Monte Carlo Simulation Analysis

Mass Growth Analysis: Asteroid Mining Spacecraft

ASE 374K Space Systems Engineering
Topic: Monte Carlo Analysis
Semester Project
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Input Parameters: Choices

Mass Estimation Spreadsheet

Element	Level 3	Level 2: CBE	Contingency	Allocated	Level 1	Notes/Assumptions:		
1.0 Payload (scientific instruments, etc)		7000	1300	8300		Payload Contents:	Mining/refining equip	
2.0 Spacecraft Bus (dry)					25388.83		Research equip	
2.1 Propulsion		782.65	227.63	986.41		% Contingenc	30%	
2.1.1 Mass of Engines	600							
2.1.2 Mass of Thrusters	54							
2.1.3 Fuel Tank	15.5							
2.1.4 Oxidizer Tank	20.3							
2.1.5 Pressurant Tank	7.4							
2.1.6 Pressurant	14.3							
2.1.7 Lines, Valves, Fittings, Regulators, etc	71.15							
2.2 ADCS		6.7	1.3	8		% Contingency: 20%		
2.3 Communications		42.4	4.24	46.64		% Contingency: 10%		
2.3.1 Low/Medium Gain Antennas	3					How many low gain and medium gain antennas: 2 Medium		
2.3.2 High Gain Antenna	12					Type and size of high gain antenna: 1.3 m diameter conical		
2.3.3 Transponders	12							
2.3.4 Diplexers	2.4							
2.3.5 RF Switches, Cables, etc	13							
2.4 C&DH		4.5	0.5	5		% Contingency: 10%		
2.5 Power		22129.8	2212.98	24342.78		% Contingency: 10%		
2.5.1 Solar Arrays / RTG(s)	11076							
2.5.2 Batteries	4000							
2.5.3 PMAD	6000							
2.5.4 Wiring	1053.8							
2.6 Structure		5712.48675	634.72075	6347.2075		% Contingency: 10%		
2.6.1 Solar Arrays actuator mass	396							
2.6.2 Antenna mechanism mass	32							
2.6.3 Landing equipment	5141.24							
2.6.4 Other (backup equipment etc)	143.25							
2.7 Thermal Control System		92.29164	9.229164	101.520804		% Contingency: 10%		
2.7.1 Surface Finishes	2.118					Type of Surface Finish: Kapton		
2.7.2 Insulation (MLI)	33.8876					0.73kg/m^2 with 16 layers		
2.7.3 Radiators	10.88					Cube shape like heritage		
2.7.4 Heaters	4.39484					Cartridge and only 1 for backup		
2.7.5 Louvers	41.0112					ATK		
2.7.6 Heat Pipes	0					Assuming none		
2.8 Other (ECLSS, etc.)		100	0	100		% Contingenc	0%	
3.0 Spacecraft Dry Mass					30943.1483			
4.0 Consumables					0	Consumables: None		
5.0 Propellant					600			
5.1 Fuel		158	31.6	189.6	189.6	% Contingenc	20%	Type of Fuel: MMH
5.2 Oxidizer		342	68.4	410.4	410.4	% Contingenc	20%	Type of Oxidizer: N2O4
6.0 Loaded Mass					31543.1483			
7.0 3rd Stage (aka Kick Stage)					N/A			
8.0 Injected Mass					189.6			
9.0 Launch Vehicle Adapter					124			
10.0 Boosted Mass					313.6			
11.0 Margin					2447	% Margin:	9%	
12.0 Total Launch Vehicle Capacity					28149.43 kg	C3 to Orbit:		Launch Vehicle: Falcon 9 Heavy

Large Systems

- Payload: The mass of the instruments and mining equipment. This mass is based off of the Falcon Heavy requirements. [1]
- Power: This system is the heaviest due to the mass of the solar arrays needed to perform mining and refining processes.

Subsystem

- Propulsion: Mass of all the thrusters and tanks. Does not include any propellant itself.
- ADCS: Mass of attitude determining hardware.
- Communications: Mass of the spacecraft and asteroid base communications system. Includes a high, low and medium gain antennas and more.
- Structure: The heaviest subsystem, most of the mass is due to the landing equipment.
- Thermal: Mass of insulation, heaters and radiators, etc… needed for deep space travel.

