Avoiding the Impossible: Re-focusing a Non-Feasible Mission 2-Hrs into a 3-Day Engineering Session

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Abstract – **Concurrent engineering offers a great many benefits to engineers and mission designers throughout the world of aerospace. The only downside of concurrent engineering, and this is somewhat unavoidable, is that you don't know the results of a design session until the end when it is completed. Usually, this is not a problem – you wouldn't start building a spacecraft before the design is finished. However, within mass and cost constrained systems, you may end up with a final design that although technically sound – is not feasible due to mass or cost limits. Employing in-session mass and cost models with flexible inputs that refine their estimates and variance as more detailed information comes in throughout a design session allows major design changes to be made when the probability of breaching a mass or cost cap exceeds a threshold level. This enables mission designers to re-focus the study, and avoid spending 3-days with 15 engineers designing a non-feasible mission. By understanding key correlations and nested relationships within mass or cost, and specifically mass or cost allocations per mission element by mission type, it's possible to get flexible-input, statistically based mass and cost estimates very early in the design process. Baseline models are seeded using mission characteristics and general parameters (outer planetary orbiter-probe mission, $500M cost cap for example) to provide a rough estimate of the expected mass or cost. As information gets solidified during the session, it gets added to the model and the estimates are updated. Continuing the orbiter-probe mission example, modeling probe heat shield cost as a percent of total probe cost, and probe cost as a percent of total flight system cost, and total flight system cost as a percent of total mission cost allows a design team to roll-up solidified information to estimate the probability of fitting within a mass or cost constraint early in a concurrent design session. When only the heat shield cost is known, the variance of the final estimate is higher, whereas when the full probe gets defined, naturally, the variance of the estimate decreases. A methodology, model, verification and demo implementation for cost limit breach are presented.**

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1. AVOID DESIGNING A NON-FEASIBLE MISSION

The main motivation of the methodology described within this paper is to help design teams optimally use their time during concurrent engineering sessions. Specifically – when working in a resource constrained environment, the ability to predict if a given mission or spacecraft design is in-feasible due to a constraint cap prior to fully completing the design can save countless design hours, and allows a concurrent engineering team to change their mission architecture early in the session. This adds significant value to the concurrent engineering environment given that it stops the design team from wasting time designing a non-feasible mission, and allows them to instead produce a mission design that is feasible given the overall resource constraints.

2. CONCURRENT ENGINEERING ENVIRONMENT & OUTPUT

Concurrent design sessions, as defined and discussed in this paper, start with a mission architecture and result in a complete mission design. This entails starting with a

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destination, an instrument suite, or a set of mass, power, thermal, pointing and data volume requirements of the expected instrument suite, and results in a closed design for the spacecraft that supports the instrument suite and can support all required maneuvers and travel to destination requirements. The design session may include planning for the operational life of the mission or focus only on the development phase of the spacecraft. The tools and ideas presented in this paper come into play when there is a launch vehicle mass limit or a total mission cost limit. Two or three mission architectures may be examined at once, allowing the team to compare each option for key needs upon completion.

Concurrent design sessions, as defined and discussed in this paper, include a team of mission designers that generally includes mechanical, telecom, command and data handling, propulsion, power, guidance and navigation, integration and testing, orbital trajectory and other relevant subject matter experts. The team of engineers and designers work together and communicate system level requirements between the subsystems to each other verbally or ideally through an integrated modelling environment. The mission design team may include a cost engineer.

Concurrent engineering system on which this is based

- Roughly 3 to 20 engineers
- Rough mission concept known
- Do engineering and design in session
- Mass and cost estimates from session design are more trustable than estimates made prior to the session
  - Includes previously verified detailed models
  - Includes known mass and cost roll-ups

3. KEY RESULTS COME POST STUDY

Typically in a design session, the total mass or cost of a spacecraft designed through the concurrent design session is not available until the end of the session. As each subsystem is designed, it's requirements are sent to the other subsystems – and so the ripple though effects of each design change on each subsystem are eventually fully incorporated into the design. When the design changes are complete, and all ripple through effects have resonated through the system – the total mass and cost of each piece of the spacecraft is tallied. Some spacecraft subsystems may be complete before other spacecraft subsystems – if the telecom requirements dictate a specific telecom system, the mass and cost of that subsystem may be defined before the required propulsion or power system (including the mass of the telecom system) is finished.

If there is a mass or cost limit – and the result of the concurrent design session is too heavy for the launch vehicle, or too expensive for the cost cap – then the design team will have successfully spent all of their time designing a closed and legitimate yet in-feasible spacecraft and mission. If the design team were able to have a solid estimate of their probability of staying below a resource limit during the design process, institutional planning may dictate a change in overall mission architecture if that probability decreases below a threshold value. For example - by removing a third instrument from a 3-day study halfway through the first day based on probabilistic expectations of infeasibility – the remaining two days may be spent designing a feasible mission, instead of spending 3 days designing a spacecraft and mission that must be discarded.

4. MODELING DURING A DESIGN SESSION

Fully understanding the system and structure of information and processes in a concurrent design session is important for planning how models will ingest information, and determining which modeling methodologies are most appropriate.

Different Parts of a Design Are Complete at Different Times

During the design session, different parts of the spacecraft are completed before others. To build on the on telecom example from above – the telecom system may be fully defined before other systems. If the mission requires a specific uplink and downlink rate, and the required subject matter experts determine that a specific telecom system is required for the mission – the mass and cost of that specific system is known. The mechanical subject matter expert may need to update their design based upon the unique structure of that telecom system, the propulsion subject matter expert may need to adjust the propulsion design based on the mass of the telecom system and the added mass of the updated mechanical design, and the power subject matter expert may need to adjust the power output of the spacecraft based on the telecom system.

Each of these pieces of information would come in *after* the telecom mass and cost was finalized – perhaps after the telecom system was complete the power system would be complete, followed by the mechanical system, then the propulsion system – followed by an update by the mechanical system to account for the larger fuel tanks required by the propulsion system. So, it is evident that models that maintains a running tally of the probability of breaking a resource constraint must be able to handle a changing number of inputs.

Different Parts of a Mission are Larger Cost Drivers

There is no surprise in the fact that certain pieces of a mission are large mass and cost drivers for the overall system. The payload with instrument suite will be a large driver of overall mission mass and cost. Within the spacecraft itself, the power system, including solar panels as the case may be, is likely to be a larger cost driver than the telecom system, especially if a COTs telecom system will fit the bill. Based on the typical weighting or 'importance' of a spacecraft subsystem to the overall mass and power, different subsystem estimates relay information with different impacts.

If a less important and less massive (kg) part of the spacecraft indicates that the overall flight system will have a high mass, and a typically more important and more massive (kg) part of the spacecraft indicates that the overall flight system will have a low mass, which estimate do you trust more? Both pieces of information should be used – but if the more massive (kg) piece of the spacecraft indicates a lower overall mass, that piece of information must be weighted more heavily. Conversely, if a typically less expensive part of a spacecraft indicates a lower overall flight system cost and a typically more expensive part of the spacecraft indicates a higher overall flight system cost, which estimate do you trust more? Again, both pieces of information should be used, but they need to be combine properly through the right weighting.

