# AE6373-A/Q Advanced Design Methods I
# Fall 2022 Class Project


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**Abstract**

The course project for Advanced Design Methods I complements the lectures by having students apply their newly-acquired skills on a relevant aerospace design problem. In teams, students will design a replacement passenger aircraft to fulfill more aggressive customer and regulatory requirements. In order to design such a vehicle, the students will use sizing and synthesis code(s) which automate design space exploration and decision making process via the use of design of experiments and statistical analysis software. Having picked a new baseline aircraft, students will attempt to meet design requirements by infusing different technology packages. Ultimately, teams will create an economically viable aircraft which meets market demands.

# Contents

# 1 General Description

## 1.1 Introduction

This semester-long project is designed to have students apply many design methods taught throughout the semester to reinforce their learning. Students will find that design is more than a simple calculation activity; it involves understanding customer needs beyond requirements, making many critical decisions, factoring in production and economics considerations, as well as performing performance analysis on design alternatives. The lectures will provide the theoretical background for all the steps required for the project. Some steps will be executed almost identically by all teams.

Teaching assistants will form randomized teams of 5 or 6 students in the beginning of the semester. The teams will have a healthy mix of different backgrounds. Each team will be given a representative baseline vehicle to start their work from. There are 5 different *seat classes* and each seat class will be given to a few teams. Teams will be assessing the feasibility and viability of the baseline vehicles in the context of aggressive performance goals as well as stringent economic and technical requirements that are representative of a future civil aviation scenario.

In order to achieve a good design, teams will implement the steps of the *Technology Identification, Evaluation, and Selection (TIES)* method. A series of templates, tutorials, technical data and other miscellaneous files will be provided as project resources to help the teams work faster, check their work, and troubleshoot their problems. The teams should focus on generating, making sense, using, and presenting the data equally. Please follow the steps carefully and include all required discussions, plots, tables, and other elements in your report and presentations.

The project is set to follow lectures during the semester, so the students are encouraged to do project work in parallel to their studies for lectures and exams. Because this is a fast-paced project, do everything in your power to keep up and seek the help of your course instructor and teaching assistants as necessary. In this project description you will find all important information regarding objectives, deliverables, student expectations, and technical requirements. Please read this information carefully and refer to it frequently.

## 1.2 Honor Code

All students participating in the class project are expected to abide by the Honor Code of the Georgia Institute of Technology. This commitment to the Honor Code is formalized with a signed declaration that the work and ideas contained within the report are solely those of the team members except where explicitly referenced or cited from another source. The declaration will be provided as part of the project resources and must be signed by all members of the team and included with the physical copy of the final report. For the distance learning students an electronic signature of the document will suffice, and must be emailed by the final report due date and time. If you have any doubts regarding the Honor Code, particularly the detailed definitions and technicalities of what comprises plagiarism, other academic misconduct, and their associated consequences, visit the Honor Code webpage at `http://www.honor.gatech.edu/`.

## 1.3 Objective

The primary objective of the project is for students to apply the advanced design techniques they learn in the lectures. The students will mainly use the steps of the TIES method to guide their work. This project also aims at simulating a realistic research effort in which a customer requests your services. Such contracts specify strict intermediary and final deadlines for updates and the final product. Students are expected to meet all such deadlines, especially the final ones for the report and presentation. By the end of the project, students will have a working knowledge of how to:

- Implement the TIES method,
- Research technologies and model their potential impacts,
- Use sizing & synthesis and economic analysis tools,
- Create a design of experiments and defend its composition,
- Generate surrogate models and check their goodness,
- Model uncertainty through Monte Carlo simulations,
- Obtain sensitivities of performance and economic metrics against design variables,
- Simulate the effects of including new technologies on a vehicle,
- Choose the right mix of technologies to meet customer requirements,
- Understand and anticipate the robustness of their proposed design
- Write a comprehensive technical report, and
- Give a technical presentation in a professional/academic context.

## 1.4 Resources

For the purposes of running simulations, EDS (Environmental Design Space) will be used. However, due to proprietary nature of the code, simulations will be run by students who work on computers that are on the ASDL network. The TAs will make sure that every team has at least one student who has access to an ASDL computer.

Teams will use a statistical software named *JMP*. JMP is used to visualize, organize, and regress design data that students will gather throughout the project. JMP will also be used to present data and work in the form of *journals*, in which any user can click and investigate data interactively. Installations of JMP can be found on ASDL, AE computer lab, and library computers. Students are allowed to take their data to any of these computers and use JMP anywhere they like. However, you cannot take the installation files from ASDL software server and install them on your personal computers as the license will not work.