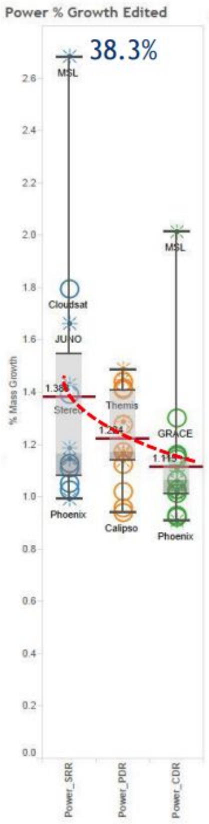
Note: This mass estimation spreadsheet was pulled from the ASE 166M, the corresponding lab class.

Input Parameters: Contingency Choice and Change

Heritage
All previous contingencies seen on the mass estimation spreadsheet on slide 2 were estimated using relevant equations and the heritage mission, Hayabusa2 by JAXA [3].

Change
To determine the ranges of each parameter the contingencies of each will be changed to better estimate the mass growth trends. The previous ranges where based off of 1 previous mission, this analysis will be based off several used in the 'NASA Mass Growth Analysis' [2]. For example the graph to the right is the growth of the power subsystem using data from previous missions such as GRACE, MSL, Cloudsat, etc...

Input Parameter	Previous Contingency	New Contingency
Payload	18%	34%
Propulsion	20%	13.6%
ADCS	20%	33.5%
Communications	10%	-12.8%
Power	10%	38.3%
Structure	11%	37.6%
Thermal	10%	51%
Other	15%	15%



Power Growth [2]

Input Parameters: Ranges

Parameter	Contingency	Lower	Median	Upper
Payload	34.00%	5810	7000	9380
Propulsion	13.60%	726.96	780	886.08
ADCS	33.50%	5.57775	6.7	8.9445
Communications	-12.80%	36.9728	42.4	45.1136
Power	38.30%	17892.105	22130	30605.79
Structure	37.60%	4636.52	5710	7856.96
Thermal	51.00%	68.54	92	138.92
Other	15.00%	90	100	115

Equations

- The median is the current best estimate determined in each specific lab.

- The Lower (5% Percentile) is determined to be 10% of the contingency below the median.

Lower = Median - 0.1*Contingency*Median

- The Upper (95% Percentile) is the the contingency amount of the median above the median.

Upper = Median + Contingency*Median

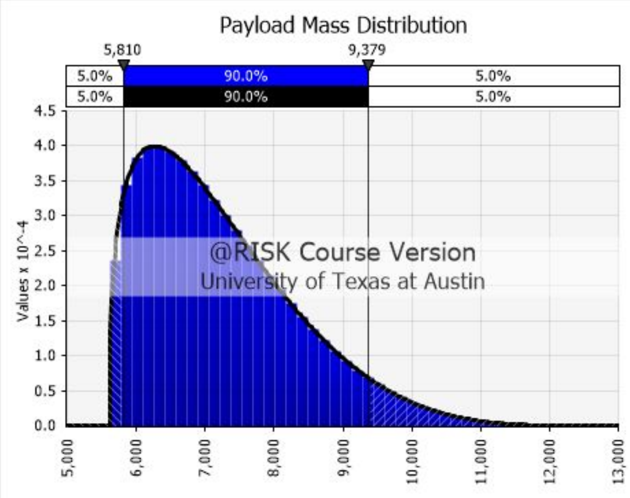
Explanation

For the ranges of each parameter the contingency used was determined from the NASA Mass Growth Report [2] as explained in slide 3.

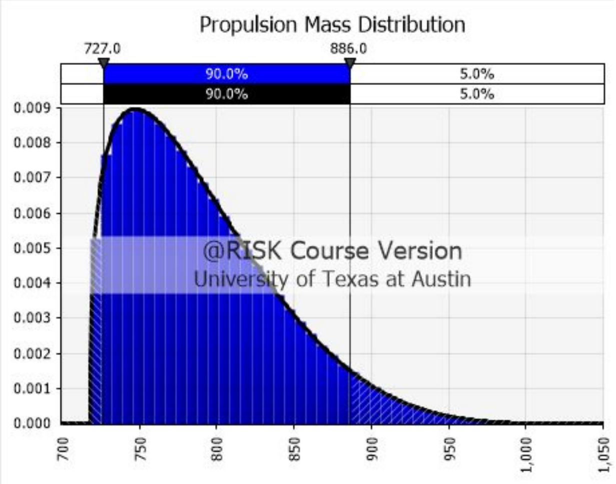
A common trend with mass growth within Spacecraft systems is their positive growth. This is evident when considering past missions as seen in reference [2]. One outlier is the communications system which has a negative mass growth.