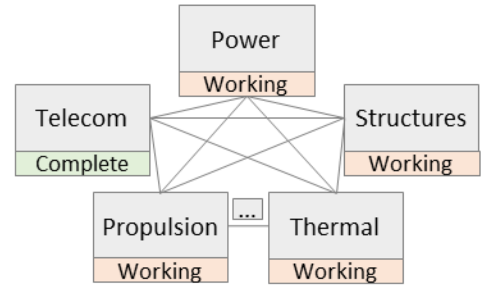
Different Levels of Variance

Mass and cost estimates from completed subsystem have significantly less variance around the mass or cost than the rough estimates for each subsystem modelled prior to the completion of the design. These more trustable mass and cost numbers are input, as they arrive, into the probability of breaking a resource-constraint models as they get completed.

As some parts of the spacecraft typically contribute more or less to overall mass or cost, different parts of the spacecraft also carry different variances. For example, using a COTs telecom system versus a custom build solar panel system – even when the concurrent engineering session is complete, and the specific mass and cost for each subsystem and spacecraft component is tallied – do you trust one of these mass and cost tallies more than the other?

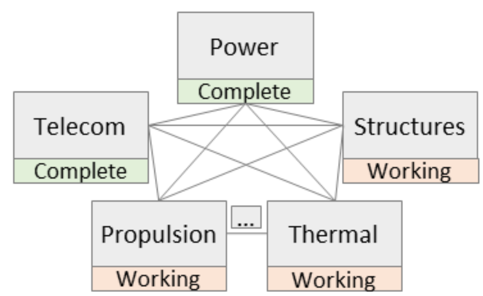
Models that provide specific subcomponent estimates have different levels of variance – Additionally, some subsystems use their own models, whereas other subsystems use specific, identified available parts – these different methods incorporated by different spacecraft subsystems effect the variance around the resulting estimates.

Incorporating variance around different pieces of the spacecraft properly will help increase the robustness mission mass and cost estimates and especially confidence levels that lead to estimates for the probability of breaking a cost constraint.



Component	kg	Range	Source
Telecom	#	*+/- 5%*	*Eng Est, COTs parts*
Power	#	+/- 25%	Est by Typical Allocation
Structures	#	+/- 25%	Est by Typical Allocation
Propulsion	#	+/- 25%	Est by Typical Allocation
Thermal	#	+/- 25%	Est by Typical Allocation
Total	**#**		**Sum of estimates with distribution from var**

Figure 1: There are higher variance levels on the component estimates that are based on typical resource allocation percentages



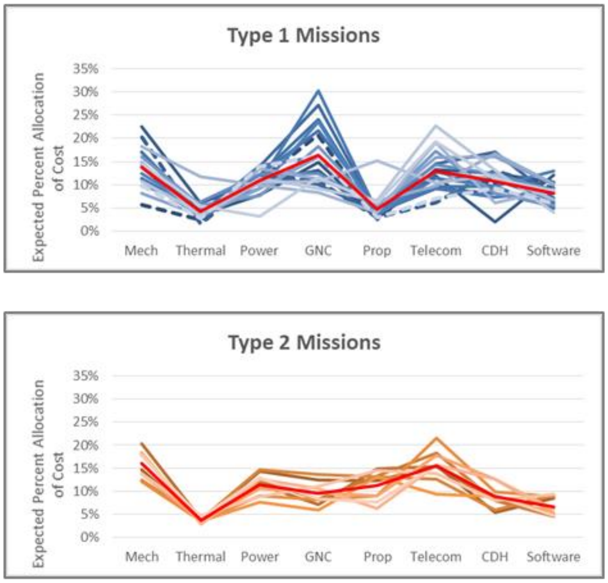
Component	kg	Range	Source
Telecom	#	*+/- 5%*	*Eng Est, COTs parts*
Power	#	*+/- 15%*	*Eng Est, Custom build*
Structures	#	+/- 25%	Est by Typical Allocation
Propulsion	#	+/- 25%	Est by Typical Allocation
Thermal	#	+/- 25%	Est by Typical Allocation
Total	**#**		**Sum of estimates with distribution from var**

Figure 2: When the telecom system is complete, known power needs inform the Power designer; power can't close before Telecom, and structures can't close before either; even though the power system has a closed design, it has a wider variance than the telecom system

5. WHY ALLOCATION PERCENTAGES

The methodology presented in this paper is primarily based on typical resource allocations per mission type. This enables us to get rough, first order total mission and spacecraft costs and masses very quickly by taking a known mass or cost, combining that information with the typical allocation of that part of the spacecraft, and working backwards to get an implied total mass or cost of the spacecraft.

$$\frac{Payload\ Cost}{Total\ Mission\ Development\ Cost} = \begin{matrix} Expected\ Percent \\ Allocation\ of\ Cost \\ for\ Payload \end{matrix}$$



$$\begin{matrix} Total\ Mission \\ Development\ Cost\ Est \end{matrix} = \frac{Payload\ Cost\ Est}{\begin{matrix} Percent\ Allocation \\ of\ Payload\ Cost \end{matrix}}$$

Figure 3: Determining Percent Allocation per component of total mission mass or cost is a very simple calculation, with major applications – especially when leveraging the differences in expected resource allocation per mission type, the analysis shows distinct differences between mission types (2 of multiple shown)

Note, this is based on two primary factors, 1) it avoids using parametric models and 2) is assumes that there are different 'types' of missions and these different types of missions have resource allocation profiles that are generally similar within types of missions and different between different types of missions. This will be shown in depth in this paper.

Parametric Model Shortcomings

Parametric models work surprisingly well in many areas – specifically – when functioning in fully defined systems, where all of the input parameters are known, and there is adequate data available for independently tuning, testing, and verifying models. However, in the context of a concurrent design session, which includes a continuously changing number of available inputs (different mission characteristics are completed at different points of a concurrent engineering session) and a highly variable environment (changes in types of subsystem components occur frequently in concurrent design sessions) – parametric models may not be the best fit.

Model Inputs Are in Constant Flux

- This Makes it difficult to model with them
- Especially in the context of changing numbers of available inputs

Given these issues with the modeling environment, more flexible models that relay on higher principles of the system to be modeled (trends in resource allocation per mission type) provide more robust estimation than classic parametric models.

Estimation by Intelligent Analogy

Determining the right groups of different mission types enables us to some extent to cost-by-analogy, in this case we're not taking an average mass or cost of analogous mission, but we're using the typical resource allocation for similar missions and applying it to the mission currently being designed.

This enables a more robust estimate, with very few input variables. Although this produces an estimate that is less exact than a finely tuned parametric model – it allows us to begin to model the overall mass and cost of a mission very early in the design process, and to estimate the probability of breaking through a resource constraint early in a concurrent engineering session.

