Launch Vehicle Engine Selection Using Probabilistic Techniques

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A new method for selecting the number of engines on a rocket stage based upon reliability and cost is presented. This method will compare a new technique for reliability analysis that results in a higher fidelity model when considering engine out capability. The cost of each vehicle configuration is calculated to find an optimal balance of system cost and reliability. The optimal solution will be determined by using a combined objective function based on minimizing campaign cost and maximizing vehicle reliability.

When performing reliability analysis with conventional practices, an engine out scenario is calculated using static tools. Another technique presented here will use a model that can adjust the failure rate of the propulsion subsystem to account for a longer burn time when an engine fails. The propulsion reliability will be combined with the other subsystem reliability estimates to calculate the reliability of the overall system. The system reliability will be one part of an objective function used in the optimization scheme.

The methodology is created by using a combination of industry standard tools along with author developed models to create an integrated framework that allows for optimization. The complete design space is explored using optimization to examine the maximum reliability and minimum cost configurations. Additionally, Monte Carlo Simulation is used to vary the single engine failure rate. The ranges for the simulation are drawn from historical data and are used to capture the effects of a higher fidelity modeling technique. Conclusions are made about the engine configuration on the S-II stage of the Saturn V based upon the methodology presented in this paper.

Nomenclature

CER	Cost Estimating Relationship.
CCF	Common Cause Failure.
DDT&E	Design, Development, Testing, and Evaluation.
DSM	Design Structure Matrix.
EDS	Earth Departure Stage.
ESAS	Exploration System Architecture Study.
FTA	Fault Tree Analysis.
MCS	Monte Carlo Simulation.
MER	Mass Estimating Relationship.
MGL	Multiple Greek Letter.
MTTF	Mean Time To Failure.
OEC	Overall Evaluation Criterion.
POST	Program to Optimize Simulated Trajectories.
REDTOP-2	Rocket Engine Design Tool for Optimal Performance - 2.
RSE	Response Surface Equation.
SPN	Stochastic Petri Net.
TFU	Theoretical First Unit.

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TLI	Trans-Lunar Injection.
WBS	Work Breakdown Structure.
β	CCF Parameter.
λ	Single Engine Failure Rate.
N	Number of Engines.
W_i	OEC Weighting.

I. Introduction

The objective of this paper is to determine the number of engines and engine thrust level for the propulsion subsystem of a launch vehicle stage based on system reliability and cost. Reliability is defined as "the probability that an item (component, subsystem, system) will perform a required function under stated conditions for a stated period of time."[1] The cost is a combination of the Design, Development, Testing, and Evaluation (DDTE) cost, and the Theoretical First Unit (TFU) cost. This cost is sometimes referred to as the "campaign" cost, but it is not a true campaign cost because operations costs are not included. The DDT&E cost is defined as all costs associated with design and development until the first operational system is delivered. The TFU cost is the cost of creating the first operational vehicle. The "campaign" cost is calculated using Equation 1. For the analysis discussed later, the number of flights is equal to twelve.

$$Campaign = DDT\&E + No.Flights * TFU \tag{1}$$

The number of engines and corresponding thrust level will be determined by using optimization of an Overall Evaluation Criterion (OEC) that combines campaign cost and reliability. Equation 2 shows the OEC used in the optimization scheme. The variable W_i is the weighting on the cost and reliability. The design variables are the engine thrust level, the number of engines, and the option of using engine out capability. An integrated model is created that combines the performance, cost, and reliability disciplines in order to vary the engine parameters and understand the impacts on each discipline. By using optimization with the integrated model, the number of engines and corresponding thrust level are determined for a launch vehicle stage.

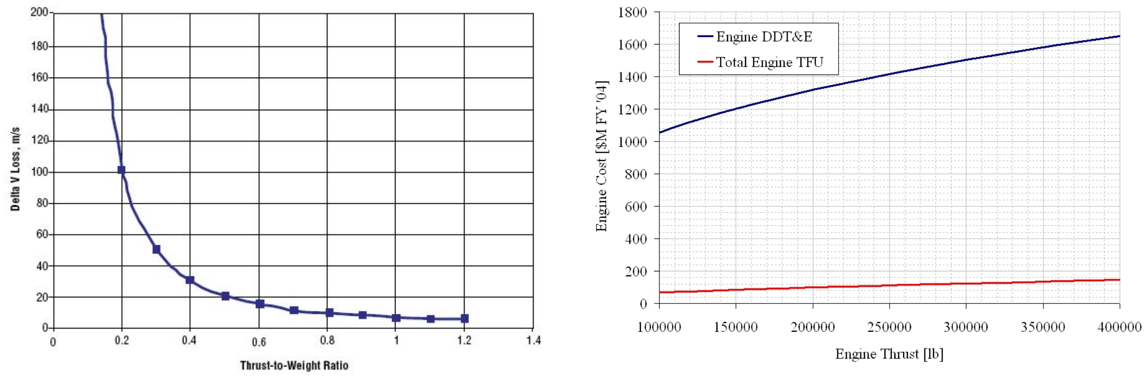
$$OEC = W_R \frac{R_{calc}}{R_{max}} + W_C \frac{C_{min}}{C_{calc}} \tag{2}$$