Several tutorials on the use of the tools for data analysis and processing will be made available through the class website in the *Project Resources* section. Additionally, lab exercises, presentations, and demonstrations will take place during some lectures. Other resources, as required will be uploaded on the Canvas website.

## 1.5 Project Report

The project report must be written using either the Microsoft Word or the LaTeX template that will be provided on the class website under *Files*. The template must be modified to match team names, number, and dates; however, the style must be followed strictly and may not be modified. Formatting is important:

- Use a technical tone
- The report must be free of spelling and grammatical errors
- The text in your figures must be readable
- Use references to link and label figures, sources, tables, and other entries
- Do not use unnecessary coloring, 3D effects, etc. on your figures
- Avoid large blank areas, move your figures around if you must (figures do not have to immediately follow the relevant text)
- Do not change fonts, use bolded or underlined letters

The project report **may not exceed 100 pages**[1] not including cover sheet, Honor Code signatures, and contents page but including references and appendices. Large code blocks and numerous irrelevant plots should not be included in appendices, as your report should include only relevant information. An electronic copy of the report must be provided, the file named with the team number and vehicle (e.g., Team-13-150PAX). The electronic copy must be uploaded to Canvas by a single member of the team by **December 6th** no later than **11:55 pm**.

The project report must include technical details of any method and software used in the project. Please include limitations, advantages, and reasoning of why each particular method was chosen even when the project description suggested the use of that method. The project report should not include points such as *"JMP was mandated by the project description; therefore, the team used it"*.

The result data are not sufficient, they must be explained and made sense of. Analysis of the results can be done via trade studies –among other studies– for designs showcasing the

[1] If you are using the LaTeX template, then you might have up to 115 pages

flexibility and power of the methods used throughout the project. Demonstration of such features will reinforce the justifications made for selecting certain methods. Below are some trade studies that must be performed. Teams are free to perform more if they think such studies will help their design, case, or reasoning. Some example trade studies are:

- The Low Cost Composite Manufacturing on Tail and Wing Structure technology (T3) was selected to be developed by a higher authority in the company. T3 must be included in the final design. How does that policy change the final selection of technologies and design?
- Which constraint is more critical: fuel burn or emissions? What is the impact if the critical constraints were to be relaxed?
- Through a political one-two punch, all technologies that have below a TRL of 5 have had significant reductions in funding. This means that projections for when these technologies will have TRL of 9 are off by 2 years (i.e., if technology 2 was predicted to have a TRL of 9 by 2013, it will now reach TRL of 9 in 2015). What impact does this have on the design? What is the best course of action?

### 1.6 Project Presentation

A final presentation, which must include a demonstration using the JMP's journal feature, will be given to the instructor, course teaching assistants, and attending classmates on **November 29th**. The order of the presentations will be determined a couple weeks before the presentation date, based on the instructor's and students' availability. The presentation must be designed to suit the following scenario:

> Your team is presenting a proposal for a next generation airliner to high-level executives and senior engineers of your company. Your team needs to provide credible technical data and a solid business case to convince the audience that your proposed aircraft will meet future market demands. These details can include what technological improvements will be necessary to enable your design, and what upcoming market forces are driving your design decisions.

Presentations are **30 minutes**. Following each presentation, teams will be asked some technical questions related to their work. Each member must be ready to answer **any** question, i.e., the question cannot be passed to another team member. It is recommended to prepare for the trade-off questions listed above as well as the ones below. The list below is not exhaustive, only exemplary.

- Does the wing size (AR, span, area) influence impact of the laminar flow technology? How is this dependence dealt with in the work presented?
- When reporting the benefits of a new technology they are developing, companies tend to overstate the benefits (e.g., "Up to a 30% reduction" does not mean there will be a

30% reduction). How does one account for such a technology using TIES? Assuming the benefits of every technology were overstated by 10%, which goals would be very difficult to meet? Why?

- Economic shocks are not only hard to predict, but also very disruptive for businesses. Name an example of how an economic shock has derailed an aerospace project. What kind of an analysis can possibly save design projects from getting canceled due to unforeseeable economic shocks? Explain.

It is recommended that teams prepare back-up slides for the above-listed trade-off questions. Back-up slides can be very useful in answering questions as well as demonstrating general preparedness for presentations.

## 1.7 Recommended Reading

Select publications associated with the TIES method are listed below. For more papers, students can search for Dr. Kirby's other publications.


1. Kirby, M. R., *A methodology for technology identification, evaluation, and selection in conceptual and preliminary aircraft design*. Dissertation, Georgia Institute of Technology, 2001.

2. Kirby, M. R., Mavris, D. N., "An approach for the intelligent assessment of future technology portfolios," 40th AIAA Aerospace Sciences Meeting & Exhibit, January 2002, AIAA-2002-0515.