6. REQUIRED CAPABILITIES

Based on the characteristics of the environment and information flow within a concurrent engineering session, the main requirements for modelling in our context are:

Flexible inputs – models must be able to function with varying number of inputs.

Handle nested relationships – there are key relationships between spacecraft subsystems and the total cost of the spacecraft, there are key relationships between different flight elements (a carrier, entry system and lander for example) and there are also key relationships between the spacecraft, payload and total mission cost – models must be able to handle nested relationships where information can flow both up and down through the parts of a mission.

Account for variance – different inputs to the models come along with different amounts of variance, be the initial estimates seeded only by an overall initial desirement for the total cost of a mission, or completed finalized subsystems of a spacecraft – models must be able to include different levels of variance with the inputs and incorporate these into the overall probabilistic estimates.

Track a study over time – while running a mass or cost constraint model throughout a concurrent engineering study, showing the progress of the study, and indicating the changing probability of breaching a resource cap over time is necessary.

Dynamic estimates – concurrent design sessions can move quickly – when 20 experts are designing an entire mission and spacecraft in 3 days, everything moves quickly; it is not possible to pause the design session to slowly estimate mass or cost – models must be dynamic in order to quickly produce outputs as the inputs change, live, throughout the course of a study.

7. DESIRED OUTPUTS

In order to help design teams optimally use their time during concurrent engineering sessions by enabling them to refocus an in-feasible mission when working in a resource constrained environment, the key capabilities and outputs of the tools discussed in this paper are

- Estimate resource allocations prior to the concurrent design session –
- Total resource summation
- Where resources are being used
- Sum of current estimated of mass or cost
- Probability that the estimated resource stays beneath a given resource constraint
- Show whether the current design of the concurrent design session appears to be 'in-family' with typical missions of that type
- Test – 'are you leaving something on the table'? Examine if typical mission of your mission type and approximate total mass or cost used *more* mass or cost somewhere – that you're leaving on the table

8. OTHER CASES WHERE THIS APPLIES

Tools that use the methodology described in this paper, and provide live running estimates of needed resources, as well as the probability that mass or cost will stay beneath a certain level, in a dynamic environment, with the ability to provide actionable answers with a varying number of inputs could add value to other parts of the mission design process.

Normal Engineering

In a non-concurrent engineering framework, a model that shows the probability of a resource breaking through a resource constraint could still be valuable.

The variable number of inputs would allow the tool to be used over the course of designing a spacecraft – even if it was designed in the classic manner, with email exchanges, system requirement documents and hand-rolled mass tallies – The number of inputs into the tool would still increase, and the variance on the estimate would still decrease, it would just occur over weeks instead of hours or days.

Dashboards

High level design-session dashboards could include the output of a tool built using the methodology described in this paper, so that in a concurrent engineering context, the lead of the study could keep a constant eye on the development and risks of the mission being designed.

Choosing Between Missions and Architectures

When examining a suite of missions that may compete for a single pot of resources – a tool created using the methodology described in this paper could be used to examine the different mass-risk and cost-risk profiles of the different mission options.

Even if two missions have the SAME total mass or cost, the allocation of those resources to key mission and spacecraft needs allows us to model their mass or cost risk profiles, based on the expected mass or cost allocations for their mission type.

This enables the manager of a campaign of missions to select the lowest risk missions and thus optimally allocate institutional resources to further advance the missions with the lowest risk.

Fast Paced Brainstorming Sessions

During mission space examination workshops, tools that quickly build spacecraft cost and total mission cost or mass as a function of payload (science instrument suite) specifically for each different mission type could add serious value to the mission space investigation. Specifically, it would allow the design team to quickly examine which mission architectures would be feasible, based on sending a specific payload to a specific destination as part of a specific mission type.

If there are potential scientific areas of interest that entail either sending an orbiter to Saturn or a lander to Mars, and the Saturn mission would require a set of scientific instruments known to be ~$35M, a the Mars mission would require a set of instruments known to be ~$45M, which overall architecture is feasible, given the expected payload cost and known mission type? How much would a science team have to shrink the cost of their instrument suite in order to move the mission into the realm of feasibility?

Targeting Key Areas for Additional Research

Allow designers to target areas of maximum values for technology development – by understanding which areas of a mission use up the most mass or cost resources, new technological developments can be targeted at the heaviest or most expensive areas of the mission types most critical to an organization.

9. METHODOLOGY – USING THE DATA AND STATISTICAL PRINCIPLES TO ACCOMPLISH THE DESIRED OUTPUTS WITHIN THE CONSTRAINTS OF THE SYSTEM

As described above, we would like to create a tool has the ability to estimate the resources required for each component of a mission, estimate the resources of the total mission, estimate the probability that the total mission resources will break through a resource cap, and function with a varying number of available inputs.

We have at our disposal data from previously flown missions, as well as from a number of completed mission studies. Separate analysis was performed outside of this paper that indicates that the data from the mission studies is highly similar to the data from the actual missions. In the analysis presented, data from actual missions and highly detailed mission studies was merged together in order to meet data needs for the analysis.

The components that we'd like to individually have an estimate for include: total mission, flight system, each flight element with the flight system, payload, each Work Breakdown Structure (WBS) line item of the mission, and each Subsystem of the flight system; when a flight system includes multiple flight elements, we'd like to have a resource breakdown for each subsystem of each flight element.

As discussed above, we will avoid using parametric models, and will focus on a version of analogy based estimation – defining our analogues missions, or 'groups of similar missions' or 'mission types' by looking for similar resource allocations or similar trends in resource allocation per group, and different resource allocations among different groups. This is accomplished using a mixture of subject matter expertise and quantitative methods. The typical resource allocations give us key relationships between the components of a mission.

An embodiment of the methodology presented to determine the probability of a resource breaking through a resource cap as updated inputs are determined is shown, followed by examples of using the expected percent allocations of cost applied within additional key tools.