During the Exploration System Architecture Study (ESAS), the vehicle thrust-to-weight ratio for the Earth Departure Stage (EDS), the second stage of the Cargo Launch Vehicle (CaLV), was partially selected by examining the bounds on the trans-lunar trajectory for both guidance accuracy and acceleration limits.[2] A graph was created that plotted upper stage thrust-to-weight ratio versus the gravity losses in order to further bound the EDS thrust level. Figure 1 was then used as a guide to determine an appropriate thrust-to-weight ratio based on the gravity losses. Lower gravity losses will result in lower required propellant masses and the vehicle gross mass will decrease. However, it is unknown if a minimum propellant mass solution leads to an optimal balance of reliability and cost.

Increasing the vehicle thrust-to-weight ratio by increasing the engine thrust results in a higher development and production cost for the engine. Figure 1 shows how the engine cost increases with an increasing engine thrust. Therefore, while a specific vehicle thrust-to-weight ratio may be the best in regard to minimizing fuel consumption, the vehicle thrust-to-weight ratio may not be the best with respect to cost. Thus, an integrated model which combines the performance, reliability, and cost disciplines will be used to determine the number of engines on a launch vehicle.

The sample problem is the Saturn V launch vehicle. The Saturn V was the spacecraft that launched the Apollo missions and provided the Trans-Lunar Injection (TLI) burn to the Moon. The Saturn V was a three stage launch vehicle with two different engines.[3] The S-IC, the first stage, used five F-1 engines; the F-1 characteristics are listed in Table 1. The S-II, the second stage, also used five engines, known as the J-2, in series to provide propulsive power. The S-IVB, the third stage, used a single J-2 engine and the J-2 characteristics are also listed in Table 1. All engines on the Saturn V had to operate successfully in order for the Saturn V to complete its mission.

The S-II and S-IVB were the main causes of unreliability for the Saturn V and the application focuses on the S-II stage. Figure 2 illustrates the contribution to unreliability of each stage of the Saturn V. The S-IC



(a) Gravity Losses for EDS Burn.[2] (b) Engine Cost as a Function of Engine Thrust.

Figure 1: Selecting an Engine Thrust Level.

Table 1: Engine Characteristics.

Parameter	**J-2**	**F1**
Thrust [psf]	230000	1740134
Isp_{vac} [s]	425	304
T/W_{eng}	72.5	94.1
Reliability	0.988	0.999
Min. Rel	0.960	N/A
Max. Rel	0.999	N/A
DDT&E [$M FY '04]	1015	1044
TFU [$M FY '04]	12	16

stage had a significantly higher reliability than the two previous mentioned stages; one reason is because the F-1 reliability was estimated at an order of magnitude higher than the J-2.[4] Therefore, the application focuses on varying the configuration of the S-II and S-IVB stages in order to increase the system reliability. The design variables are the number of engines on the S-II and the J-2 thrust level. Engine out can also be selected on the S-II stage. The S-IC stage is scaled up and down to use a constant mass and stage thrust-to-weight ratio in order to provide the same change in velocity needed before S-II ignition. The S-IVB stage will be affected by the J-2 thrust level because both the S-II and S-IVB stages will use the same engine.

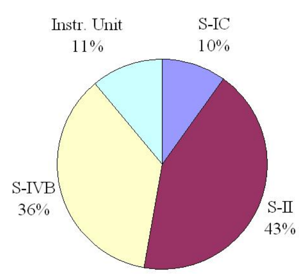


Figure 2: Saturn V Stage Unreliability Contribution.[4]

II. Background

In addition to the number of engines and thrust level, the option of selecting engine out for a propulsion subsystem is included as a design variable for the optimization scheme. Engine out refers to a scenario where a launch vehicle can successfully achieve its mission even though an engine has been lost. Apollo 13, in addition to its notorious in-space accident, had a center engine shutdown on the S-II stage of the Saturn V two minutes prior to the scheduled cut-off.[5] The Saturn V was able to complete its mission but the burn time of the S-II stage was extended by approximately 100 seconds. Figure 3 is a comparison between the nominal Saturn V trajectory and the Apollo 13 trajectory.

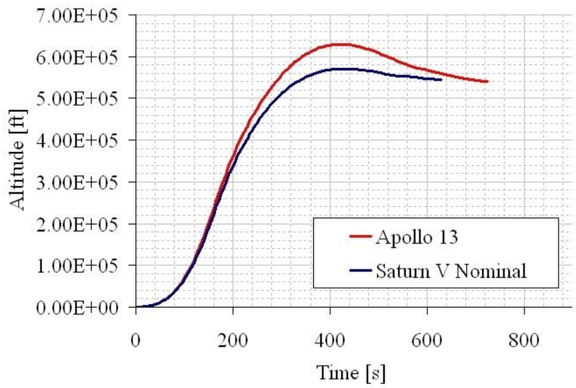


Figure 3: Trajectory Comparison Between a Nominal Saturn V and Apollo 13.