3. Kirby, M. R., Mavris, D. N., "A technique for selecting emerging technologies for a fleet of commercial aircraft to maximize R&D investment," World Aviation Congress & Exposition, September 2001, SAE-2001-01-3018.

4. Kirby, M. R., Mavris, D. N., "A method for technology selection based on benefit, available schedule and budget resources," World Aviation Congress & Exposition, October 2000, SAE Paper No. 2000-01-5563.

5. Kirby, M. R. and D. N. Mavris, "Forecasting technology uncertainty in preliminary aircraft design," World Aviation Congress & Exposition, October 1999, SAE paper no. 1999-01-5631.

6. Mavris, D. N., Kirby, M. R., "Technology identification, evaluation, and selection for commercial transport aircraft," 58th Annual Conference Of Society of Allied Weight Engineers, May 1999.

7. Mavris, D. N., Kirby, M. R., Qiu, S., "Technology impact forecasting for a high speed civil transport," World Aviation Congress & Exposition, September 1998, SAE-985547.

8. Mavris, D. N., Mantis, G., Kirby, M. R. "Demonstration of a probabilistic technique for the determination of economic viability," 1997, SAE-975585.

9. Persons, T., Macking, M., "TECHNOLOGY READINESS ASSESSMENT GUIDE: Best Practices for Evaluating the Readiness of Technology for Use in Acquisition Programs and Projects," U.S. Government Accountability Office, 7 January 2020.

10. Mavris, D. N., Bante, O., DeLaurentis, D. A., "Robust Design Simulation: A Probabilistic Approach to Multidisciplinary Design." Journal of Aircraft, vol. 36, no. 1, American Institute of Aeronautics and Astronautics Inc, 1999, pp. 298–307

## 1.8 Tips and Comments

Avoid dedicating too much time and detail to the initial stages of the project and then leveling off. Keep in mind that all the tasks of the first few steps have been tremendously facilitated with the provision of data, files, and system models. This project is designed for you to focus on the generation and (most importantly) analysis of data. The skills required to perform the tasks described in this document will be taught in the lectures of the class.

Familiarize yourself with all parameters relevant to the modeling of your aircraft. This includes technical terms, ADM theory terms, control variables and metrics pertaining to performance, technology and economics. Know what they mean and how they are representative of the different attributes of the vehicle you have modeled.

When inserting an image do not make it any larger than what it needs to be. On the other hand avoid reducing the size of the image so much that the information meant to be transmitted is lost (e.g., values in the axes of a plot are not readable). Whenever adding multiple related images (e.g., PDF and CDF for a given metric) try to set them side by side and not one on top of the other whenever possible. This makes more efficient use of your space.

The requirements in the project description are provided for teams to have a clear indication of what issues must be addressed/answered in the project and in the report. However the report must include all this information with a fluent tone and smooth transitions from topic to topic, and NOT in a fragmented, question-&-answer format.

It is strongly recommended that you plan to print a version of the final report to do a final hard-copy revision. Print this copy to two pages per side and double side to save paper. Keep in mind that proofreading and correcting often takes more time than anticipated.

Create a project timeline/calendar so you know what tasks need to be completed and exactly how many weeks you assign to each of them. This provides good task force and time management skills and facilitates your completing of the project deliverables in time.

Try not to compartmentalize the project such that each team member is working independently. This project is inherently multi-step, multi-disciplinary, and integrated in nature and therefore the results generated will not be optimal if students do not work together every step of the way. However, this does not preclude each team member from taking a leadership role on different elements of the project. Bear in mind that this project also includes a peer-review component, where students will be able to assess the contribution of their teammates.

# 2 Project Steps

The 8 steps contained in the TIES method are as follows.

1. Problem definition
2. Baseline and alternative concepts identification
3. Modeling and simulation
4. Design space exploration
5. Determination of system feasibility/viability
6. Specify technology alternatives
7. Assess technology alternatives
8. Select best family of alternatives

The specific requirements relating to each step are listed below under Subsections 2.1–2.8. Additionally, this project contains three additional sections aimed to: i) expose students to current technology development programs around the globe in the context of aviation's environmental impact, ii) chose a final design under the context of robustness, and iii) put forth a business case. The requirements listed in this section are the minimum expected work. Original thought and creativity in going beyond the minimum requirements will be rewarded.

## 2.1 Step 1: Problem Definition

Starting with the **Problem Definition** phase and using the TIES method, the primary objective of this step is to identify the need for the vehicle under design. This can be done by mapping the "voice of the customer" to the "voice of the engineer" and demonstrating that the new design fulfills the customer's needs. In most cases this need is identified through market forecasts. Alternatively, a *request for proposal (RFP)* can be published by the government or the customer. This mapping is performed through a *Quality Function Deployment (QFD)* process taught in the *Aerospace Systems Engineering* class. The outcome of this step is the identification of the system level metrics that capture the customer requirements. The metrics of interest are provided in Table 1 as well as the target and/or constraint values. Some of the metrics are percent reductions from the baseline vehicle. In order to get the actual values, the baseline aircraft must be run through EDS once and its performance values must be collected. Once the values are obtained, the target values can be calculated.