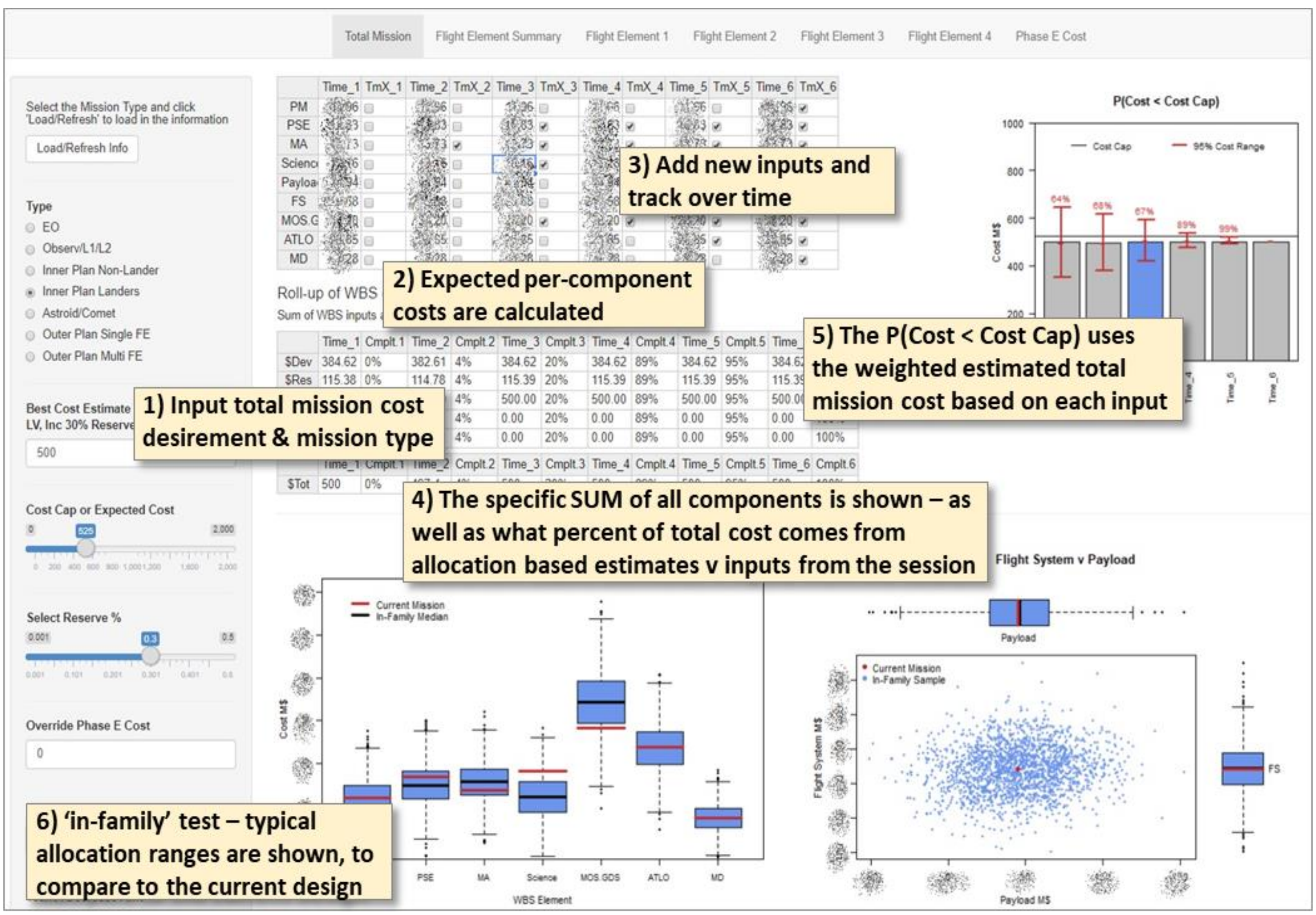


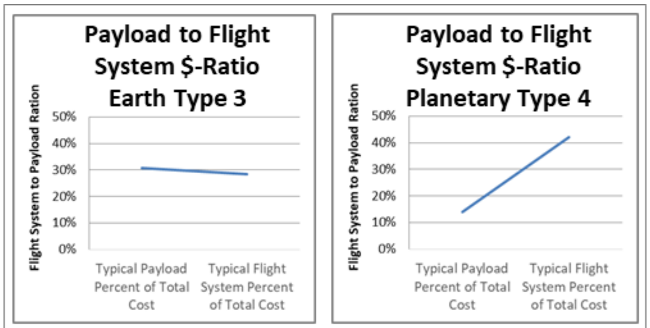
Figure 4: Employing the methodology presented enables a statistical P(Cost < Cost Cap) Dashboard tool

When different types of missions are defined, then the consistent resource allocations per mission component are used to estimate the other components of the mission – such that with each additional input, we have more estimates for the other components of the mission, and the combination of having more estimates and those estimates being based on more trust-worthy information decreases the variance in the estimate.

Based on the decreasing variance in our estimates for each component of the mission, we will have an evolving probability of the resource in question breaking through a resource cap. Details behind these calculations variance and probabilistic estimation are presented subsequently.

10. ALLOCATION PERCENTAGES AND ADDITIONAL TOOLS

Expected percent allocations provide significant value beyond the specific methodology presented; they create a web-of-connections that allows mission designers to build fully informed mission architectures within low knowledge environments.



INPUTS: PL + FS or Tot Cost	
FS+PL $M	-
Tot A-D Cost	$495
Mission Type	Earth 3
% Reserves	30%
OUTPUTS: A-D, $M FY16	
PM	$12
PSE	$12
MA	$12
Science	$20
Payload	$150
FS	$140
MOS/GDS	$20
ATLO	$10
Mission Design	$5
Reserves	$115
Total	$495

INPUTS: PL + FS or Tot Cost	
FS+PL $M	-
Tot A-D Cost	$495
Mission Type	Planetary 4
% Reserves	30%
OUTPUTS: A-D, $M FY16	
PM	$12
PSE	$12
MA	$12
Science	$15
Payload	$80
FS	$200
MOS/GDS	$25
ATLO	$15
Mission Design	$10
Reserves	$115
Total	$495

Figure 5: Fast cost breakouts allow mission designers to investigate payload capacities for different architectures

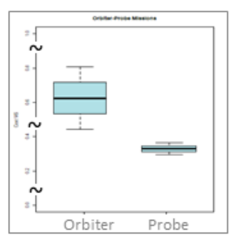
With Payload cost, we can estimate Flight System cost for different potential destinations using the unique relationships per mission type. From there, either Payload + Flight System or total mission A-D development cost desirement can be input to see the expected per component allocations. Different typical resource allocations for different types of missions allow us to quickly get an idea of what we may need to spend on each component of the mission; actual figures have been edited, but the point is – some mission types will need more money for their Flight System and other components than other missions.

Continuing the $500M outer planetary orbiter-probe mission example, what would we expect to spend on our probe? How much might each probe subsystem cost?

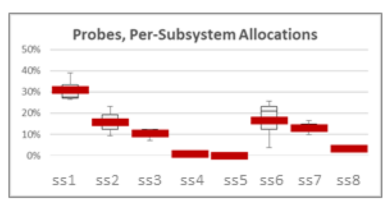
Total Cost: $500M
Mission Type: Outer Planetary Multi Flight Element

INPUTS: PL + FS	
FS+PL $M	-
Tot A-D Cost	$500
Mission Type	Outer Planetary Mx FE Type 5
% Reserves	30%
OUTPUTS: A-D, $M FY16	
PM	$15
PSE	$15
MA	$15
Science	$10
Payload	$75
FS	$200
MOS/GDS	$25
ATLO	$18
Mission Design	$12
Reserves	$115
Total	$500

The per WBS Breakdown indicates that we get $200M for the total Flight System



The per Flight Element Breakdown indicates that we get 30% of our $200M Flight System for the Probe, yielding $60M



For more detail, we can apply the Probe Subsystem allocations to the $60M

Figure 6: Applying percent allocations shows how much we may expect to spend on the probe – can we build the probe for that cost figure? We can test for feasibility here; specific numbers have been edited

By walking up and down the web of information in this manner, we could estimate the entry system cost for a Mars Lander based on the desired payload cost.

