Designing an External Fuel Tank for the Space Shuttle

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INTRODUCTION:

Multidimensional design optimization is a difficult task for even the most experienced of engineers. For such instances, it is often useful to utilize a visualization tool such as ATSV (Advanced Trade Space Visualization). Specifically, ATSV provides multidimensional visualization tools and visual steering commands to aid in the design of complex engineering systems. The purpose of this design project was to assess the utility of ATSV as a visualization tool during a design optimization problem. The approach taken was to optimize a specific design problem using both Microsoft Excel and ATSV in order to compare the processes.

We optimized the size and shape of an external fuel tank used by the National Aeronautics and Space Administration (NASA) on a space exploration vehicle. The problem had the objective of improving NASA's Return on Investment (ROI) by resizing the fuel tank. The model provided to the team included sufficient information for structural and aerodynamic analyses. This model divides the external fuel tank into three hollow geometric segments: a cylinder, a hemispherical end cap, and a conical nose. The optimization problem is formulated to maximize ROI subject to design variables and constraints. The design variables control the tank size and shape, and the constraints limit the possible designs due to tank volume, and experienced stresses and vibrations. This problem was solved using both ATSV and Excel, and the programs were assessed based on their ability to produce the clearest and most easily determined results with the highest confidence.

PART A

Our group used the Excel Solver program that was already generated with only minor changes to fix the constraints in Solver. First, we explored the Excel program and learned how it was set up, the units used, the constraint normalization, and how the design variables were non-dimensionalized. Three of us collaborated on a single computer as we proceeded through the design process. We did not have set roles such as leader, operator, or scribe. It took us about an hour to complete the problem using Excel. We ran the Excel optimization program a number of times changing options in the solver program until we reached the same solution multiple times. The ROI for this point was 0.322. We did not examine any of the intermediary optimization boxes during our solution process. We also did not consider optimizing any of the design variables individually, but we did check the first few runs to ensure that all constraints were satisfied. The Excel program readily generated an optimized solution. It was, however, difficult to ascertain the effects different design variables had on the system. We could have graphed some of the results in Excel and obtained some visual information. Overall, we felt like this was a simple problem, and the Excel program gave us a simple solution.

To solve the problem in ATSV, we first gathered a set of 500 points to better learn the different features in ATSV. Four of us worked on this part of the project together but only one person operated the program. This made it somewhat difficult for all of us to fully explore and learn the program. First, we looked at the 2D scatter plots and decided to focus on length, radius, and thickness-1 as these variables exhibited patterns with ROI. Next, we examined the 3D glyph plot with these three variables on the axes and the color set to ROI. The plot looked great, but there was no discernable pattern to aid in finding an optimal solution. As we began to focus on the optimization problem we discovered that we were unsure how the program was intended to be brushed to meet the constraints. The constraints were normalized in the program and were not easy to correlate to the printed information provided. After making initial guesses and checking specific points with the Excel program we had our problem properly constrained, but we only had one feasible point. We then gathered 5,000 additional points but still only had three feasible points. We tried using the attractor, generating another 10,000 points, and constraining the design variables but were not able to gather enough points to use ATSV as a visualization tool for design optimization.

Identifying the constraints and generating points extended our design session to three hours, and we were not sure how best to proceed with gathering more feasible points. At this point we had fewer than 10 feasible points so we found the one with the highest ROI and decided that it would be our solution for the optimization problem. Because the ROI values for the few feasible designs were similar relative to the other 15,000 or so designs, we were forced to view data for each feasible design to find the highest value. We could not determine how to change the scale of the ROI variable to visually determine the highest ROI among the feasible points. The ROI for this point was 0.208 which is less than the value generated by Excel.

Overall, ATSV was awkward and frustrating. If we were more familiar with the program, it may have been easier. There were two main problems with using ATSV to solve this problem. First, it was difficult to generate feasible design points, resulting in less than 10 points. This made it very difficult to visualize any patterns in the feasible designs. We also generated a few points based upon the results of the Excel program and these were separated from the feasible points generated by ATSV, leading to further uncertainty about the visualization results for this problem. Second, there was no apparent way to zoom in on a feasible area or adjust the scales of the axes or both. Our few feasible points were all red when plotted in a glyph plot and we could not discern any difference in ROI among these points.

Our collaborative design approach seemed effective, but we probably did not need all three or four of us as only one person could drive the program and our individual input was not incredibly insightful. A two person team would have been just as effective. If we had solved the problem on separate computers, the process would have been slightly faster and we could have compared results and options.

