission as a whole. This allows insight into and optimization of the controlling factors earlier in the mission planning stage.

Background

Organizations transform resource inputs into functional outputs. For spaceflight the inputs include data, materials, and technical expertise, while the functional output is a successful spaceflight mission. The efficiency of the transformative process (whereby the inputs used are the minimum required to create the output) helps to maximize the success of the mission. Three things control this transformative process for spaceflight systems, and thus its efficiency: cost, schedule, and technical feasibility (CST).

Technical feasibility in the form of performance and reliability is historically given the most weight in the aerospace industry. Spaceflight systems must be high functioning and highly reliable, and often are unique. To move away from unique, 'one-off' systems with the design phase as the driver, to flexible, long-lifespan systems where operation is the driver, cost and schedule increase in importance. The general management effort is to try to control two of the three (Johnson 2003), but NASA's successful projects in the "Faster, Better, Cheaper" (FBC) program showed this to be limited thinking. (Ward 2010) All three must be optimized to get the most out of the project.

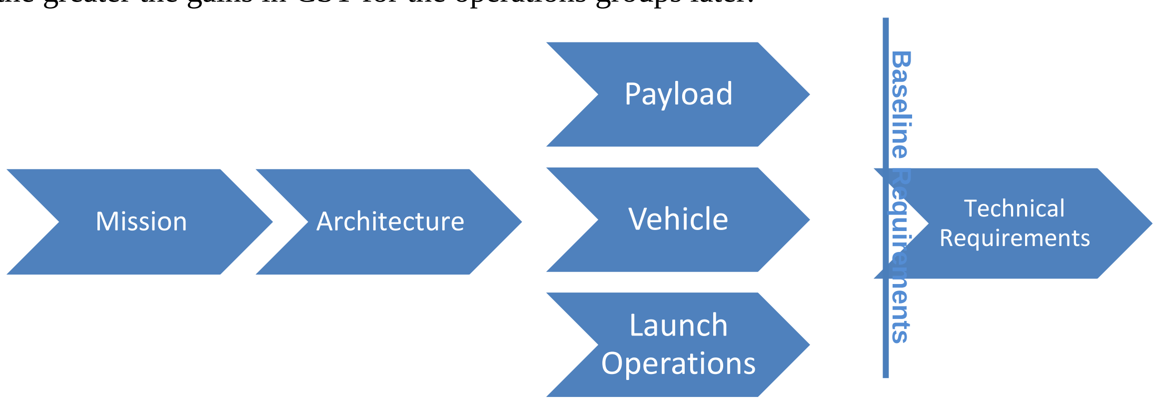
At the design level, spaceflight CST is directly affected by complexity and technology reliability or readiness level (TRL). The greater the number of interfaces in a system, the higher the cost, longer the schedule, and lower the technical reliability will be. Additional analysis and testing are required to reduce the risks related to the incorporation and operation of each new system. FBC projects succeeded notably when the complexity of technical, operational, and organizational systems was reduced, and specifically where the focus remained on the minimum functionality required for the stated mission. (Ward 2010)

Many failures happen at the interfaces of systems, and the more systems in a project the more interfaces must be defined and managed. Proper interface control requires definition of the interface: who transfers and who accepts what crosses the interface, and the approval process for dealing with conflicts. (Johnson 2003) Poor communications are cited as the cause for many failures in the FBC programs – places where designers failed to properly define or transfer information across technical, operational, or organizational interfaces. (Ward 2010)

The TRL of any technology used for spaceflight is based on testing, the history of that technology's use in other applications, and any spaceflight time. The longer this pedigree the easier and less costly in time and money it is to integrate into a new spaceflight system - the simpler it is to incorporate into the design. Both complexity and technology reliability come down to a standard design rule: use the simplest design solution required to get the job done. This concept is also known as systemic efficiency: using the fewest resources to provide the function needed. (Johnson 2003)

Design Basis

Planning for spaceflight means answering two questions: where are you going and why. These answers give planners the mission and concept of operations (con-ops) respectively, and lead directly to the mission architecture. A planner has three sets of tools to use in answering these questions: the payload, the launch vehicle, and the launch site. The mission and con-ops set requirements for the orbit, payload size (and divisibility), and timing issues such as on-orbit rendezvous or planetary alignment criteria (called the mission architecture). These are the minimum requirements to accomplish the stated goals of the mission. Once these high level requirements are set, initial mission[1] efficiency becomes a matter of CST tradeoffs among the operations groups, since the next lower set of decision points refine the functionality requirements for each of the three primary spaceflight operations groups (payload, launch vehicle, and launch operations). These decision points affect CST for the operations groups on a sliding scale of best to worst, based on the launch location and infrastructure, vehicle design and configuration, and any optional functionality the planners decide they need. Once this baseline is set, the technical requirements for each operations group can only be changed with significant effort and loss of efficiency in the design phase – the more effort is put into the early phases of mission planning, the greater the gains in CST for the operations groups later.



