Vehicle Wide Optimization of Subsystem Trade Study Option Selection

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SUMMARY & CONCLUSIONS

As demand for highly reliable complex systems increases, engineers are being forced to consider the risk implications of design decisions earlier in the conceptual phase of projects and with greater accuracy. In highly mass constrained systems, in order to achieve increased reliability, buying down risk with mass cannot be considered from a 'stove-piped' stand point, but rather it must be approached from a global system perspective. The Altair lunar lander design team was able to implement a process of Risk Informed Design utilizing the Valador Reliability Tool [1] (VRT) in order to achieve high reliability. This tool is able to quickly and accurately produce estimates of the risk of Loss of Mission (LOM) and Loss of Crew (LOC) and provide insight to the designers as to how their decisions will impact overall mission success.

During a design analysis cycle, the VRT can analyze isolated subsets of this risk for trade studies in order to produce alternate low-risk options. The results of these independent studies produce a database of options for various trade studies scored on the basis of LOM, LOC, and Delta-Mass required to implement each option. Using this information, the Risk Reduction Efficiency (RRE), or reliability improvement per unit mass, can be calculated as the change in Risk between the baseline and the option divided by the cost of selecting this option.

For any given delta-mass to spend globally reducing risk there exists an optimum set of options to select across the range of trade studies that will maximize the reliability of the entire system. The Optimizer Tool (OT) employs ad hoc optimization techniques based upon the RRE to produce a Pareto Frontier of the set of options which combine to create the highest reliability system for each incremental delta-mass.

This curve is extremely useful for identifying the point of diminishing returns for spending mass to improve reliability. Moreover, the OT can help identify where the design team may have 'under-invested' in a trade study (passed on a more massive option) by comparing the set of vehicle design team choices to the optimizer choices at the same mass. Similarly, the tool can identify where the design team 'over-invested' in an option to reduce risk by comparing the design team choices to the optimizer choices with the same risk. These exercises add value by challenging the design team to provide rationale for each decision that does not follow the optimized selections of the OT and thus helps to identify and document when a decision was made for reasons outside the scope of reliability. By examining the evolution of the optimizer selected option sets as mass increases, trends can be discerned which speak to the relative value of various options. In the end, the Pareto Frontier serves as a benchmark to judge the efficiency of the design team in producing a highly reliable system. The Pareto Frontier, combined with other Lunar Campaign aspects can also be used to calculate the Expected Mass Delivered to the moon per year. Overall, the OT is not meant to make design decisions, but rather to get the design team to attack the risk in the system from a global perspective and to encourage thoughtful discussion concerning design decisions.

1 INTRODUCTION

As part of NASA's Constellation Program, the Altair lunar lander will serve as the vehicle to return man to the moon. The spacecraft is analogous to the Lunar Module (LM) of the Apollo program, except the performance requirements have been increased considerably. Unlike the LM, Altair will be capable of transporting four astronauts to any place on the moon for a period of seven days instead of only transporting two astronauts to select locations on the moon for about a day. These performance requirements increase the necessary complexity of the system. The effect is compounded by the constraint on mass that has been determined by the selection of the Ares V as the launch vehicle. To meet these ambitious performance requirements while staying within the control mass, the Lunar Lander Program Office (LLPO) has adopted a risk based design approach during the conceptual phase of the project. Using this approach, the team first designed a minimally functional lander which could complete the mission under the mass budget, but with an unacceptable risk of LOM or LOC. Then, this approach seeks to improve vehicle reliability by focusing design efforts on the risk drivers of the design using the available unallocated mass to buy-down risk. To perform the risk analysis necessary to implement risk based design during the conceptual phase of the project, the LLPO has utilized the VRT. Through interaction between risk analyst and designer, the VRT uses a component based method to identify all initiating events which may lead to a LOM/LOC situation. For each component, the tool takes in a predicted failure rate, expected duty cycle, and applicable system responses to a loss of component functionality. The deterministic tool is able to quickly produce results at the component, system, and vehicle level while easily adapting to the rapidly changing design space.