When the burn time of a stage increases, the engine reliability will decrease when the survivor function is an exponential distribution. The equation for calculating the reliability with an exponential distribution is Equation 3. Fault tree analysis (FTA) cannot adjust for an increased burn time. However, a reliability technique called Stochastic Petri Nets (SPNs) can incorporate time adjustments and/or failure rate changes within its reliability analysis. Therefore, the reliability of a propulsion subsystem that uses engine out can be properly assessed.

$$R_i(t) = e^{-\lambda_i t} \tag{3}$$

Stochastic Petri Nets are a state space tool built on the Petri Net foundation. SPNs have the same goal of all other quantitative reliability techniques: to determine system reliability.[6] A variety of SPNs exist because of their recent development. With respect to this paper, only one type of SPN will be used. The development and accompanying software package has been created by Dr. Vitali Volovoi of the Aerospace Systems Design Laboratory at the Georgia Institute of Technology.[7]

In the example SPN application illustrated in Figure 4, there is a state that represents system operating (i.e. "system ok"), a state for single component failure, and another for system failure. The scenario modeled is a shared load example, where if a component fails, the remaining component must account for the additional workload in order to ensure successful system operation.

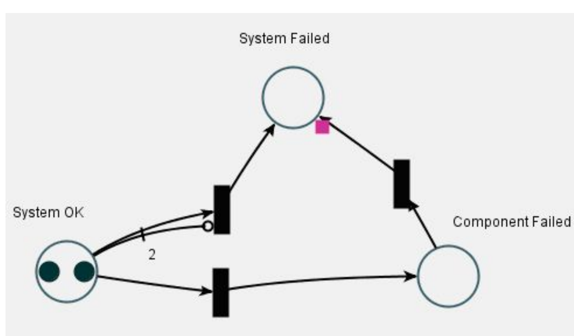


Figure 4: SPN example problem.[7]

The tokens (i.e. black circles) in Figure 4 move throughout the diagram to represent each of the different states. A token in system failure will represent a failed mission. The black boxes are termed transitions and govern the manner in which tokens move around. The transitions have failure distributions, such as the exponential distribution, associated with them and the tokens will move according to these failure rates. The arrows are directional to illustrate the direction of token movement. An inhibitor is used in Figure 4. The inhibitor is represented by the line with a circle at the end and marked with a "2" in the middle. The tokens cannot move directly to the failure state until one component fails. When a component fails, a token will move to the component failed state. The second token is now exposed to a higher failure rate because only one component is operational. System failure is now more likely than the initial component failure because of the higher failure rate.

SPNs use Monte Carlo Simulation (MCS) to determine system reliability.[7] The reliability is calculated using the magenta square located next to the system failed state which counts the number of times a token enters the system failed state during MCS. SPNs also use the mission time to determine system reliability. If the simulation ends before a token reaches the failed state, then mission occurred successfully. The MCS setting will use thousands of runs to ensure that the true probability of failure is calculated.

Common cause failure should also be included in any reliability model that uses component redundancy, such. CCFs can bypass component redundancy by causing multiple components of the same type to fail because of something inherent in all of the components. One type of CCF could be a manufacturing defect that invaded all of the engines on a propulsion subsystem. Therefore, engine out capability is negated and the vehicle will fail due to CCF.

Common cause failures (CCFs) will be incorporated using the β version of the Multiple Greek Letter (MGL) model.[8] The full MGL model is shown in Equation 4. Only the β version is necessary because once two engines fail, the propulsion subsystem is assumed to fail. For all reliability calculations that require CCF, an assumption is made that β is equal to 0.1.

$$Q_k = \frac{1}{\binom{m-1}{k-1}}(1-\rho_{k+1})(\prod_{i=1}^{k}\rho_i)Q_t \tag{4}$$

III. Reliability Analysis

III.A. Engine Out Modeling

For fault tree analysis, engine out scenarios can be modeled using a 'm' out of 'n' fault tree that builds upon a catastrophic engine model proposed by Huang.[9] In their model, the benefits of engine out are reduced because of a catastrophic failure mode. The catastrophic failure model assumes that a certain percentage of engine failures will occur in an "uncontained" manner and cause immediate system failure. An example of an uncontained failure would be an explosion of one of the engines. A catastrophic failure is different from common cause failure (CCF) because the catastrophic failure mode only affects one engine but causes the complete system to fail. Huang and et. al[9] propose that the catastrophic percentage is between 20 and 40 percent based on historical data. This value is very important when performing reliability analysis for engine out and steps are taken to mitigate the uncertainty regarding the true catastrophic failure percentage.

In the model created by Huang,[9] the failure percentages are treated as a proportion of the engine reliability. In this paper, the percentages are brought down to a lower level and used on the actual failure rate, λ. Assuming an exponential distribution, the percentages are applied to the overall failure rate, λ, so that the single engine reliability is the same but the effects of the catastrophic failure mode are still captured. CCF is included with the β version of the MGL model. A fault tree representation of this new catastrophic failure model is shown in Figure 5.