[1] Efficiency later in the mission, once the payload is in space and moving towards its objective, is established by functional tradeoffs among the systems within the payload itself. For the purposes of this paper, we are concerned only with the initial mission efficiency, since that is where most of the ongoing resources are expended.

Figure 1. Spaceflight planning flowchart.

Functional efficiency for the system is improved by improving the functional efficiency of one or more of the operations groups. Functional efficiency for each of these operations groups may be maximized by limiting the requirements on the organization (reducing the needed function) or by increasing the internal efficiency of that organization (reducing the inputs required for the functional output). Systemic efficiency is most effectively reached when the three operations groups balance the cost, schedule, and technical reliability required for all of the functional requirements for the mission, understanding that some functional responsibilities are more flexible than others and that the earlier such balancing trades are discussed and agreed to across the operations groups the fewer the resources required to implement them[2].

Mathematical Modeling of Functions

Once the decision points for each operations group are established, the relationships among those decision points, and how those relationships affect the CST for the operations groups and the overall spaceflight design can be explored in greater detail. The mathematical description of this is based on the concept of functional efficiency, the effectiveness of the use of available resources in carrying out the function of the system. From prior research on resource requirements for long-term spaceflight missions we determined that the efficiency of a system (α, day^{-1})[3] is based on a ratio of the function it performs (F, m^{-3}day^{-1}), the rate of degradation of that function in the established environment (δ, day^{-1}), the resources available in the environment (I, kg^{-1}day^{-1}), and the concentration of those resources (R, kg m^{-3}). (Murphy, 2009)

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

For an initially Earth-based spaceflight system, δ will be one, since even though the environment causes significant systemic degradation it is reparable by human intervention and for our purposes will be considered to be repaired as needed. Also due to our focus on the initial stages of spaceflight, R is considered to be one, since the environmental concentrations of necessary resources are at the planning default level. This leaves us with functional efficiency as a ratio of the function of the system and its available resources, given by:

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

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[2] While functions may be moved, the flexibility of each operations group to trade functionality varies. Changing the functionality of launch infrastructure is extremely costly in time and money – all flexibility must be planned well in advance. The payload has tremendous flexibility in how it can accomplish its tasks once in orbit and generally has the shortest design schedule, but it is very limited in the functions it can do prior to launch. The launch vehicle thus becomes the most flexible of the three operations groups, especially if that flexibility is planned for with something like 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.

[3] The units of these functional terms are defined as follows: day^{-1} is translated as "per day"; m^{3} is translated as "meters cubed"; and kg is kilogram. Work (F) is done in units of effort per day, for instance. The original equations from which these are derived are in the given reference, Murphy 2009, available from the author on request.

As noted above, there are three major operations groups or subsystems for designing a spaceflight system: launch operations (O), payload (P), and vehicle (V). The functionality and resources of each subsystem affects the cost, schedule, and technical readiness (the efficiency) of the overall spaceflight system in a predictable way due to their interrelatedness – absolute failure in one leads to absolute failure in the system; inefficiencies in one will show as an inefficiency in the system overall. In a system of systems, such as a spaceflight mission (S) or series of missions making use of the same subsystems, the efficiency of the overall system is shown by the relationships among its subsystems:

$$\alpha_s = \alpha_O \alpha_P \alpha_V$$

$$\alpha_s = \frac{F_S}{I_S} = \frac{F_O}{I_O}\frac{F_P}{I_P}\frac{F_V}{I_V}$$

The functions required by the mission (F_S) split among the three functional operations groups (F_O, F_P, F_V), as do their resources (I_O, I_P, I_V). For the mission to succeed, all of the basic functional requirements must be met in at least one of the operations groups. Functionality metrics for each subsystem will thus impact the system as a whole, as well as the efficiency of the individual subsystem. A function required for the system as a whole can be moved from one subsystem to the next, but must remain, with its associated resource costs, within the overall system. Resource inputs for a function can be moved from one subsystem to another, but must address the minimum required functionality. These resource trades provide the potential improvements in system efficiency that are the subject of the remainder of this paper.