Most recently, the team completed a design analysis cycle which focused on minimizing the risk of a Loss of Mission occurring during a nominal mission. During the design cycle, over 300 design options were created for more than 20 different applicable trade studies. This paper explores the concept of the 'optimal set' of design options and discusses applications of this knowledge when making risk informed design decisions.

2 OPTIMIZATION

Implementation of risk informed design requires the design team to make reliability a key trade study metric; however, the design team must also take into account functionality, performance, operational constraints, and other such considerations. The optimizer tool aides the design team by creating a global perspective based entirely on risk. The tool takes in a set of independent trade study options, produced utilizing the VRT, which can be combined to form a complete vehicle system configuration. Constrained by a mass budget, the OT chooses the options with the highest RRE to form a complete system with the highest overall reliability that fits within the mass budget. The OT produces an array of products which helps to inform the design team, explore the design space and identify the "differences that make a difference."

2.1 Theory & Implementation

The key metric involved in this process is RRE, which is defined as the benefit in reliability gained by a switch from a baseline option to a trade study option divided by the cost, in kilograms, of implementing said option. For a specified mass budget, the OT works by first calculating the RRE for all possible options. Next, the OT examines the option with the highest RRE. If there is mass available to buy this option and it will reduce the overall vehicle risk, the tool does so, updates the baseline to the new configuration and then re-computes the RRE scores based upon the new baseline configuration. This process is repeated until the entire specified unallocated mass budget has been spent and the optimal risk solution has been found. If this process is repeated for an array of mass budgets, then the OT will produce a Pareto Frontier of the lowest risk solutions for the range of masses. This frontier of optimal solutions represents the 'best' configurations, in terms of risk, given the initial set of trade study options.

2.2 Inputs

The OT requires a database of trade study options scored on the basis of risk and mass. In addition, these options must be independent of one another; meaning that the selection of one option in a specific trade study has no effect on the selection or results of any other trade study. Independence can be achieved through careful selection of trade study boundaries. Upon combining a single selection from each trade study, the resulting configuration is a complete system.

2.3 Results

The OT outputs several key products which are useful in aiding in the design decision making process. The Pareto Frontier, which is generated for both LOM and LOC, shows the design team the best they could hope to achieve in the absence of outside constraints, as shown in Figure 1. Each stacked bar consists of a single option from each of the twenty trade studies considered. Much value is added by comparing the design team's selected configuration against the results of the OT. In addition, the shape of the curve indicates the potential impacts of spending more or less mass to improve the reliability of the system.

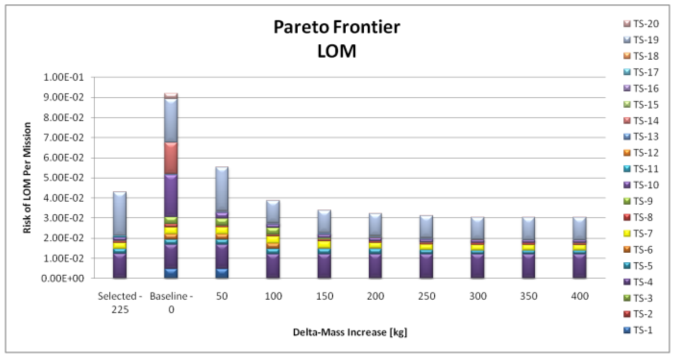

Figure 1 – Pareto Frontier of LOM

It is very instructive to identify where the curve begins to flatten out and the returns of spending additional mass diminish. This can yield insight as to what level of unallocated mass should be spent to arrive effectively at a lower risk design. Moreover, the design team can gain insight to the efficiency of their efforts to reduce risk by inserting the design team selected configuration into the Pareto Frontier and comparing the reliabilities of nearby optimizer configurations.