The top calculation Figure 5 is the unreliability for a five engine configuration with engine out. The model is the S-II propulsion subsystem with a 20% catastrophic failure percentage and 10% β model for CCF. The single engine reliability for the J-2 was 0.988.[4] The middle 'OR' gate signifies a benign engine failure mode where at least two engines must fail before the system will fail. On the same level as the benign engine failure mode are the failure modes that cause immediate system failure: a common cause failure along with the catastrophic failure probability for each engine in the configuration.

Equation 5 shows how the engine out reliability is calculated using Figure 5. N is the number of engines and λ is the original engine failure rate. The catastrophic failure percentage is C.F. and CCF is represented

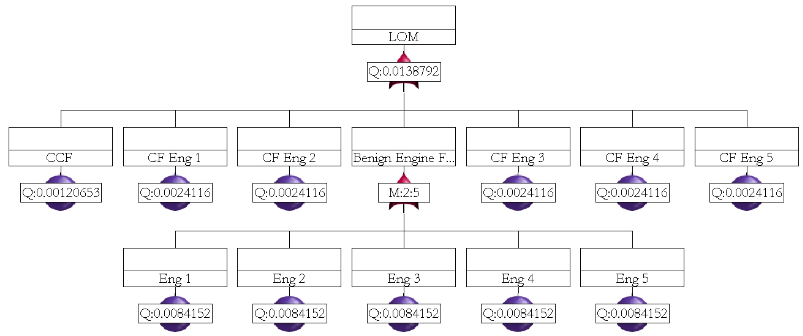


Figure 5: Engine Out Failure Model.

by β. This engine out model is used to perform all of the engine out reliability calculations; MCS is also incorporated and will be discussed later.

$$R_{EO} = (e^{-\beta * \lambda_{eng} t}) * (e^{-C.F. * \lambda_{eng} t})^N * [N * (e^{-(1-\beta-C.F.)\lambda_{eng} t})^{N-1} * (1 - e^{-(1-\beta-C.F.)\lambda_{eng} t})] \tag{5}$$

The catastrophic engine model can be combined with SPNs to calculate the propulsion subsystem reliability for engine out scenarios. By using SPNs, the effects of an increased burn time can be included. Figure 6 is a higher fidelity version of the catastrophic failure model shown in Figure 5. CCF is incorporated by the token in the top left, the catastrophic failure mode is represented by the tokens to the right, and the benign failure modes are represented by the five tokens in the bottom left. An inhibitor is placed on the catastrophic failure rate to stop this failure mode once a benign engine fails. The next engine failure will automatically cause a loss of system, so the catastrophic mode does not need to be singled out.

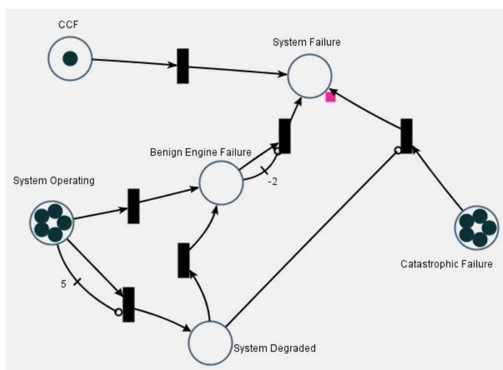


Figure 6: SPN Failure Model.

For the engine out reliability analysis using SPNs, system failure occurs once a token reaches the state with the magenta square. Thus, a single token can move from either the CCF or catastrophic failure modes. If a benign engine failure occurs, the remaining four tokens move to the degraded state. If another failure occurs, then an inhibitor will open up and the system will fail. The transfer of the four remaining engines to the degraded state allows for an adjustment of the failure rate, simulating an increased burn time for an engine out scenario. An assumption is used in this analysis that an engine will fail immediately upon stage ignition; therefore, a stage with engine out capability will have to burn for the maximum amount of time.

One shortcoming of the developed SPN software is the integration into a larger system model. The failure distributions are not easily adjusted and the simulation time of the SPNs is not conducive for use in a larger optimization scheme. Therefore, uncertainty analysis is combined with the catastrophic engine model shown in Figure 5 to account for a longer burn time in engine out scenarios. Both the single engine reliability and the catastrophic failure percentage have input distributions and the system reliability calculation is the 70% certainty value from the MCS.

Table 2: Engine Out Model Unreliability Comparison.

Eng. Configuration	SPN	C.F. Eng. Model	% Diff.
4 Engine Out	0.0210	0.0203	3.18
5 Engine Out	0.0257	0.0252	2.19
6 Engine Out	0.0307	0.0301	2.08

Table 2 shows good agreement between the SPN analysis and the catastrophic engine model with uncertainty. The S-II propulsion subsystem of the Saturn V, which used five J-2 engines, is used as the baseline. Since there is good agreement between the two models, the catastrophic failure model with uncertainty will be used to capture the effects of an increased burn time for stages that have engine out capability.

III.B. System Reliability Modeling

Each stage of the Saturn V is used for the system reliability calculation. The system reliability calculation is shown in Figure 7 for the Saturn V launch vehicle. In Figure 7, the reliability of each stage of the Saturn V is represented and is combined using Equation 6 for the system reliability calculation. Equation 6 is the formula for calculating the reliability of elements in series.