Launch Operations

The functional processes of launch operations are processing/integration of the launch vehicle, processing/integration of the payload, logistics, launch management and control, and any post launch responsibilities including retrieval/refurbishment of reusable segments. (Assessment, 1988) (Voss 2011) These functions should be considered as early as possible because they are based largely on fixed infrastructure that requires large capital investments to change. For most missions, launch operations with established infrastructure will be the least flexible group for trades and will instead place requirements on both the vehicle and payload. The question to answer for each trade option is, "Does the operations design solution optimize resource use across the three groups?"

Table 1: Launch Operations functional efficiency effects from resource loading by vehicle and payload.

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	

Integrating launch operations-related function into vehicle and payload design could reduce the inputs (resources) required by the launch operations group significantly – minimal increases in CST for vehicle and/or payload design can result in large reductions of CST for launch operations. This is especially important when considering that ongoing operations costs can be the largest part of a launch system's budget over the life of a program[4].

The actual launch infrastructure is the most visible part of launch operations, and generally the biggest investment in CST. The launch vehicle transports from delivery or assembly points, ground data systems including interfaces with both vehicle and payload, launch towers, and any required pad environment modifications are all investments made at the beginning of a spaceflight program and require significant time and resources to change. The CST overlap here is with vehicle design and mission operations, which must work with the launch operations team to determine optimal numbers and timing of launches.

Once the vehicle and payload elements are at the launch site, processing and integration functions take over. These are primary functions for the launch operations group and focus on integration of vehicle sections into the flight vehicle configuration, and integration of the payload into the transport section of the vehicle.

Table 2: Launch Ops: Integration/Processing tradeoffs and potential efficiencies.

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.

[4] Flight rate is often used as one measure of launch operations costs (cost per flight to launch), and thus more flights over a longer time will reduce the per-flight cost of launching a specific system. Thus if a vehicle or launch system is not planned for consistent use, its per-flight costs will be higher than a vehicle launching on a more consistent schedule. This demonstrates a flaw with the per-flight cost as a metric, since it penalizes systems with lower flight rates even if their operational efficiency is better in other areas.

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 management operations resources include the computers that monitor the vehicle and payload prior to and during launch, providing telemetry data and command generation for staging maneuvers, and that signal the vehicle to launch, as well as the humans that operate these computers. (Johnson, 2003) Vehicle and payload design affect the CST for this operations subset by setting their required data monitoring. Range safety requirements must also be considered and are a standard baseline to use when planning data management. Whether a vehicle has a development flight instrumentation (DFI) sensor package, or an operational sensor package will affect the data management. DFI packages are far more extensive and add additional video as well as comprehensive health and safety data downlinks, so that the designers can get a complete picture of how the vehicle and payload react during launch and ascent. Whether or not all this information is recovered real-time, or is recovered from a recorder after the launch will also affect CST, especially of launch operations and vehicle design. Operational data packages primarily include those sensors needed to verify safe operation and allow for manual abort procedures, as well as any information mission operations deems critical. Some of this information can be gathered and transmitted by the payload, so tradeoffs between vehicle and payload are recommended for optimal CST. Flight test vehicles and payloads that begin sampling data at launch have a larger data requirement: they are gathering information from the moment the launch signal is given or earlier, and much of this information will be downloaded to the launch management operations group.

Rightsizing in this case involves determining the minimum information needed for a successful launch. For a payload, this may only mean location data, or a ‘go’ signal from the vehicle on successful staging of the payload segment. For the vehicle, this includes basic telemetry such as acceleration and flight position (roll, pitch and yaw), which will provide the data required to initiate an abort should one be necessary. Adding additional data tracking during launch and ascent, while a minor CST issue for the vehicle or payload, can become a major addition to CST for launch management.

Table 3: Launch Ops: Management tradeoffs and potential efficiencies.

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.	

Oversight of manufacturing/production and where the sections of a vehicle or payload are turned over to the launch operations group are optional functionality for that organization, since they can be provided by the manufacturer of the launch vehicle.