As is evidenced within the process flow of the analysis performed above, the key relationships within the different components of the mission offer a flexible input method that allows for the estimation of each component of the mission.

11. ANALYTICAL COMPONENTS USED IN IMPLEMENTATION

The backbone of the methodology presented is typical resource allocations per component of a mission – which provide us with the key relationships per mission component. We need these typical allocations ore trends in allocations to be consistent within each 'type' of mission, and we would expect them to be different across different types of missions. For example – we would expect a $500M Earth Orbiter to spend a higher percent of it's total budget on the instrument suite (payload) than the percent of total budget we would expect a Mars Lander mission to spend on their instrument suite.

Key pieces of analysis used:

- Estimating expected resource allocations
- Estimating total needed resources from subcomponent inputs
- Discussion of variance
- Sampling the total cost estimates
- Weighting and combining the total cost estimates
- Determining the probability of the resource being beneath a resource cap
- Choosing the 'types' of missions - Examine different mission types to look for differences in key relationships within mission cost and mass (allocations)
- Key Focus of Separating Missions by Type - The major defining factors that were used in determining the different 'mission type' groups for this analysis were
- Resulting Mission Types with Distinct Key Relationships

Estimating Expected Resource Allocations

Determining expected resource allocations per mission component was accomplished by finding the average percent of total mission resource per mission component per mission type. Specifically, the cost of each WBS line item was divided by the total mission cost, in order to find the percent allocation of total mission cost to each line item, for each mission.

Likewise, the expected per flight element cost allocation was determined by dividing the cost of each flight element by the total cost of the whole flight system.

Likewise, the expected per flight element subsystem cost allocation was determined by dividing the cost of each flight element WBS 6.0 subsystem cost by the total cost of the flight element.

Typical resource allocations are based on percent of total development budget, phases A-D, excluding launch vehicle.

Estimating Totals from Component Inputs

In order to estimate a total resource needed for a mission based on it's typical percent allocation per component and the current input for that component, we just have to divide the current input for that component by it's expected percent allocation. If Telecom gets 10% of total spacecraft budget, and the Telecom system comes in at $5M, then we have our first estimate for the total spacecraft cost - $5M/10% = $50M

Discussion of Variance

At the beginning of a study, there is the most variance around each estimate. The tool is seeded with a rough expected total mission cost, or total mission cost desirement – and then each WBS estimate is determined, from the expected resource allocation breakdown of the mission type selected.

During the concurrent engineering session, more detailed models, engineering expertise and/or grass roots determinations are made about the expected mass or cost of the needed components of the mission. These more trustworthy estimates still *have* a variance about them – even if it's a roll-up of COTs parts, things often change during the final development and construction of a mission, so we will be certain to maintain a distribution around any estimates from the concurrent engineering session.

With each piece of new, more trustworthy information that comes in, we get total mission cost by working backwards form the component of the spacecraft we have new information for, and the expected typical cost allocation of the total mission that we expect that component to get. These estimates for total mission cost have a reduced variance about them, and therefore reduce the variance in the estimate for the total mission mass or cost as provided by the methodology presented. In addition to having less variance around the estimates for total mission mass or cost based on new tool inputs, we also have *more* inputs, which also serves to reduce the variance around the estimate.

Sampling the Total Cost Estimates

In order to determine a probability that a total mission resource will break a resource cap, we need to have *distributions* on the estimates – and not *only* point estimates. The distributions around estimates used in the methodology are normal distributions, and the variances used are informed by outside analysis that examine the typical variances per mission type or per mission component. The methodology employs monte carlo sampling to generate empirical distributions about total resource estimates – this allows us to *decrease* the variance when around a total resource estimate based on a trustworthy mission component input from the engineering session. For cost estimates, sometimes log-normal distributions are used – analysis indicates that the data from the systems we are investigating are somewhat normal, and using a normal distribution is acceptable.

Weighting and Combining the Total Cost Estimates

When employing the methodology presented, multiple estimates for total resource needed are created – some of these estimates are based on a $10M telecom system, some of these estimates are based on a $14M WBS 4 Science budget, and some of these estimates are based on a $90M Payload suite. It is important to weight the estimates correctly when combining them.

If the estimate from your WBS 4 Science cost of $14M indicated an expected total mission cost of $350M, and the estimate from your payload cost of $90M indicated an expected total mission cost of $475M – would you weight those the same? No – mission components that are typically larger mission mass and cost drivers should be weighted higher and mission components that are exceptionally large in the *current design* of the mission should be weighted higher, as they may pose a specific mass or cost risk to the given mission architecture.

In order to properly weight the different total resource estimates, the methodology presented used the following – determine what percent of the total current sum of mission components each component represents, and then weight that components total resource estimate accordingly. This ensures that the items that require the highest amount of resources, and are likely to be the largest cost risk items, aren't erased by low estimates from low risk items – if a $10M off-the-shelf telecom system comes in *as expected*, that doesn't reduce the risk of a custom build solar panel from coming in high – it just removed the telecom system from the cost risk category.

Finding the Probability of Breaking the Resource Cap

The output of the tool for the main goal of the methodology presented is a probability that the result of the study will result in a mass or cost beyond a resource cap that makes the mission in-feasible. In order to estimate that probability, the key relationships between the components of the mission are used to estimate the total resource needed – with a variance based on how many of the inputs are based on results from engineering during the concurrent engineering study.

The probability of breaking through the resource cap is a function of the difference in the estimated total resource needed for the mission, the variance around that estimate, and the resource constraint.

Choosing the Different Mission 'Types'

There are many different methods that can be used to identify different 'groups' within a population. Multiple cluster analysis methods exist, and engineers and mission designers have multiple opinions about which missions or types of missions should be grouped together.

The primary driver that will determine which missions we group together is: where are there consistent allocations or consistent trends in allocation of mass and cost per mission component. Subject matter expertise was also used in determining which potential groupings to investigate, and whether or not groups should be merged when there is not clear quantitative evidence of group separation.

Various types of cluster analysis have also been used, including hierarchical, k-means, density and principle component based methods. The results from this separate analysis is not discussed in detail within this paper, but the general results were consulted for consistency with the groupings used in the methodology presented in this paper. In this outside analysis, there was solid evidence of division between mission types, there was some overlap between some inner planetary non-landing missions and some Earth focused missions.

Key Focus of Separating Missions by Type – Looking for separation of 'types' of mission by focusing on consistent resource allocations or trends in resource allocation is the optimal method for the methodology presented, as this method optimally minimizes the different in allocation of resources per mission component with each distinct mission type group. By minimizing the variation in per mission component allocation, we get a more accurate and precise estimate of the resources required for each component of the mission, and a more accurate and precise estimate for the total resources needed for a mission. This methodology doesn't *force* differences in resource allocation per mission component across different groups, but it does optimally separate out missions with different per component allocations from each other.