This is the reason for the Upper mass estimate to be further from the current best estimate compared to the Lower mass estimate. This is to better model the mass distribution of a spacecraft as time progresses through its planning.

Input Parameter Distributions (10000 iterations)



Cell	Value
P5	5810.00 kg
P50	7000.00 kg
P95	9380.00 kg
Std Dev	1115.86
Mean	7218.88 kg

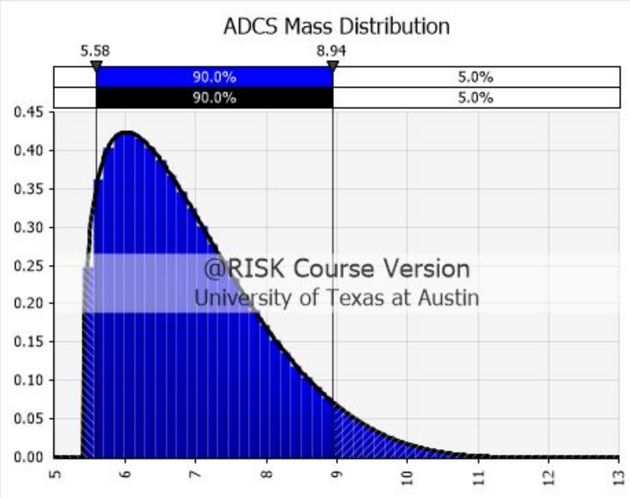


Cell	Value
P5	726.96 kg
P50	780.00 kg
P95	886.08 kg
Std Dev	49.73
Mean	789.59 kg

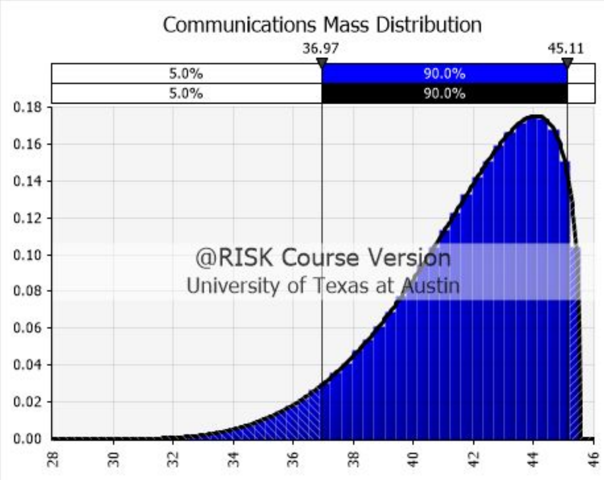
- The range of the payload mass is was determined using the contingency as described in slides 3 & 4.
- A 90% confidence interval is appropriate for a normal distribution of this type to limit any outliers outside 45% either side of the mean.
- A PERT distribution is appropriate for this parameter because the weighted average (mean) for the payload should be closer to the P5 than P95 to minimize cost and stress on launch.

- The range of the propulsion mass is was determined using the contingency as described in slides 3 & 4.
- A 90% confidence interval is appropriate for a normal distribution of this type to limit any outliers outside 45% either side of the mean.
- A PERT distribution is appropriate for this parameter because the weighted average (mean) for the propulsion subsystem should be closer to the P5 than P95 to minimize cost and stress on launch.