Launch operations managers must also consider whether a vehicle or payload has reusable or refurbishable segments, and work with vehicle designers to determine what ground support this will require after a launch, such as the recommended recovery and refurbishment processes. These issues must be considered when determining whether reuse/refurbishment is actually efficient from a CST perspective: does it require fewer resources to make a new part than reuse the old one?

Table 4: Launch Ops: Production/Recovery tradeoffs and potential efficiencies.

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. Simplifies inventory management: storage, tracking, integration processing, hazard management. Speeds up launch retry due to a malfunctioning part.
	Minimize on-site integration.	
	Provide in-line replacement of bad parts.	
	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.

Mission/Payload Operations

The functional processes for the mission/payload operations for our purposes in this paper[5] are accessing the target orbit, initiating the payload instruments/purpose, and integration between the bus (spacecraft flight shell) and payload (instrument package). (Johnson, 2003) Decision points for mission operations relate to how it gets where it needs to be (the target orbit), how many payloads have to be at that orbit and during what time scale for the mission to succeed (flight rate), data management, and the payload/instrument activity level during launch and ascent. These are considered payload operations from the overlapping viewpoints of the vehicle and launch operations. The CST for the payload is generally focused in the instrument set, since that is where the value of the mission and its overall success will be judged. However, CST tradeoffs among the operations groups can greatly affect the design of the bus, and may affect when the payload becomes operational and how many instruments it carries. The more self- contained a payload is (the less connections for fuel, data, gases, et al., it has with the launch vehicle or launch operations infrastructure), the less affected it is by design decisions for the other two operations groups. Target orbit issues will be discussed more under the vehicle section, and data management was looked at with launch operations. For this section, cargo type and size, flight rate and activity are the areas on which the payload is most dependent on the other operations groups. The question to answer for each trade option is, "Does the payload design solution maximize mission gain while minimizing resource usage across the three groups?"

Table 5: Payload functional efficiency effects from resource loading by vehicle and launch operations.

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

[5] Most of the actual functional processes of the payload, whether human, instrument, or cargo, occur outside of sphere of the launch operations and launch vehicle. These functional processes are contained only within the payload operations group and the CST for those processes is not significantly affected by the other two operational groups unless multiple launches are required to secure the mission operations.

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

The basic payload consideration of size narrows the choices of launch vehicle, and whether the payload is cargo or human places limits on vehicle environments and launch operations.

Table 6: Payload: Launch tradeoffs and potential efficiencies.

Vehicle and Launch Ops Resource Tradeoffs (I_V, I_O)	**Payload: Launch Efficiencies (F_P/I_P)**
Mitigate vehicle and natural environments.	Reduces non-mission structural additions like shrouds, escape systems, and isolated electronics.
Provide consumables at the launch site.	Reduces fuel storage systems and battery needs, extending possible pad stay time.

Orbital targets fall into two general categories: within the Earth- Moon system and outside the Earth-Moon system. Within the Earth- Moon system are primarily low energy orbits such as low earth orbit (LEO), geosynchronous orbit (GEO), geostationary transfer orbits (GTO), and trans-lunar injection orbits, for which the launch vehicle provides most of the energy and which can be reached with minimal effort from the payload bus. Targets outside the Earth-Moon system, such as orbits for trans-planetary injection and intra-solar system exploration, require greater power and precision by the launch vehicle and payload bus for planetary slingshot trips. In addition, launch site location determines which orbits can be reached with a minimum energy (such as polar or geostationary orbits).

The launch location is a CST issue, because launch sites provide different levels of infrastructure and the various available locations provide prime energy vectors for different orbits depending on their latitude. Payloads will have to consider pre-loading support, on-pad supply availability, and abort restrictions (such as whether their launch will be over populated areas). The energy vector considerations arise from a basic fact of the rocket equation (see below): the velocity of a launch vehicle on the pad is not zero; it depends on the latitude of the launch site location, and the planetary rotation rate and radius. Depending on the needed orbit, an equatorial launch site (with latitude of zero) will add the planet's rotational velocity to the vehicle's launch vector for the most additional energy, while a polar launch will add nothing to the vehicle's launch vector. The payload's launch site location must always have latitude of equal or less than the target orbit inclination. (Open-aerospace.org 2010)

Table 7: Payload: Orbit tradeoffs and potential efficiencies.

Vehicle and Launch Ops Resource Tradeoffs (I_V, I_O)		**Payload: Orbit Efficiencies (F_P/I_P)**
Increase orbit reached at launch.		Reduces number of transport systems and fuel required.
Optimize launch site.		Reduces fuel required to reach orbit.
	Various sizes of vehicle and payload	Increases mission options.