A useful exercise is to compare the design team's selected configuration against specific outputs of the optimizer. For example, one exercise is the comparison of the selected configuration against the optimized configuration which uses the same mass as the selected configuration. The differences between these two configurations highlight trade study options in which the team may have under-invested mass in an option. The team is then forced to come up with rationale for why each decision deviates from the purely risk based optimal solution. Or what's more, the design team may end up revising their initial selection, which was made within the context of a single trade study, based upon the global discussion. This exercise can be repeated for a comparison of the selected configuration versus the optimal solution with the same risk. This comparison will highlight areas where the design team may have over-invested in a particular option.

In addition, more insight can be gained into the global value of trade study options by examining the trends of the optimizer in detail. For example, the behavior of the OT to purchase options consistently indicates a high value for said option. Or if the optimizer seems to jump around and select a variety of different options for a particular trade study, then this indicates that this particular trade study is relatively not as important to the overall global reliability as other trade studies.

Finally, the Pareto Frontier optimized configurations can be used to create an expected value delivered chart. This chart is extremely useful in translating the system risk scores into more meaningful metrics. For example in the case of Altair, the metric of concern is expected mass delivered to the surface of the moon per year. For each configuration along the optimizer frontier, it is possible to calculate the expected value of payload delivered per year by assuming the length of a programmatic delay due to a LOM or LOC event occurring. This curve readily identifies the point at which adding more mass to improve reliability actually hurts the overall program capabilities, as shown in Figure 2. This figure shows that when initially spending mass to buy down risk, the total potential value delivered decreases, but the expected overall value delivered increases. However, it also shows that it is possible to spend too much mass and decrease the expected value delivered. This methodology can be tailored to the specific operation goals of an arbitrary complex system.

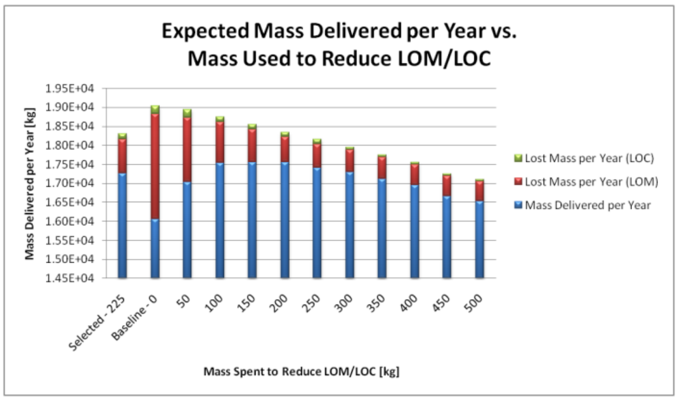

Figure 2 – Expected Mass Delivered per Year Chart

2.4 Future Work

In future implementations of this optimization process, it would be useful to improve the OT in several ways. The incremental mass step size in the frontier should be scalable to allow increased granularity at key areas in the curve. This additional detail would yield greater insight into the behavior of the optimal system in an area of interest. This change would also increases the understanding of the trends found in the optimizer configurations.

In addition, it would be useful to force the optimizer to include or exclude certain options. This would lead to more instructive comparisons between the optimizer and design team given that the design team can sometimes be 'forced' to make design decisions based upon other compelling sources other than purely risk. Moreover, it would beneficial to augment the OT to include uncertainty distributions of trade study options to allow for a more enlightened examination of the results.

3 CONCLUSION

Risk informed design helps the design team by aiding in the efficient and effective allocation of resources. By focusing in on key reliability metrics, it is possible to come up with optimal design solutions that are useful in verifying the decision-making process. These tools are not meant to make the design decisions, but rather to inform the designers of the risk implications of their decisions, to spawn thoughtful discussion and to develop concrete rationale for design decisions. And what's more, this process can be applied to a wide range of design projects outside the scope of manned space exploration.

As the political realities which have forced NASA to make crew safety and mission reliability a design driving requirement begin to spread to other industries, the demands upon complex systems to operate reliably and to continue operating in light of a failure will continue to increase. These demands will further require reliability analysis to evolve and mature tools which can effectively, rapidly, and accurately add value to design projects earlier and earlier in the conceptual design phase.

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