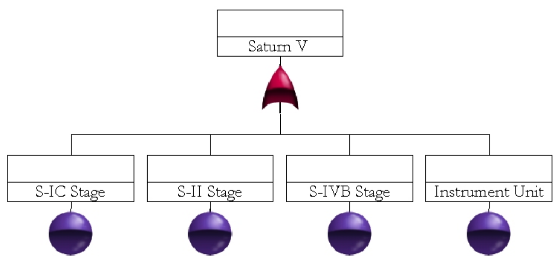


Figure 7: Saturn V Reliability Calculation.

$$R_s(t) = \prod_{i}^{n} R_i(t) \tag{6}$$

For the stage reliability calculation, the propulsion subsystem is combined with the remaining subsystems to calculate the stage reliability. Figure 8 shows an example for the S-II stage without engine out capability. The propulsion subsystem with no engine out capability is calculated using Equation 6 according to the number of engines on the stage. If engine out were selected for the S-II stage, then the catastrophic engine model shown in Figure 5 would be used in place of Equation 6 for the propulsion subsystem reliability calculation.

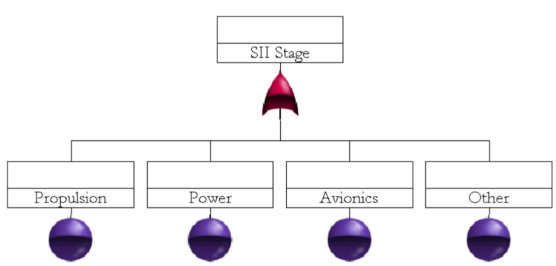


Figure 8: SII Stage Representation with No Engine Out Capability.

IV. Integrated Model

IV.A. Performance and Cost

Performance and cost models are needed to examine the effects of changing engine design parameters on the complete launch vehicle. The launch vehicle mass estimates are determined by using Mass Estimating Relationships (MERs).[10] The Saturn V Work Breakdown Structure (WBS) is listed in Table 3 along with a validation of the MERs compared to the Saturn V subsystem masses.

Table 3: Saturn V WBS.

Subsystem	Reference Mass [lb]	Mass Estimate [lb]	% Diff.
S-IC Stage			
Structures	142162	142450	0.2
Main Prop.	47020	45062	4.16
Engines	92490	93347	0.93
Power	947	973	2.77
Avionics	3457	3417	1.15
Separation	1375	2331	69.51
Total Dry	**287451**	**287579**	**0.04**
Total Gross	**5030911**	**5090577**	**1.19**
S-II Stage			
Structures	62169	62379	0.34
Main Prop.	10217	10282	4.36
Engines	15925	15873	0.32
Power	817	897	2.96
Avionics	4432	4310	2.74
Separation	3761	3750	0.12
Total Dry	**97375**	**97492**	**0.12**
Total Gross	**1081781**	**1089583**	**0.72**
S-IVB Stage			
Structures	13686	13648	0.28
Main Prop.	2986	2886	4.02
Engines	3185	3175	0.32
Power	2157	2181	1.10
Avionics	2522	2601	3.11
Separation	2699	3034	12.42
Total Dry	**27235**	**27504**	**0.99**
Total Gross	**264709**	**262694**	**0.76**
Total SV Gross	**6551541**	**6486333**	**1.01**

The trajectory analysis is completed by using Response Surface Equations (RSEs) of the Program to Optimize Simulated Trajectories (POST).[11] The orbit parameters along with the trajectory constraints are listed in Table 4. RSEs are used to speed up the optimization process. The thrust level of the engine is the independent parameter and the dependent parameter is the propellant mass of the stage.

The propulsion discipline uses a RSE fit of a conceptual powerhead design code called Rocket Engine Design Tool for Optimal Performance - 2 (REDTOP-2).[12] A RSE is used to calculate the engine thrust-to-weight ratio based on the thrust level. The engine thrust-to-weight ratio is transferred to the mass estimating discipline to calculate the engine mass. A RSE is used to speed up the design process.

The method for calculating DDT&E and TFU costs is based on NAFCOM. These costs are created with a simplified version of NAFCOM which uses Cost Estimating Relationships (CERs). Mass is the independent variable and an equation such as Equation 7 is used to calculate the cost. In Equation 7, the cost of an engine

Table 4: Saturn V POST Assumptions.

Parameter	**Value**
Max. Q [psf]	780
Max. Accel [gs]	4.0
TLI δV [ft/s]	10900
Final Velocity [ft/s]	25622
Perigee Altitude [nmi]	90
Apogee Altitude [nmi]	97
Lunar Payload [lb]	100932

is calculated by raising the mass of the engine to a power and then multiplying by a coefficient. Figure 1 showed how cost will increase as a function of engine thrust, which is correlated to engine mass with the RSE.

$$Cost_{engine} = 1.85 * M_{engine}^{0.8} \tag{7}$$

Uncertainty analysis is also incorporated in the cost model based on discussions and guidance from NASA experts.[13] Figure 9 illustrates how uncertainty analysis is used based on expert recommendation. In Figure 9 minimum value is the mass estimate from the conceptual design tool. This value is then given a 15% margin, which becomes the most likely value for MCS. The maximum value is created with a 30% margin on the mass estimate. The final cost calculation is the 70% certainty result from the MCS.