Optimize facilities capabilities and accommodations.	Propellant types	
	Abort requirements	
	Integration requirements	
Maximize orbits from location.		Reduces energy to orbit.

Flight rate includes two considerations for payload CST: number of launches possible in a given time period, and flight availability, which involves on-pad natural environments concerns and launch vehicle and ground system adaptations to those, vehicle inspection and pad check out time.

The launch operations section above discussed several ways the vehicle design operations group could assist in mitigating these issues. Generally, the payload has few options to mitigate natural environment effects on flight availability.

Table 8: Payload: Flight Rate tradeoffs and potential efficiencies.

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. Adds schedule flexibility.
Increase pad availability.	
Increase infrastructure for vehicle refit (transport, storage, assembly structure).	Improves flight availability. Reduces time between launch attempts.

Data management CST for the payload revolves around accessing data and bandwidth from the payload for telemetry, health and safety, commanding, and payload and ground interface systems. Unless human intervention is planned for an abort potential, there is little to no data required by mission operations until the payload goes 'live'. Launch systems have limitations to the available bandwidth, and how much of this data is available during a launch and to whom has a significant effect on the CST distribution, as does how many of the vehicle and/or payload systems have to be (or are requested to be) monitored. Some launch information can be gathered and transmitted by the payload, so tradeoffs between vehicle and payload are recommended for optimal CST.

Table 9: Payload: Data management tradeoffs and potential efficiencies.

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 Design

The basic functional process of the vehicle is simple: get the cargo to the preferred orbit. How this is done determines the vehicle complexity and all technical issues associated with that. Vehicles can be expendable or reusable; human rated or not human rated; have boosters; and have single or multiple stages, with the same or different engines and propellants. (Johnson 2003) These decision points are made during the vehicle design stage and cannot for the most part be adjusted later without significant hits to CST. Too many alterations and the design is essentially a new vehicle requiring a return to the testing phase of technology readiness.[6] The question to answer for each

[6] Vehicle development will include flight test articles, including full vehicles, designed primarily for testing subsystems of the launch vehicle as part of improving the TRL of the technology. These articles have different design requirements from flight vehicles, particularly in relation to operability and sensors. Flight test vehicles may require more complex integration and pad operations and will definitely place a larger load on the data management aspect of launch operations. (Johnson, 2003)

trade option is, “Does the vehicle design solution minimize the use of resources across the three groups?”

Table 10: Vehicle functional efficiency effects from resource loading by launch operations and payload.

<table>
<tr><th colspan="2" rowspan="2">Vehicle Functional Efficiency, F_V/I_V</th><th colspan="3">How does it affect other operations groups?</th></tr>
<tr><th colspan="2">Associated Launch Operations Resources, I_O</th><th>Associated Payload Resources, I_P</th></tr>
<tr><td colspan="2" rowspan="9">Propulsion</td><td rowspan="4">Engines</td><td>storage</td><td rowspan="4">Mass to orbit</td></tr>
<tr><td>integration</td></tr>
<tr><td>hazards</td></tr>
<tr><td>number</td></tr>
<tr><td rowspan="4">Propellants</td><td>storage</td><td rowspan="4">Induced environments</td></tr>
<tr><td>integration</td></tr>
<tr><td>hazards</td></tr>
<tr><td>number</td></tr>
<tr><td colspan="2">Cryogenics</td><td>Trajectory</td></tr>
<tr><td colspan="2" rowspan="3">Configuration</td><td colspan="2">Number of stages</td><td>Number of flights required per mission</td></tr>
<tr><td colspan="2">Number of engines per stage</td><td>Induced environments</td></tr>
<tr><td colspan="2">Natural environments</td><td>Natural environments</td></tr>
<tr><td colspan="2" rowspan="3">Materials</td><td colspan="2">Integration</td><td rowspan="3">Integration</td></tr>
<tr><td colspan="2">Checkout process</td></tr>
<tr><td colspan="2">Transport</td></tr>
<tr><td colspan="2" rowspan="4">Design Lifespan</td><td colspan="2">Reusable/Refurbishable</td><td>Flight Rate</td></tr>
<tr><td colspan="2">Number and type of engines</td><td>Flight Availability</td></tr>
<tr><td colspan="2">Use of boosters</td><td>Planning time</td></tr>
<tr><td colspan="2">Additional DFI flights</td><td>Request upgrades</td></tr>
<tr><td rowspan="12">Optional</td><td>Ascent Only</td><td colspan="2">NA</td><td>Additional bus capability</td></tr>
<tr><td>Shroud</td><td colspan="2">Launch release</td><td>Ascent release</td></tr>
<tr><td rowspan="2">Steering</td><td colspan="2" rowspan="2">Data interface integration</td><td>Avionics integration</td></tr>
<tr><td>Data management</td></tr>
<tr><td rowspan="2">Abort Response</td><td colspan="2" rowspan="2">Abort systems checkout</td><td>Data management</td></tr>
<tr><td>Recovery capability</td></tr>
<tr><td>Trans-lunar Injection</td><td colspan="2" rowspan="2">NA</td><td rowspan="2">Simplified bus</td></tr>
<tr><td>Trans-planetary Injection</td></tr>
<tr><td>GTO+ Kick stage</td><td colspan="2">NA</td><td>Additional bus capability</td></tr>
<tr><td rowspan="3">Hold Attempt/
Launch Recycle</td><td colspan="2">Consumables</td><td rowspan="3">Consumables</td></tr>
<tr><td colspan="2">Pad stay time</td></tr>
<tr><td colspan="2">Transport</td></tr>
</table>