Input Parameter Distributions (10000 iterations)



Cell	Value
P5	5.57 kg
P50	6.70 kg
P95	8.94 kg
Std Dev	1.05
Mean	6.91 kg

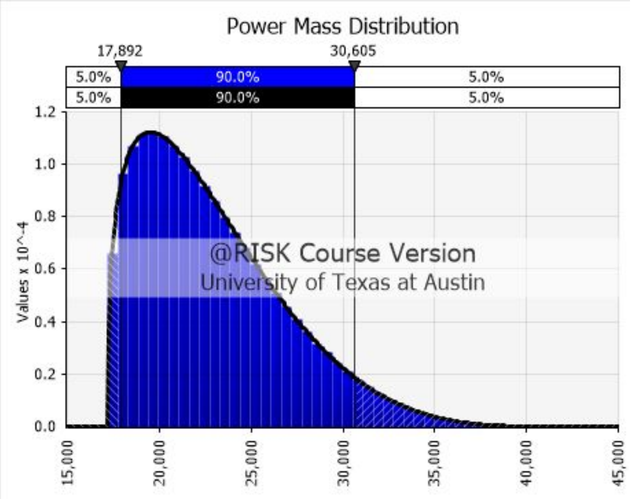


Cell	Value
P5	36.97 kg
P50	42.40 kg
P95	45.11 kg
Std Dev	2.55
Mean	41.90 kg

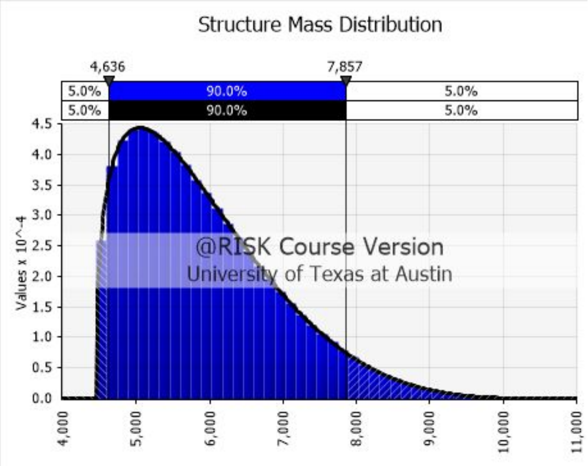
- The range of the ADCS mass is was determined using the contingency as described in slides 3 & 4.
- A 90% confidence interval is appropriate for a normal distribution of this type to limit any outliers outside 45% either side of the mean.
- A PERT distribution is appropriate for this parameter because the weighted average (mean) for the ADCS subsystem should be closer to the P5 than P95 to minimize cost and stress on launch.

- The range of the communications mass is was determined using the contingency as described in slides 3 & 4.
- A 90% confidence interval is appropriate for a normal distribution of this type to limit any outliers outside 45% either side of the mean.
- A PERT distribution is appropriate for this parameter because the weighted average (mean) for the communications subsystem should be closer to the P5 than P95 to minimize cost and stress on launch.
- Note this normal distribution the oppositely skewed due to the its negative growth level.

Input Parameter Distributions (10000 iterations)



Cell	Value
P5	17892.11 kg
P50	22130.00 kg
P95	30605.79 kg
Std Dev	3,973.68
Mean	22909.51 kg

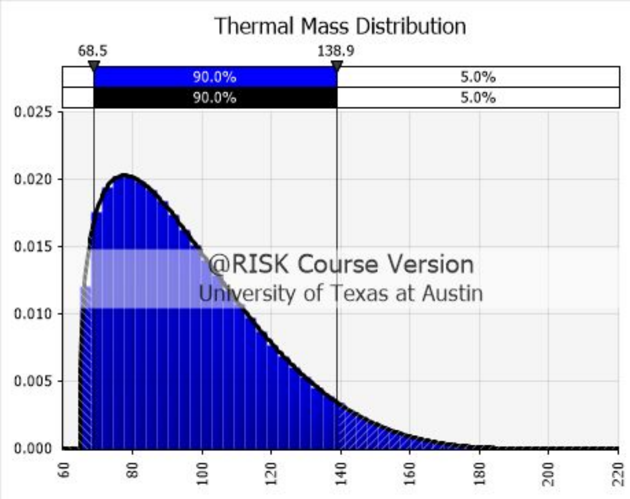


Cell	Value
P5	4636.52 kg
P50	5710.00 kg
P95	7856.96 kg
Std Dev	1,006.71
Mean	5907.46 kg