It is important to examine trends in resource allocation per mission type as well – as some resource allocations will vary depending on the total size or cost of a mission, *within* a given type of mission. Different types of missions will have resource allocation percentages that change in different ways, so it is important to include the change in resource allocation per mission component, when determining the different type of missions.

For example – the percent allocation of total cost that the Payload gets for Earth Orbiters **increases** as the total cost of the mission cost increases – because generally, it only takes a certain amount of money to get your mission into Earth's orbit, and then the rest of your money can go towards a more expensive instrument. If you have $250M, you may need to spend $150M to get to Earth's orbit and stay there, whereas if you have $500M, you may need to spend $150M to get to Earths orbit, but now you have $350M out of $500M instead of $50M out of $200M for your instrument suite (note: if your instrument suite increases in cost or mass, there are typically increases in your flight system, but for the purposes of this example, Earth Orbiter Payload is shown to *not be a constant* percent of total mission cost). However, consider a Mars Lander – if your payload increased by even $10M, you know that you'll have more mass to land on Mars, so you know that as your Payload costs increase, you can expect your flight system costs to increase a lot as well – so perhaps the percent of total mission cost that goes to payload does *not* increase as your total mission cost increases (or more specifically, it does not increase as much as it does for other mission types, an Earth Orbiter for example).

Resulting Mission Types with Distinct Allocations

The different mission types that were found, based on grouping missions with consistent per component resource allocations or consistent trends in per component allocations are:

- Earth Orbiters
- Observatories and L1/L2 missions
- Inner Planetary non-Landing missions
- Inner Planetary Lander missions (includes static landers, rovers, anything that must descend and land gracefully)
- Asteroid/Comet missions
- Outer Planetary Single-Flight Element missions
- Outer Planetary Multi-Flight Element missions (a probe and an orbiter would be a multi-flight element mission)

We won't go into the specifics of each case, but it is clear that there are noticeable and consistent relationship within a number of the groups of 'types' of missions, that are different between different types of missions

12. STEP-BY-STEP APPLIED STATISTICS

In order to combine the information from the key relationships between mission components based on the typical allocations of per mission component resources, and to get an estimate with a distribution around that estimate for a resource required for the mission design, the following steps are taken.

1. The total mission resource cap is input to the tool – at the start of a concurrent engineering study, a normal distribution is placed around this estimate with a variance determined through outside analysis
2. The expected resource allocations per mission component, for each WBS line item, are determined and displayed using the resource cap input
[study commences and engineering happens]
3. An input is updated – for example, the telecom expert has determined the total cost of the needed telecom system
4. A new amount of total mission resource needed is estimated based on the input from the telecom system
    a. Dividing the input by it's expected resource allocation gives us an estimate for the total amount of resource needed
        i. (If Telecom gets 10% of total spacecraft budget, and the Telecom system comes in at $5M, then we have our first estimate for the total spacecraft cost - $5M/10% = $50M)
    b. That mission estimate is sampled from a normal distribution centered around the mission estimate, and with a variance decreased based on the fact that it is an engineering based resource estimate
    c. For mission components that have not gotten any updates – the resource estimates are still based on the total initial resource input and the expected resource allocation percentage
        i. Each of these per component resource allocations is divided by the typical resource allocation – yielding a number of total resource needs *that have the same value* as the initial total resource input (but these are still each estimated, so they can be sampled and we can get a probability on the total resource needed)
        ii. Each of these estimates are then sampled from a normal distribution with a wide variance (as they are NOT based on engineering input)
    d. The total resource estimates (this includes all of the samples taken from each estimate) are weighted and combined
        i. The formula for weighting the different mission estimates places a heavier weight on larger total resource estimates, where that weight is determined by summing up the total mission components, and dividing each components estimate by the total sum of the components
    e. When another input comes in, that process is repeated
    f. This continues until all mission components have inputs based on the concurrent engineering study
    g. At this point, there are 9 total mission estimates – each components' estimate is divided by the typical percent allocation of resources to that component, yielding the 9 total resource estimates
    h. These are each sampled from a normal distribution, now all of them have the lower

level of variance, as they are engineering based inputs

i. These are all weighted in the same fashion – each components' resource allocation is divided by the sum of all of the components – and combined

j. Yielding an estimate for total resource need and a distribution around that

k. This resource estimate and it's distribution are compared to the resource cap – and the probability that the resource estimate is above the resource cap is calculated based on the distribution

13. KEY MASS & COST DRIVING RELATIONSHIPS

We are interested in the typical resource allocations for all components of a mission, but there are some components that give us the most important information, and drive the mass and cost of the total mission. Payload to flight systems relationships, and Payload + Flight System to total mission relationships – per mission type – are the most important relationships in our system.

Spacecraft cost-growth risk – the area where mission mass or cost growth risk usually materializes is in the spacecraft. Whether it's due to changing payload requirements, or ambitiously designed and costed space crafts – this is where mass and cost growth happens. By having a good understanding of typically required spacecraft resources needed for a given payload, mission designers can understand their mass and cost growth risk profile.

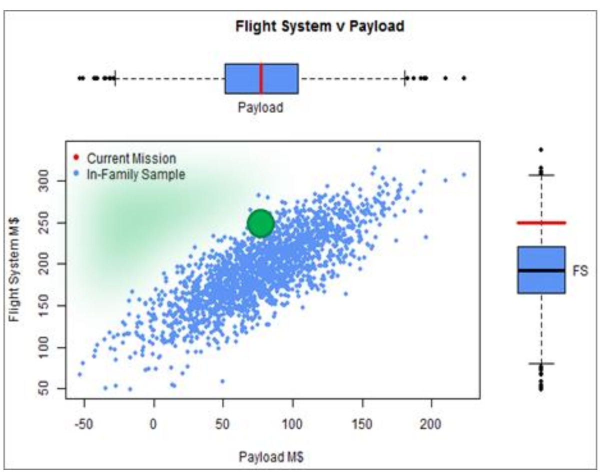


Figure 8: If Flight System funding is high relative to the Payload, there is a lower Flight System cost growth risk

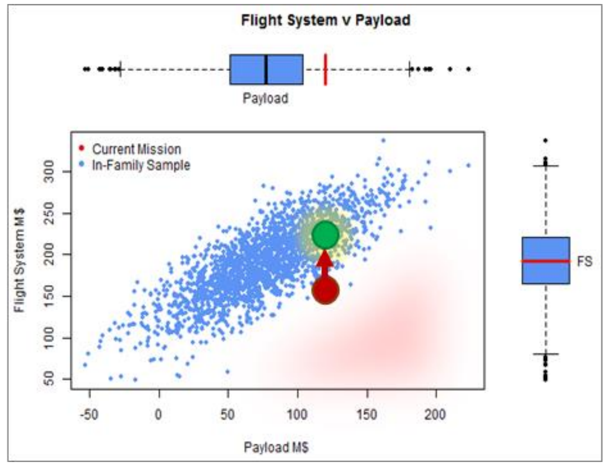


Figure 9: If Flight System funding is low relative to the Payload, there is a higher Flight System cost growth risk

The other key relationship in our system is between the total mass or cost of the mission, and the combination of the Payload and Flight System. When we estimate a required flight system based on the payload we want to fly – and we have the ability to estimate the per WBS costs of each component of the mission from the total mission cost – that means that getting to the total mission cost from the sum of the Payload and Flight System cost is very important. Fortunately, and this is a great thing to see – the typical relationships of Payload + Flight System to Total Mission cost are quite consistent, within each 'type' of mission.