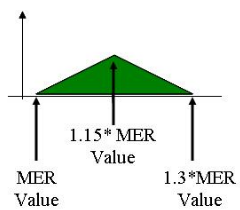


Figure 9: Cost Uncertainty Analysis.

IV.B. Design Process

Figure 10 illustrates the design process with a Design Structure Matrix (DSM). The algorithm relies upon FTA with MCS for the reliability modeling and CERs with uncertainty analysis for the cost calculations. The performance disciplines are represented with RSEs in order to accelerate the design process. The optimization scheme uses a grid search in combination with a coordinate pattern search to find the best combination of design variables for a balance of cost and reliability. Using a grid search will examine the complete design space while also finding the optimum balance of reliability and cost.

The design variables for the Saturn V application are listed in Table 5. Each change in design variable results in a different vehicle configuration with its own reliability and cost. The J-2 engine thrust has a large effect because it changes the J-2 engine thrust-to-weight ratio, the S-II and S-IVB thrust-to-weight ratio, and drives the engine cost. The number of engines is coupled with the engine thrust level because there are certain combinations of design variables that are infeasible for the Saturn V mission. For example, using four engines with a thrust level of 220,000 pounds will not complete the required Saturn V performance. Engine out capability changes the dry mass and the structural fraction of the vehicle. With the design variables listed in Table 5, an optimal engine configuration for the S-II and S-IVB will be determined based on an even weighting of reliability and cost.

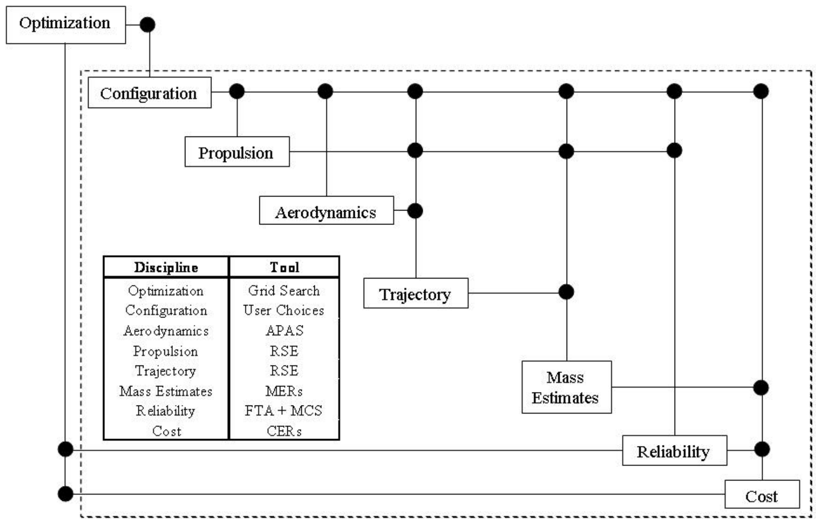


Figure 10: Design Structure Matrix.

Table 5: Saturn V Design Variables.

Design Variable	**Minimum**	**Maximum**	**Type**
J-2 Thrust Level [lb]	220000	460000	Continuous
S-II Number of Engines	4	6	Discrete
S-II Engine Out	No	Yes	Discrete

V. Results

The sample problem for engine selection is the Saturn V launch vehicle. Only the J-2 thrust level will affect both the S-II and S-IVB stage, but the thrust level is not coupled with reliability. The problem is constrained by requiring the S-II and S-IVB to use the same engine, like the original Saturn V vehicle. However, the number of engines and engine out capability, as listed in Table 5, will only affect the S-II stage. For stages with engine out capability, the number of engines on the stage is quoted, but the actual number of engines operating is one less than the value quoted. For example, a four engine configuration with engine out capability only requires three engines for successful operation of the S-II stage.

The grid search optimization evaluates all combinations of the design variables. The thrust level increment is 10,000 pounds. A penalty is included in order to eliminate infeasible combinations. The ranges for the J-2 thrust levels according to the number of engines and engine out capability are listed in Table 6.

Table 6: J-2 Thrust Ranges.

Design Characteristics	**Variable Selection**	**Variable Selection**	**Variable Selection**	**Variable Selection**	**Variable Selection**	**Variable Selection**
No. of Engines	4	4	5	5	6	6
Engine Out	No	Yes	No	Yes	No	Yes
Min. Thrust [lb]	250000	320000	220000	240000	210000	220000
Max. Thrust [lb]	340000	410000	310000	340000	300000	310000

The results of the optimization are illustrated in Figure 11. There are discrete jumps in the data points in Figure 11. These are caused by the discrete choices of the number of engines and whether or not engine out capability is included.