QUESTIONS:

1) **Were you able to find equally good solutions using the Excel Spreadsheet and ATSV?**
   We found our Excel solution to be better than the solution produced by ATSV, in terms of ROI. Additionally, we spent about 5-6 times as long finding a solution using ATSV and were less confident in the solution we did obtain due to the random nature of design generation as opposed to the systematic searching of Excel.

2) **Which version of the problem was easier to solve: ATSV or Excel, why?**
   The problem was easier to solve using Excel. Excel was more familiar to us as an optimization tool. We really appreciated the ability to see the actual solution values. We also liked being able to easily see the equations in Excel enabling us to be sure of the calculation methods if there was a question. We had problems with the brushing in ATSV but that might be more due to the fact that we did not actually write the problem into ATSV.

3) **To what extent did you feel that you understood the problem using:**
   Excel: 4 **ATSV:** 2
   Neither tool really gave us a clear understanding of the problem in the amount of time we spent solving the problem. Excel rated a little higher because it was easier to use and

expectations were not has high. Where as ATSV we were told would let us "see the design space" and yet we were unable to get to that level of problem solving in the program.

4) **How useful were the visualization capabilities within ATSV? (1-5 scale)**
Our feasible design space was so small that we had a hard time figuring out any relationships among variables. Being able to zoom in on an area and change the scales so color, for example, is better represented in the small window of design space of interest. We like the multiple scatter plots and found those useful. For the glyph plot we really only focused on three dimensions although we might have used more if we could change the scales. On a scale of 1-5 we would rate the usefulness of the visualization capabilities a 3. It was good to be able to see the design space, but this capability was not particularly useful in this problem for optimization.

5) **What capabilities did you find most useful within ATSV?**
The ability to produce individual scatter plots. The glyph plot was also nice, and we enjoyed being able to rotate the plot in three dimensions. Brushing was a great feature but it would be nice if the glyph plot would update by changing scales to reflect the brushing. We also liked to be able to click on a point and see the properties of that design. We did not use the parallel coordinates feature but might have if we had spent more time and gathered more feasible points.

6) **Are there capabilities that you wished ATSV had as you tried to solve the problem?**
A way to generate points only within the feasible brushed constraint region would be very useful. The purpose of setting constraints is not to narrow the design space but to establish the design space. However, it seemed like this was not how ATSV was set up. A data import feature or another way to edit and filter raw data points would also be helpful. The ability to add specific points for comparison as a separate feature would be nice. Finally, a way to update the scales of the glyph plots to see some sort of differentiation in the region of interest.

7) **Did you feel that you received adequate training before using ATSV? (1-5 scale)**
We felt like there was not much training, just a basic rundown of the capabilities of the program, but the program seems fairly intuitive and we were able to figure it out fairly easily. We discovered later, however, that we were incorrect in establishing the brushing in the actual problem. When solving the specific problem, it would have been nice to have a little better background of how it was set up in ATSV. In using the actual ATSV program we were able to navigate fairly well and never tried to get help from the program or other sources. We would rate the training we received a 4.

8) **Was the problem described clearly enough for you to be able to solve it?**
We had a hard time visualizing the problem because the variables were normalized. This is partly of a function of not setting up the problem in ATSV. If we had been involved in this step, we would have had better understanding of the problem. Still the problem seemed simple enough that normalizing was not necessary and dealing with the real numbers would have helped our understanding of the problem. Besides the variables and constraints the problem seemed straight forward, and we did not have any other problems.

9) **Are there other applications beyond optimization where you think ATSV would be helpful?**
Decision making such as shopping for a car would be useful in ATSV. The issue is the ability to write the problem into the program. Perhaps anywhere large sets of data are used to make decisions based on tradeoffs between variables.

10) **Any suggestions to improve this process?**
Easier or simpler problem generation in ATSV or a way to view and edit the problem would be helpful. Suggestions or direction in the program on where to proceed based on the data gathered and the progress to date would also be helpful. A "what to do next" button would guide the user in the problem. For example if after brushing there were only a few feasible points the program could alert the user that more points should be gathered and using the attractor feature would be beneficial.

PART B:

The design project began with the in class distribution and explanation of the problem. Teams were formed, contact information exchanged, and an initial meeting to begin working on the assignment was scheduled. Prior to the first meeting, team members read *Trade Space Exploration of Satellite Datasets Using a Design by Shopping Paradigm,* received in class training in ATSV, and studied the assignment handout. At the first meeting team members discussed the problem to achieve a consensus of thought concerning the problem statement and the required work.