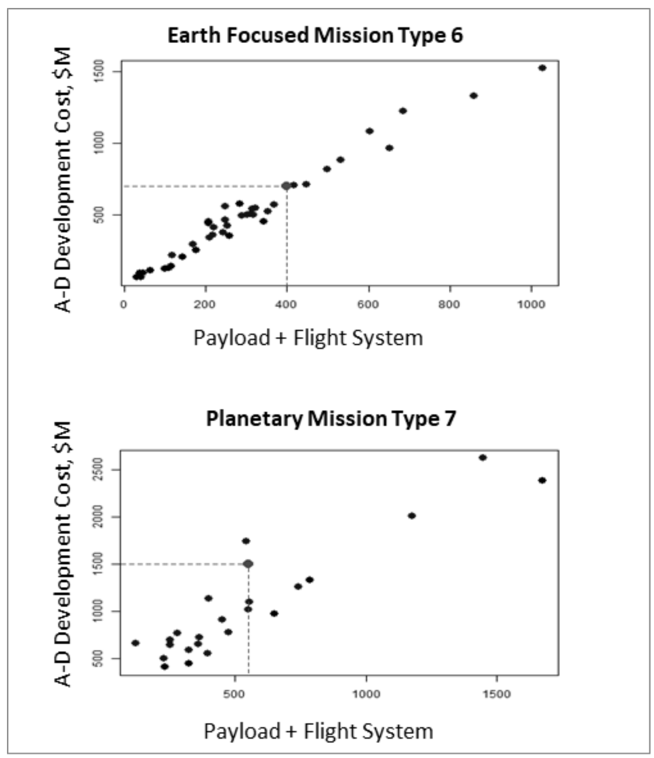


Figure 10: There are solid relationships between total mission A-D development cost and Payload + Flight System cost, this is true for different mission types as

well; in this example, a mission that is being designed is compared to the data, to examine if the mission being designed appears to be ‘in-family’

14. TESTING FOR BEING ‘IN-FAMILY’

A typical concern when design a new mission is, “is this in family?” By understanding the expected resource allocations per mission component, a design team can compare the resource allocations per mission component of the current mission being designed to the expected allocations to make that comparison. The probability that the cost will stay beneath a cost cap as a function of how ‘out-of-family’ a design is can be quantitatively measured.

The sums of the inputs at Time_1 though Time_6 are all the same, but P(Cost < Cost Cap) are not

	Time_1	TmX_1	Time_2	TmX_2	Time_3	TmX_3	Time_4	TmX_4	Time_5	TmX_5	Time_6	TmX_6
PM	13.24	☐	13.24	☐	13.24	☐	10.24	☐	13.24	☐	13.24	☐
PSE	13.68	☐	13.68	☐	13.68	☐	10.68	☐	13.68	☐	13.68	☐
MA	17.11	☐	17.11	☐	17.11	☐	14.11	☐	17.11	☐	17.11	☐
Science	12.74	☐	12.74	☐	12.74	☐	9.74	☐	12.74	☐	12.74	☐
Payloa	62.99	☐	72.99	☐	102.99	☐	122.99	☐	62.99	☐	62.99	☐
FS	210.22	☐	200.22	☐	170.22	☐	170.22	☐	210.22	☐	210.22	☐
MOS.G	28.19	☐	28.19	☐	28.19	☐	25.19	☐	28.19	☐	28.19	☐
ATLO	17.36	☐	17.36	☐	17.36	☐	14.36	☐	17.36	☐	17.36	☐
MD	9.07	☐	9.07	☐	9.07	☐	7.09	☐	9.07	☐	9.07	☐

Roll-up of WBS costs

Sum of WBS inputs and auto-populated WBS estimates

	Time_1	Cmplt.1	Time_2	Cmplt.2	Time_3	Cmplt.3	Time_4	Cmplt.4	Time_5	Cmplt.5	Time_6	Cmplt.6
$Dev	384.62	0%	384.61	0%	384.61	0%	384.62	0%	384.62	0%	384.62	0%
$Res	115.38	0%	115.38	0%	115.38	0%	115.39	0%	115.38	0%	115.38	0%
$A-D	500.00	0%	500.00	0%	500.00	0%	500.01	0%	500.00	0%	500.00	0%
$E	0.00	0%	0.00	0%	0.00	0%	0.00	0%	0.00	0%	0.00	0%
LV	0.00	0%	0.00	0%	0.00	0%	0.00	0%	0.00	0%	0.00	0%
	Time_1	Cmplt.1	Time_2	Cmplt.2	Time_3	Cmplt.3	Time_4	Cmplt.4	Time_5	Cmplt.5	Time_6	Cmplt.6
$Tot	500	0%	500	0%	500	0%	500.01	0%	500	0%	500	0%

Based on the methodology presented, we can see that increasing Payload funding and decreasing Flight System and management funding decreases our probability of staying within our cost cap

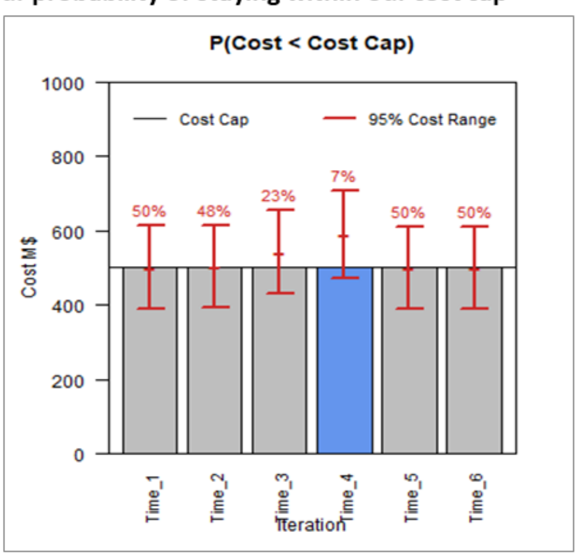


Figure 11: The methodology presented penalizes missions for having very unusual cost allocations, this helps the design team be aware of risks that are not evident when only looking at the sum of the components

This comparison can be made visually by plotting a graphical output of the expected allocations and the allocations of the current mission, and the degree to which a mission is out of family can be captured quantitatively. The nature in which total resource need is estimated presented above yields a higher total estimate the *further* away from typical allocations a mission design is. Even if the specific *sum* of all of the components of the mission are the same, the more ‘out of bed’ the mission, the lower the probability of staying beneath a resource constraint. This set up penalizes having strange cost allocation schemes, even if the total cost sums up to the cost cap amount.