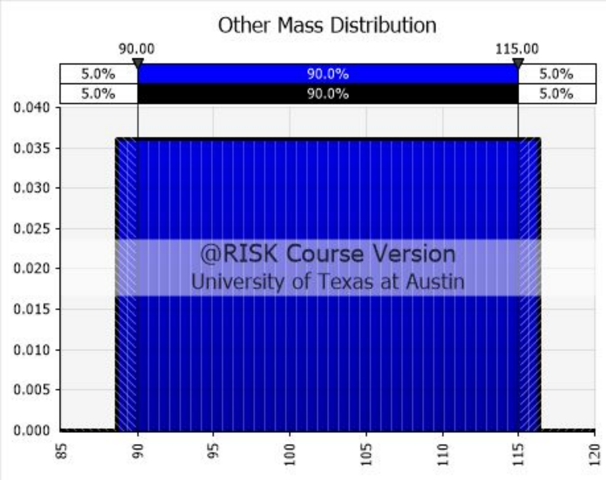
- The range of the power mass is was determined using the contingency as described in slides 3 & 4.
- A 90% confidence interval is appropriate for a normal distribution of this type to limit any outliers outside 45% either side of the mean.
- A PERT distribution is appropriate for this parameter because the weighted average (mean) for the power should be closer to the P5 than P95 to minimize cost and stress on launch.

- The range of the structure mass is was determined using the contingency as described in slides 3 & 4.
- A 90% confidence interval is appropriate for a normal distribution of this type to limit any outliers outside 45% either side of the mean.
- A PERT distribution is appropriate for this parameter because the weighted average (mean) for the structure subsystem should be closer to the P5 than P95 to minimize cost and stress on launch.

Input Parameter Distributions (10000 iterations)



Cell	Value
P5	68.54 kg
P50	92.00 kg
P95	138.92 kg
Std Dev	22.00
Mean	96.32 kg



Cell	Value
P5	90.00 kg
P50	100.00 kg
P95	115.00 kg
Std Dev	8.02
Mean	102.5 kg

- The range of the thermal mass is was determined using the contingency as described in slides 3 & 4.
- A 90% confidence interval is appropriate for a normal distribution of this type to limit any outliers outside 45% either side of the mean.
- A PERT distribution is appropriate for this parameter because the weighted average (mean) for the thermal subsystem should be closer to the P5 rather than P95 to minimize cost and stress on launch.

- The range of the propulsion mass is was determined using the contingency as described in slides 3 & 4.
- A 90% confidence interval is appropriate for a normal distribution of this type to limit any outliers outside 45% either side of the mean.
- A uniform distribution for all the other mass subsystem was most appropriate as this mass will not likely increase/decrease like the other subsystems. To be consistent with the other subsystems a 90% confidence interval is used.

Model Description

- 7 of the 8 input parameters were best modeled using the PERT distribution.
- PERT distributions are exclusively used for ‘modeling expert estimates’ [4], where there is a given lower and upper guess.
- As demonstrated in slides 5 → 8 each mass subsystem had initial bound guesses using contingencies provided by NASA research [2] and previous ASE 166M labs.
- Using the @RISK software, provided by The University of Texas at Austin, the equations to the right were used to produce graphs as shown in the image.
- The communications mass subsystem mimics the black plot in the graph due to its negative contingency which demonstrates a negative mass growth rate. The other 6 PERT distributions mimic the red plot as they have positive mass growth rates.

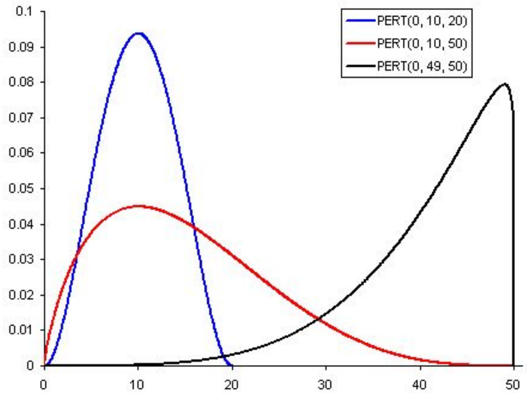


Image Credit [4]

$$\alpha_1 = \frac{(\mu - a) * (2b - a - c)}{(b - \mu) * (c - a)}$$

$$\alpha_2 = \frac{\alpha_1 * (c - \mu)}{(\mu - a)}$$

$$\text{The mean } (\mu) = \frac{a + 4 * b + c}{6}$$

Equation Credit [4]

Model Description continued…

- The ‘Other mass subsystem’ was modeled using a uniform distribution [5].
- This was appropriate for this subsystem as when the sample mass of each other subsystem increases/decreases, the other mass will follow that trend uniformly.
- This was done by averaging out the consistencies to best use for the upper and lower mass of this normal distribution.
- The graph was then produced using the @RISK software provided by The University of Texas at Austin using the equation to the right.