Primary vehicle design decisions include propulsion, payload requirements, configuration, materials usage, design lifespan, and any optional functions not provided by ground or payload during launch.[7] The minimum basic requirements for this are set by what is known as the 'rocket equation' (given below in metric units).

$$\Delta v = v_e \cdot \ln\left(\frac{m_0}{m_f}\right) => \Delta v = I_{sp} \cdot g \cdot ln\left(\frac{m_0}{m_f}\right)$$

[7] Many of the functions that can shift from one group to another, and optional functions, can move to the vehicle.

The change in velocity of the vehicle (*Δv)* is determined by the velocity of the vehicle's exhaust *(v_e)* times the ratio of the vehicle's final and initial masses *(m_0, m_f)*. In general the vehicle's exhaust velocity is measured by the engine's specific impulse, or I_{sp}, which is based on the engine's acceleration efficiency, times Earth's normal gravity at sea level (9.81 m/s^2). A fraction of this velocity is also determined by the Earth's rotational vector at the launch site. During design of the vehicle, various masses are considered as fractions of the total launch mass, including the payload *(λ)*, propellant *(p)*, and structure *(δ)*. (Open-aerospace.org 2010) These fractions are used to determine the separation velocities and masses requiring lift for each stage of the vehicle during ascent.

$$\lambda = e^{\frac{-v}{I_{sp} \cdot g}} - \delta \quad => \quad \delta = \frac{m_f - m_\$}{m_0} \quad => \quad p = 1 - \lambda - \delta$$

Trades among these elements - I_{sp}, payload mass, propellant mass, and structural mass - determine the eventual functional capability of the vehicle and are the focus of most of the decisions made during vehicle design.

Propulsion decisions drive many vehicle decision considerations. Developing an engine from scratch requires ten years and approximately $2 billion; minor modification of an existing engine runs 3- 5 years and around $450 million; mission-specific modifications to an existing engine costs about $1 billion and 7 years. This includes basic testing, but the numbers could be higher if the engine needs to be rated for human spaceflight. (Snoddy 2011)

Table 11: Vehicle: Propulsion tradeoffs and potential efficiencies.

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.

Vehicle configuration encompasses decision points such as functional interfaces, induced and natural environments interfaces, avionics and software, trajectory (which determines 'max q', the point of maximum aerodynamic stress the vehicle has to survive) and number of stages. As noted previously, the number of functional interfaces relates directly to the vehicle's complexity: the more interfaces that exist, the greater the chance that a mismatch will occur at that boundary, leading to a failure.

The number of stages a vehicle has is based on the size of the payload it expects to carry and the propellant/engine combination it will use. While staging adds additional steps to a launch (and associated induced environments), it does provide for a larger payload capacity to a higher orbit, and it has been used on enough vehicles to make it a standard technology option, generally reducing the CST associated with it. Principle concerns for CST in staging include the overall vehicle mass fraction for each stage, the number of total and unique stages, and the Δv split (the optimum point of stage separation).

Table 12: Vehicle: Configuration tradeoffs and potential efficiencies.

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.