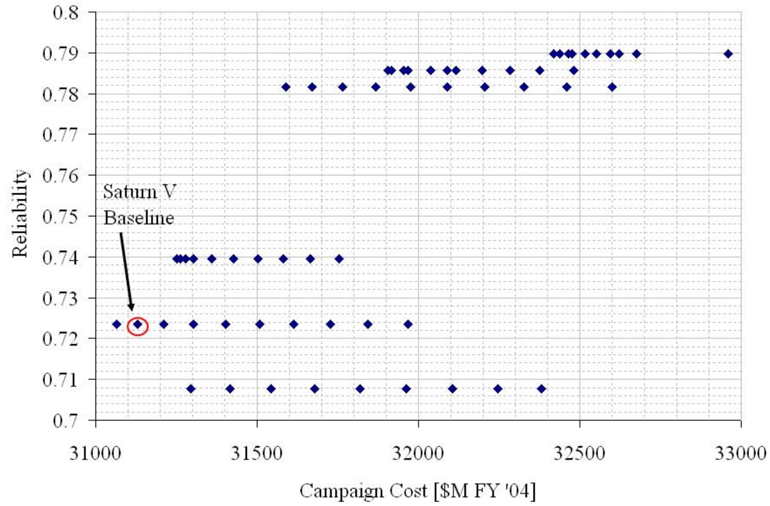


Figure 11: Saturn V Results.

The results from Figure 11 are illustrated in Figure 12 with the Mean Time To Failure (MTTF) as the y-axis instead of reliability. In Figure Figure 12, the results of changing the number of engines can be examined. As expected, a lower number of engines will result in a higher reliability. Additionally, configurations with engine out capability have higher system reliability compared to configurations without engine reliability.

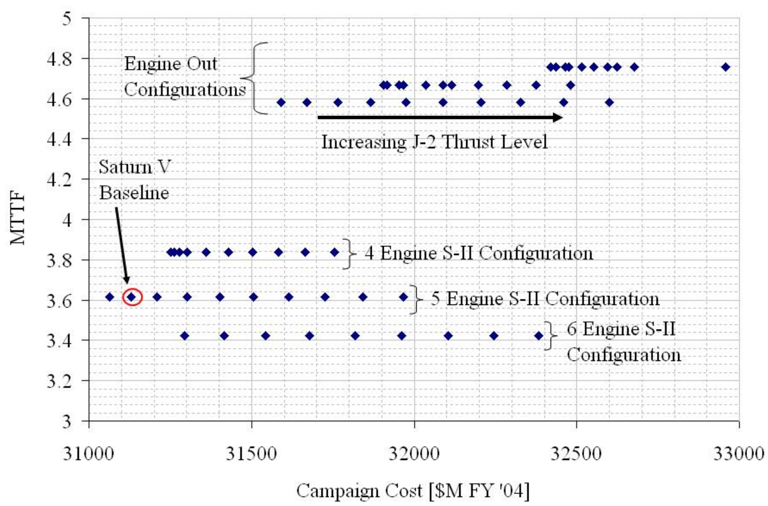


Figure 12: Saturn V Detailed Results.

The campaign cost increases as the engine thrust increases. Figure 1 illustrated the correlation between campaign cost and engine thrust. The lowest cost configuration in Figure 1 uses five engines on the S-II without engine out capability. Table 7 lists why a five engine configuration is the lowest cost configuration. All costs are quoted in $M FY '04. A comparison of the gross masses of each configuration in Table 7 is listed in Table 8. A comparison of the trajectories in in Table 7 is shown in Figure 15.

In Table 7, the five engine configuration uses less propellant mass and has a lower engine thrust compared to the four engine configuration. Therefore, the cost will be lower for a five engine configuration because of its lower dry mass and lower engine cost. When comparing the five engine configuration in Table 7 with the six engine configuration, the cost of a six engine configuration is higher because it carries an extra engine. Table 9 lists a comparison of the S-II TFU costs for the configurations listed in Table 7. All costs are quoted in $M FY '04.

Table 9 shows why the six engine configuration with its minimum thrust level is not the minimum cost configuration. The S-II TFU difference will multiply for every flight in the campaign. Since there are 12

Table 7: Minimum Cost [$M FY '04] Configurations.

No. of Engines	J-2 Thrust Level [lb.]	Engine Out Capability	S-II Propellant Mass [lb.]	J-2 Eng. DDT&E	Total S-II Eng. TFU	Campaign Cost	System Reliability	OEC Value
5	220000	No	963148	1002	59	31064	0.7234	1.8749
4	260000	No	997735	1052	52	31252	0.7395	1.8889
6	220000	No	928766	1002	71	31294	0.7077	1.8484

Table 8: Mass Comparison of the Minimum Cost Configurations.

No. of Engines	J-2 Thrust Level [lb.]	Engine Out Capability	SIVB Gross Mass [lb.]	SII Gross Mass [lb.]	SV Gross Mass [lb.]
5	220000	No	265617	1087253	6532618
4	260000	No	269573	1122560	6705966
6	220000	No	265071	1056324	6393650

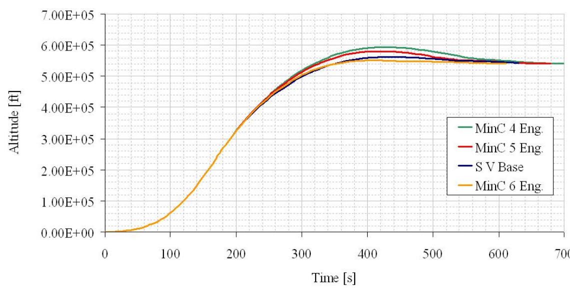


Figure 13: Trajectory Comparison for Minimum Cost Configurations.