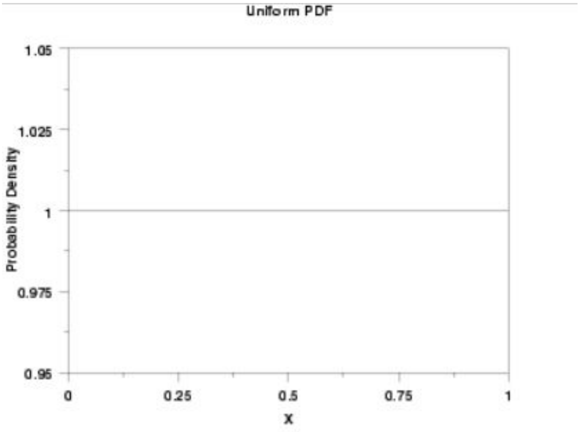


Image Credit [5]

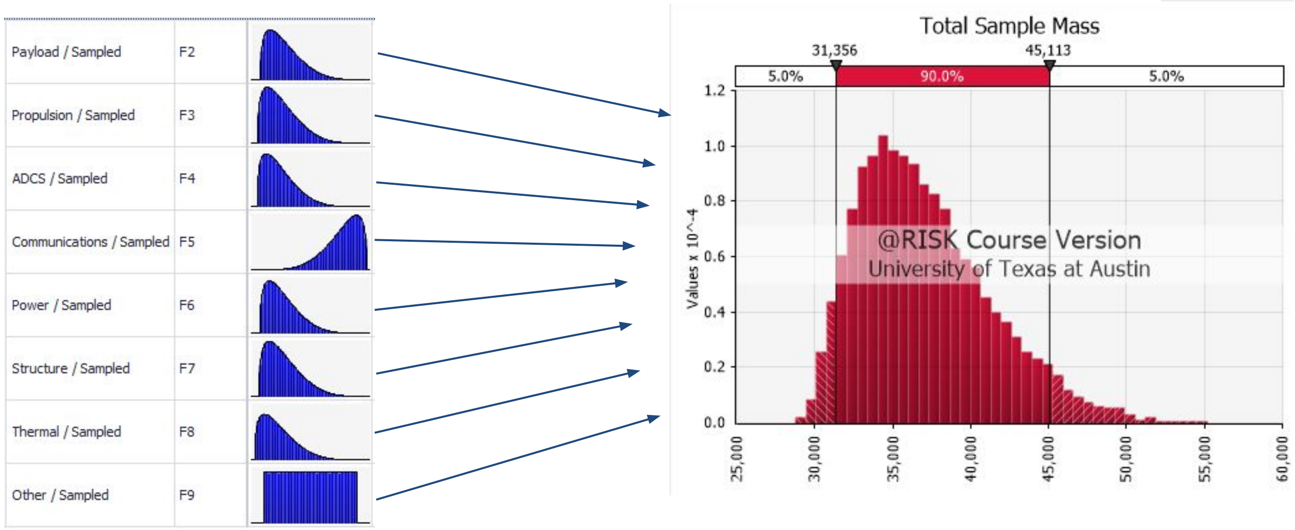
$$f(x) = \frac{1}{B-A} \qquad \text{for } A \le x \le B$$

Equation Credit [5]

Input Variables to an Output Variable

Input Variables → Summation (Σ) → Output Variable

$$\sum_{lower}^{upper} Input\ Masses \mid i = 50{,}000 = Output\ Mass\ Histogram$$

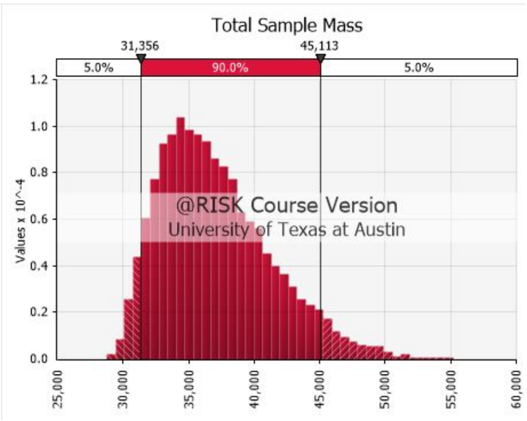


The output variable was determined using the summation of all the input variables. This is an appropriate way to equate the total sample mass of the spacecraft as the mean represents the best final mass estimate before all mass systems are finalized. A sample size of 50000 was used to reduce sample error.