Induced environments are the effects the vehicle has on itself (see table 13 below) – effectively the interfaces between vehicle system functions. These environments are considered internal interfaces for the vehicle, with the same caveats as functional interfaces, save that the actual interfaces are not always physical (hardware to hardware). During the design phase, the effects of one system on other systems and the vehicle as a whole during launch and ascent must be predicted to mitigate these environments, and may impact the overall design or flight profile of the vehicle. In general, unless the individual induced environment affects the payload or launch pad, CST effects are primarily the vehicle's responsibility. Some CST from vibration, debris, shock, and separation-induced environments may be traded in mitigation efforts with the payload, and the use of water-suppression systems by launch operations can mitigate acoustic and heating issues at launch, but require additional time for pad refit between launches.

Table 13: Vehicle Induced Environments

Aerodynamics	Differential Pressure	Acoustics: random
Aerodynamic Pressure	Ignition Overpressure	vibration, aero, vibro,
Aerodynamic Heating	Plume Heating	propulsion system
Buffet	Plume impingement press.	Shock
Debris	Quasi-Periodic Excitation	Thermal Interface

Natural environments are those conditions native to the launch site that are encountered by the launch vehicle during its time on the pad through to delivery of cargo. These include such issues as winds, air temperature, air pressure, salt content and humidity at the ground and in the atmosphere above the launch site; precipitation issues; flora and fauna; natural and triggered lightning, and ionizing radiation during launch. CST effects are based on how long the vehicle and payload are exposed to these environments and who provides mitigation.

Table 14: Vehicle: Natural Environments tradeoffs and potential efficiencies.

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	

Avionics and software design decisions are based on which functions cannot be hardwired into the vehicle, what information has to move from one part or system of the vehicle to another, and what information has to be collected and transmitted to the payload or ground. Vehicle avionics consists of telemetry, developmental flight instrumentation (DFI),[8] health and safety sensor networks, payload data links, and vehicle-to-launch-operations data sharing, which includes range safety required data.

Table 15: Vehicle: Avionics tradeoffs and potential efficiencies.

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.	

The materials used in the vehicle generally refer to those used for structural elements such as tanks, bulkheads and the outer surface of the vehicle, since those elements make up the bulk of the structural mass of a vehicle. Currently there are two primary types of materials available for use: metals such as aluminum and steel, and composites, which are carbon fiber, fiberglass, or Kevlar coated with a resin. CST issues here revolve around mass and construction concerns, specifically the use of rolled versus milled metals, and the production and testing of composites which can be complicated in larger shapes. The number of unique materials used will also affect production and assembly costs as interface contact issues must be dealt with.

Payload considerations for the vehicle design were principally covered under payload operations, but could include many of the optional functions to be discussed below. Vehicle-provided payload support during launch and ascent can also include data feeds, vibration mitigation, and power.

Lifespan of the vehicle design is defined as how long that particular vehicle design will be operational - how reliable the design is to fly and how flexible a set of mission parameters it can accommodate. If a vehicle is reusable or refurbishable, this will also include a materials lifespan for those parts that will experience launch and ascent multiple times, including any boosters, payload carriers, and engines. Vehicles can be designed with individual flexibility, allowing one design to accommodate multiple payloads, or with block upgrade capability, where additional capacity can be designed in as needed. A vehicle with individual flexibility, such as removable boosters or additional stages for multiple configurations, also has increased complexity, since each launch configuration requires analysis and testing of the changed interface configurations. Block upgrades require retention of engineering designers and continual adjustment of risk factors with the addition of new technologies, as well as potentially multiple design and testing tracks working contiguously.

Table 16: Vehicle: Lifespan tradeoffs and potential efficiencies.

Payload and Launch Ops Resource Tradeoffs (I_P, I_O)	**Vehicle: Lifespan Efficiencies (F_V/I_V)**
Optimize infrastructure for propulsion and configuration set.	Create family of vehicles using the same engines and initial stages, and/or boosters.

[8] This is seen primarily on test articles but is also sometimes used on operational vehicles to monitor areas with previously noted anomalies.

Increase flexibility in payload deployment.	
Extend mission planning time.	Provide block upgrade options for existing vehicles. Extend cost and schedule options. Incorporate required upgrades earlier in planning.

Optional vehicle functions are parts of the mission plan which can be accomplished either by the vehicle or the payload. The assignment of the functions affects CST on both elements, as well as impacting aspects of the launch operations flow, and the split should consider carefully all repercussions of the functional designations. Is this function necessary? Does the functional split maximize the available resources?