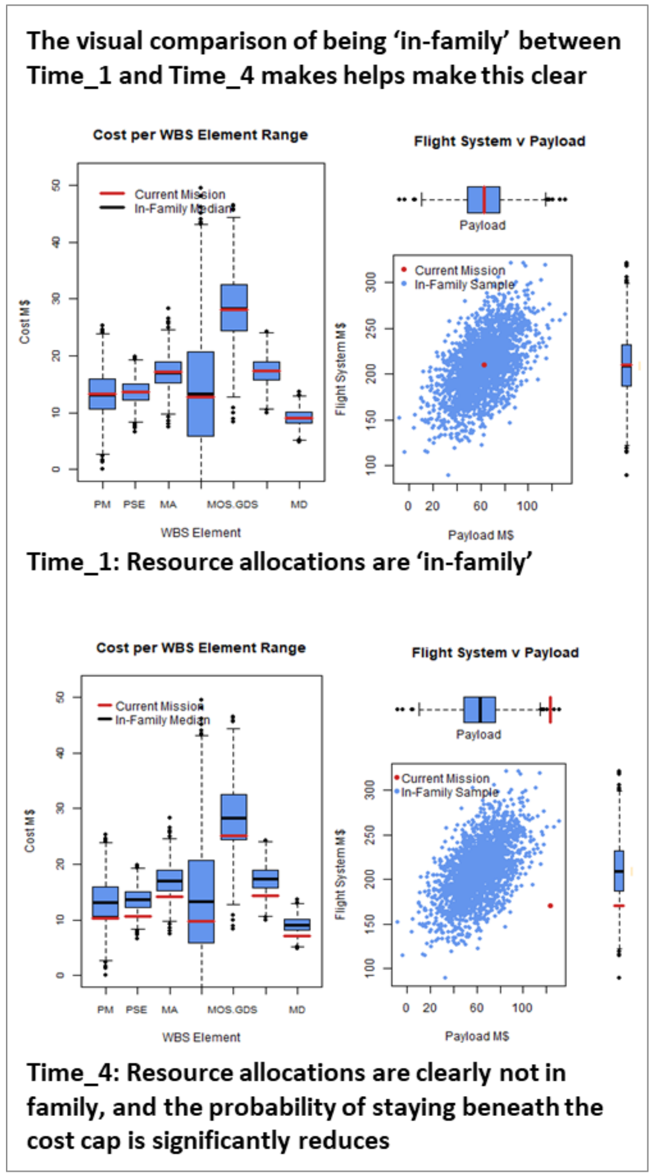


Figure 12: Clear visual warnings about being ‘out-of-family’ help designers stay aware of what’s happening during lively design sessions

15. ADDITIONAL IMPLEMENTATION OPTIONS

Stand-out additional methodologies that accomplish the goal of providing an estimate that a resource breaches a resource cap include – working the with covariance matrix of allocation of actual resources per mission component, including total mission resource (instead of working with the percent allocations), employing Bayesian network that updates the estimates for each node (component of mission) based on the inputs of the other nodes, and additional methods may also work well.

16. SUMMARY

Employing the methodology presented, specifically by using the expected resource allocation percentages per mission component per mission type supports tools that can add significant value to the concurrent engineering environment. Tools based on the methodology presented allow mission designers to make major design changes when the probability of breaching a mass or cost cap exceeds a threshold level. This enables mission designers to re-focus a concurrent engineering study, and avoid spending 3-days with 15 engineers designing a non-feasible mission.

ACKNOWLEDGEMENTS

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration

REFERENCES

[1] Manuele, F. A. “Leading & Lagging Indicators.” *Professional Safety.* vol. 54, no. 12, pp. 28–33, 2009.

[2] Rhodes, D. H., Valerdi ,R., and Roedler G. J. “Systems Engineering Leading Indicators for Assessing Program and Technical Effectiveness.” *Systems Engineering.* vol. 12, no. 1, pp. 21-35, 2008.

[3] Kluger, J. and Cray, D., “Management Tips from the Real Rocket Scientists.” *Time*. Nov. 2005.

[4] Wall, S., “Use of Concurrent Engineering in Space Mission Design.” *EuSEC 2000 Proceedings*. Munich, Germany, 2000.

[5] Karpati, G., Martin, J., Steiner, M., and Reinhardt, K., “The Integrated Mission Design Center (IMDC) at NASA Goddard Space Flight Center.” *IEEE Aerospace Conference 2003 Proceedings*. Big Sky, MT, 2003.

[6] McGuire, M., Oleson, S., Babula, M., and Sarver-verhey, T., “Concurrent Mission and Systems Design at NASA Glenn Research Center: The origins of the COMPASS Team.” *AIAA Space Conference 2011 Proceedings*. Long Beach, CA, 2011.

[7] Mulqueen, J., Hopkins, R., Jones, D., “The MSFC Collaborative Engineering Process for Preliminary Design and Concept Definition Studies.” *AIAA Space Conference 2011 Proceedings.* Long Beach, CA, 2011.

[8] Moeller, R. C., Borden, C., Spilker, T., Smythe, W., Lock, R., “Space Missions Trade Space Generation and Assessment using the JPL Rapid Mission Architecture (RMA) Team Approach.” *IEEE Aerospace Conference 2011 Proceedings*. Big Sky, Montana, 2011.

[9] Hihn, J., Chattopadhyay, D., et. al., “Aerospace Concurrent Engineering Design Teams: Current State, Next Steps and a Vision for the Future.” *AIAA Space Conference 2011 Proceedings*. Long Beach, CA, 2011.

[10] Warfield, K., and Hihn J., “Spreadsheets in Team X: Preserving Order in an Inherently Chaotic Environment.” *42nd Hawaiian International Conference on System Sciences (HICSS 42) Proceedings.* Waikoloa, HI, 2009.

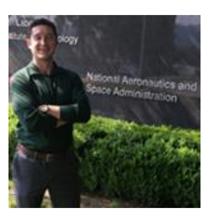
[11] Morse, E., Leavens, T., Cohanim, B., Harmon, C., Mahr, E., and Lewis, B., “Next-generation concurrent engineering: Developing models to complement point designs,” *IEEE Aerospace Conference 2006 Proceedings.* Big Sky, MT, 2006.

[12] Garthwaite, P. H., Jolliffe, I. T., Jones, B., *Statistical Inference.* Oxford University Press, 2006.

[13] Zarifian, P., Imken, T., Matousek, S., E., Moeller, R. C., et. al., “Team Xc: JPL's collaborative design team for exploring CubeSat, NanoSat, and SmallSat-based mission concepts.” *IEEE Aerospace Conference 2003 Proceedings*. Big Sky, MT, 2015.

[14] Akhundov, J., Werner, M., Schaus, V., Gerndt, A., “Using timed automata to check space mission feasibility in the early design phases.” *IEEE Aerospace Conference 2003 Proceedings*. Big Sky, MT, 2016.

BIOGRAPHY



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