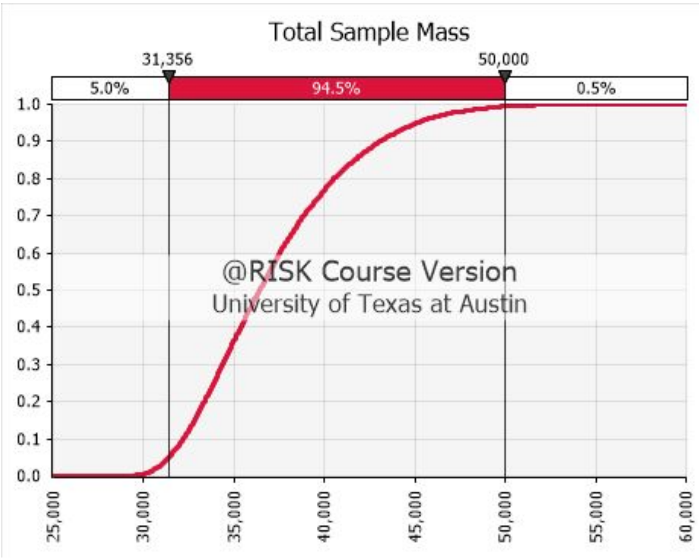
Cell	Value
P5	31382.11 kg
P50	36393.57 kg
P95	45170.46 kg
Std Dev	4,237.51
Mean	37073.24 kg

Output PDF & CDF

PDF



CDF



- As discussed in the previous slide, a 90% confidence level was kept for the PDF to be consistent with the input variables.
- The output CDF range was changed to a 94.5% confidence level so the mass levels out to a more accurate representation of the possible max mass of 50,000kg.

- The CDF plot describes the mass growth trend and can be marked at specific milestones of planning. For example at the 31,356 kg marker, this could be the “PDR” mass, in between at the 40,000 kg marker would be the “CDR” marker and at the 50,000 kg marker would be the “Actual mass”.
- This is consistent with similar Mass Growth Analysis reports such as in reference [2].

Summary

- The mass of the spacecraft for the Asteroid Mining mission can be modeled and estimated by running a Monte Carlo analysis on specific subsystems.
- 2 types of models were used to model the subsystems being a PERT distribution and a Uniform Distribution.
- Using the distributed samples of each subsystem, the estimated mass of the entire spacecraft can be estimated with a confidence level of 90%.
- The output histogram PDF of the Total Mass can be converted into a CDF plot to represent the growth change of mass over a period of time.

References

- [1] SpaceX. “SpaceX Falcon Heavy Data Sheet.” *Space Launch Report*, June 2019, www.spacelaunchreport.com/falconH.html.
- [2] Larouche, Vincent. “NASA Mass Growth Analysis - Spacecraft & Subsystems.” *2014 NASA Cost Symposium*, 2014. *Tecolote Research*, www.nasa.gov/sites/default/files/files/12_Larouche_NASA_Cost_Symposium_2014_MassGrowth_Final_TAGGED.pdf.
- [3] Choi, Charles. “Japan’s Asteroid-Smashing Probe Reveals a Surprisingly Young Space Rock.” *Space.Com*, 19 Mar. 2020, www.space.com/asteroid-ryugu-young-japan-hayabusa2-reveals.html.
- [4] Vose Software. “Vose Software.” *VOSE*, 2017, www.vosesoftware.com/riskwiki/PERTdistribution.php.
- [5] NIST Gov. “1.3.6.6.2. Uniform Distribution.” *Engineering Statistics Handbook*, www.itl.nist.gov/div898/handbook/eda/section3/eda3662.htm. Accessed 5 May 2021.