Table 17: Optional functionality tradeoffs and potential efficiencies.

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	Additional stage on vehicle. Reduces boost system and fuel required on payload.
Geostationary Transitional Orbit kick	
Hold and launch recycle	Minimize consumable usage prior to launch. Minimize pad damage prior to launch. Minimize hazard mitigation to transport off the pad.

System Integration

Spaceflight missions do not happen without integrated planning. All three primary systems - payload operations, launch operations, and the vehicle – must be integrated from the earliest point possible to work coherently together and make the most of the cost, schedule and technical environments each has in its own right. The earlier that integration effort is made the lower the cost, shorter the schedule, and better the technical decisions – in other words, the greater the efficiency - for all three, and the more likely the mission will be a success.

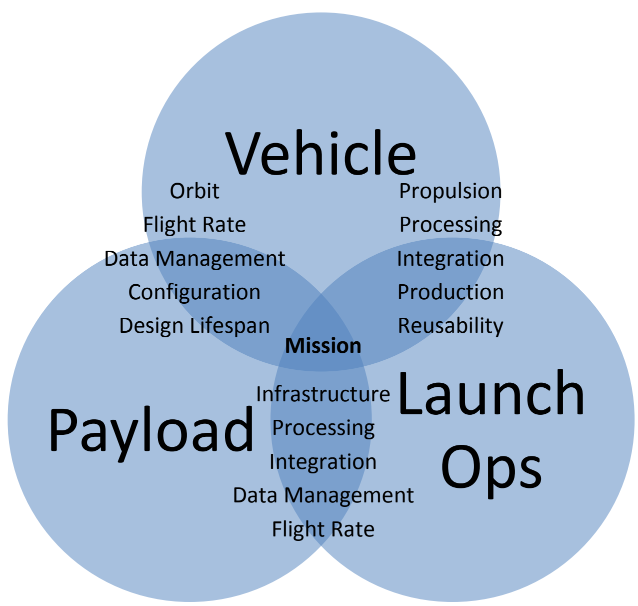

Figure 2. Mission operational groups and their functions.

There are basic requirements to designing and building a launch vehicle. There are basic requirements for a payload to survive in space. There are basic requirements to safely and successfully launch a rocket. These are the functional processes of the spaceflight operations groups. But each of these circles of functional requirements overlaps with the other two – what is done in one will have an effect on the cost, schedule, and technical requirements of the others.

Efforts to reduce cost and schedule and improve the technical reliability for the vehicle can move complexity and technology adaptation issues to launch support or payload operations, and vice versa. In order to minimize cost, schedule and technical issues for a spaceflight mission, the system as a whole must be considered and the impacts of individual decisions on each of the three functional areas must be taken into account.

Systemic efficiency in spaceflight can occur with significant improvements to one operations area, such as new engine technology, checkout systems, or a breakthrough material, but also with many smaller changes across multiple operations groups. These multiple smaller changes, while not as technically compelling or individually impressive as the "game changing" technologies, are often easier, faster, and safer to implement.

Conclusion

Spaceflight mission systems must move towards a balance of cost, schedule and technical reliability. The 'Faster/Better/Cheaper' programs NASA used for many highly successful missions in the late 20th century showed that optimizing those three goals is possible by focusing on the minimum functions required for the mission and simplifying the working interfaces. The framework given in this paper shows how this can be done for larger and more complex programs by optimizing among the three principle operational groups and their functions. By moving away from an absolute focus on maximum technical performance and opting for balanced functionality among the payload, vehicle, and launch operations infrastructure, spaceflight systems of the 21st century can move towards an operational efficiency that is both flexible and sustainable.

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Biography

Karen Murphy studied biology and writing at the University of Alabama in Huntsville while working for the Microgravity Biotechnology Laboratory at UAH. From 1991 to 1998, this laboratory flew ten Space Shuttle middeck locker payloads, providing experience in experiment and hardware design, testing, flight requirements, and data recovery and analysis. Karen later went to work at NASA's Marshall Space Flight Center supporting materials science and radiation shielding research, *in situ* resource utilization, and lunar regolith studies. Recently she supported systems integration and data management for the Constellation program and NASA's Space Launch System (SLS). She earned a Master of Science in Space Studies from the University of North Dakota and currently works logistics planning for SLS.