We spent little time designing a collaborative approach to solve this problem. Instead, a process evolved where the team would collectively decide what needs to be done next. Sometimes this meant meeting as a group, other times this meant meeting in subgroups or working individually. Group meetings mainly addressed steering decisions or how to extract information from ATSV. Subgroup meetings dealt with topics such as solving Excel or preparing a PowerPoint presentation of our work. Individual efforts addressed subjects such as writing or proof reading this report. Team members worked well together and the collaborative approach that evolved was sufficient to complete this assignment. Better communication between team members, an earlier consensus of project requirements, and an intermediate report with instructor feedback, would most likely have improved our design process and our final product.

PART C:

Two of our research projects have little relevance to this particular problem. Rex's comparison of different energy sources and Peter's investigation into modularity are not particular related to this optimization problem. Justin's optimal sensor network configuration is similar in that both incorporate optimization routines, but Justin's is more qualitative than quantitative, reducing the relevance. Finally, Clint's project also investigates optimization but seeks to include multiple disciplines so has limited application to this single disciplinary problem.

RESULTS:

Using Excel to solve this problem, three of us spent about one hour. That time was split into three sections, 1) becoming familiar with the spreadsheet (about 10 minutes), 2) determining and setting the constraints (about 30 minutes), and 3) finding the optimal solution (about 20 minutes). Once the constraints were ascertained and set, we ran the Solver routine. It quickly became apparent that the number of iterations needed in Solver to arrive at an optimal solution was greater than the default setting. We ran the Solver routine numerous times (about 5-10) with a higher number of iterations until the objective function (ROI) did not change with subsequent runs. Our final ROI using Excel was 0.3219 with the following design parameters: Ln = 1.1808, Rn = 0.8994, h/Rn = 2.3919, t1n = 0.8792, t2n = 0.8853, t3n = 0.8188.

Finding an optimal solution with the Advanced Trade Space Visualization (ATSV) tool proved much more difficult compared to Excel. Our group spent about 3 hours during two sessions to determine a solution. In addition, some of us worked on the problem outside of our group sessions. We started the initial session by spending about 15 minutes becoming familiar with the specified problem and how to generate random designs. We initially generated about 500 designs, but after setting the constraints we were reduced to a single point. Much of the subsequent time in the initial session was then devoted to determining how the constraints were calculated and what values they should target. During the second session, we compared constraint values in ATSV and Excel and determined that they were identical in both programs, and that our initial single point was, in fact, the only feasible point among the points generated. We then generated about 15,000 points, yielding about 7 feasible points. We chose the point with the highest ROI among those points as our optimum point. The ROI obtained using ATSV, ROI = 0.2076, was substantially less than the Excel value. This design point generated by ATSV had the following design parameters: Ln = 0.8211, Rn = 1.0860, h/Rn = 1.6723, t1n = 1.2264, t2n = 1.9648, t3n = 1.1194.

CONCLUSIONS:

Using ATSV to find an optimal solution with this tightly constrained problem was difficult and resulted in a lower ROI compared to the value obtained by using Excel. We spent more than four times as long searching for a solution using ATSV compared to Excel and the optimal value was about 64% of the value obtained using Excel. There were 2 main reasons why it was difficult to use ATSV to find an optimal solution for this problem. First, we could not find a method to generate only feasible design points given the constraints. Thus, we needed to generate about 2,000 design points to obtain each feasible point. Second, we could not find a way to visually distinguish the few feasible points in terms of the objective function. Because the ROI for each of the feasible points was similar to each other relative to the other thousands of points, they all appeared similar on the glyph plots (e.g. they were all red). We could have possibly used some of the other graphing features to determine the optimal point, but there did not seem to be any list of points or other way to view the variables in the best design except my picking the correct dot on a graph.

Due to the limited number of feasible data points we generated, we felt we could not fully utilize the advantages of ATSV for visualizing trade-offs with various design options. It is difficult to make any firm conclusions when there are only 7 data points. This conclusion was confirmed when we also manually put in design points that were close to the optimum produced by Excel. The Excel optimal points formed a small cluster in the design space that was distinct from the cluster produced by ATSV. Clearly, ATSV was not showing us the entire feasible design space, and we were uncomfortable making any conclusions about the design space.

The strength of ATSV lies in its ability to show trade-offs within or near feasible design spaces, but with this problem and the limited data, we could not visualize these trade-offs. Because we could not take full advantage of the visualization capabilities of ATSV, using this product did not enhance our understanding of the problem. Consequently, Excel proved to be faster at producing a better solution without sacrificing problem understanding.