Table 9: SII Cost [$M FY '04] Comparison for Minimum Cost Configurations.

No. of Engines	J-2 Thrust Level [lb.]	Engine Out Capability	S-II Propellant Mass [lb.]	J-2 Eng. DDT&E	Total S-II Eng. TFU	S-II DDT&E	S-II TFU
5	220000	No	963148	1002	59	4367	685
4	260000	No	997735	1052	52	4427	678
6	220000	No	928766	1002	71	4423	706

flights in the campaign calculation, the cost impact of using six engines on the S-II stage will result in a higher campaign cost in Table 9 for the six engine configuration compared to the other two configurations.

Another result derived from Figure 11 is that a minimum propellant mass solution is not the minimum cost configuration. Figure 14 was created to examine the interaction between engine thrust, propellant mass, and campaign cost. The configuration in Figure 14 is the original Saturn V configuration with five engines on the S-II stage. The only difference between the vehicles used in Figure 14 and the Saturn V is the varying J-2 engine thrust level.

The optimal configurations are determined by using an even weighting on both the system reliability and campaign cost. Table 10 lists the optimal configurations based on the OEC and the number of campaign flights. All costs are quoted in $M FY '04.

A six engine configuration is the optimal configuration due to its low thrust level. The four and five engine configurations in Table 10 are the optimal four and five engine solutions for the objective function.

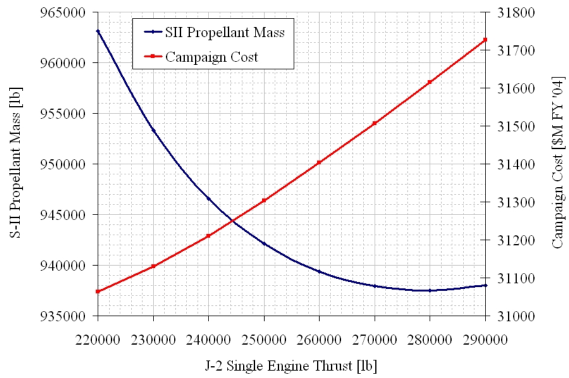


Figure 14: Campaign Cost and Propellant Mass as a Function of Thrust Level.

Table 10: Optimal Configurations.

No. of Engines	J-2 Thrust Level [lb.]	Engine Out Capability	S-II Propellant Mass [lb.]	J-2 Eng. DDT&E	Total S-II Eng. TFU	Campaign Cost	System Reliability	OEC Value
6	220000	Yes	979295	1002	71	31590	0.7817	1.9306
5	260000	Yes	1026524	1052	64	31905	0.7858	1.9261
4	350000	Yes	1051428	1146	60	32420	0.7898	1.9158

Even though the reliability of the six engine configuration is lower compared to the other configurations in Table 10, the reliability penalty is not enough to offset the difference in campaign costs. A comparison of the gross masses of each configuration in Table 10 is listed in Table 11. A comparison of the trajectories in in Table 10 is shown in Figure 15.

Table 11: Mass Comparison of the Optimal Configurations.

No. of Engines	J-2 Thrust Level [lb.]	Engine Out Capability	SIVB Gross Mass [lb.]	SII Gross Mass [lb.]	SV Gross Mass [lb.]
6	220000	Yes	265531	1110677	6635651
5	260000	Yes	269644	1160619	6874308
4	350000	Yes	278337	1189583	7040568

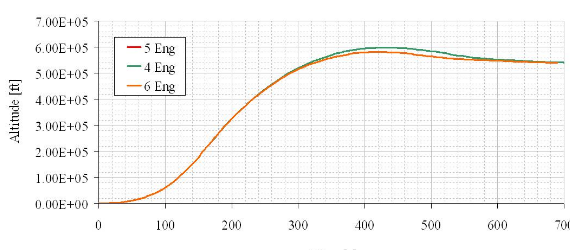


Figure 15: Trajectory Comparison for Optimal Configurations.

VI. Conclusion

By varying the J-2 thrust level, the number of engines, and the option of engine out capability, an optimal S-II configuration was determined based on reliability and cost. Using an integrated model, the impacts of varying the design parameters listed in Table 5 were captured on the complete system. While the higher fidelity modeling of the SPNs was not utilized, the catastrophic engine model with uncertainty was able to incorporate the effects of increasing the burn time for engine out scenarios.

The Saturn V reliability was improved by 8% for an additional $400M [FY '04] in campaign costs in the demonstration application. The optimal configuration would have used a lower thrust level than the baseline J-2, but using six engines on the S-II stage would have completed the required mission. By using an integrated model, the number of engines and thrust level were optimized for a balance of reliability and cost on the S-II stage of the Saturn V.

Appendix

Table 12: Saturn V MCS Reliability Ranges.

Subsystem	**Minimum**	**Maximum**	**Distribution**
J-2 Engine Reliability	0.96	0.999	Triangular
Catastrophic Percentage	0.2	0.4	Uniform

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