### 2.1.1 Requirements for Step 1

**Defining the need** Reviewing the literature about projections on passenger traffic and cargo growth, congested airways, or changing regulations is a good place to start to find a need for the new aircraft.

**Defining potential markets** Teams must determine the number of aircraft sold in the same seat class and competing designs.

**Metrics** Metrics of interest presented in Table 1 must be defined. Also, the importance of these metrics must be established. What is the qualitative significance of lowering or increasing the metric values, i.e., what options or benefits does it provide to the designed vehicle?

**Document** The findings must be documented in the report. Additionally, a summary of the findings must be included in the JMP journal as paragraphs, graphs (JMP graphs or images), and tables.

- This is the first main section of the report. Graphs, citations, trusted opinions as well as hard facts are needed to support the claims.
- Similarly, this is the first outline item (the collapsible box) in the JMP journal. The journal must be structured to allow a fairly novice user easily navigate through and understand the design case. The journal must be treated as a less detailed, but interactive report. Instead of finding details and static tables and figures, the user will see animations, interact with figures, and possibly look into the full blown tables that are used to create the argument for design. The journal must be thought as guided pattern discovery for the user. It is a solid argument for the final design as the users will see the design's superiority in the data themselves.

Table 1: Goals for the system level metrics

| **Parameter (EDS Variable Name)** | **Target** |
|---|---|
| **Performance** | |
| Design block fuel (desBlockFuel) | $-20\%$ |
| Economic block fuel (econBlockFuel) | $-20\%$ |
| Operating empty weight (OEW) | $-25\%$ |
| Take-off field length (TOALL_TOFL) | $-15\%$ |
| Wing span (Wing_Span) | constraint |
| **Emissions** | |
| Nitrogen oxide emissions (dPfooNOx) | $-54\% < CAEP/8$ |
| NOx certification limit (CAEP8_Limit) | constraint |
| **Economics** | |
| Acquisition price with spares (Avg_UnitCostSpares) | $-15\%$ |
| Research, development, testing, and evaluation cost (RDTE) | minimize |
| Direct operating cost plus interest (DOC_I) | $-20\%$ |
| Required yield per revenue passenger mile (RPM) | minimize |

## 2.2 Step 2: Baseline and Alternative Concepts Identification

Once the customer requirements are defined in terms of quantifiable engineering parameters, the thrust of the TIES method begins with the definition of the concept space. Initially, the experience, knowledge, and intuition of the designer is utilized to identify a potential class of vehicles and provides the methodology with a starting point for selecting potential solutions to satisfy the customer requirements. The focus of this step is two-fold: identify the space of alternative concepts that is based on a defined class of vehicles, and establish the geometric and propulsive design space for which system feasibility is sought.

### 2.2.1 Space of Alternatives

In the design of any complex system, there exists a large combination of particular subsystems or system characteristics that may satisfy the problem at hand. For example, how many engines are needed, does the aircraft have a tail or a canard, what type of high lift system is needed? A functional and structured means of decomposing the system and identifying component options can be done through the use of an *Analysis of Alternatives (AoA)* analysis. A matrix of alternatives (or a morphological matrix) can be used during this step. The matrix of alternatives is formed by identifying the major functions or characteristics of a system on the vertical scale and all the possible alternatives (or system attributes) for satisfying the characteristics on the horizontal scale. The matrix of alternatives breaks down the conceptual design space by organizing it in either the functional or the physical space. Once the matrix is populated, an alternative design concept is defined as a thread within the matrix. All possible design alternative combinations define the alternative concept space and are defined by the matrix of alternatives. In general, one alternative concept is established to begin the feasibility investigation and will be called the baseline concept and is typically drawn from mature or present day technologies.

As discussed before, this baseline is actually provided to each team. This baseline will serve as the answer to the analysis of alternatives study. However, each team must make arguments to support the use of the specific baseline they are given. The commercial airline industry requires more than a single class of vehicles; therefore, finding an argument for each baseline should not be difficult. Because they are provided with the baseline, teams should not waste much time in this step and focus their work on the application of TIES. Nevertheless, the analysis of alternatives must be performed leading to the answer already provided. Teams are expected to report on the size of the conceptual design space they investigated before picking the baseline.

Once the baseline values have been obtained, students must check whether the design variables are in the (given) nominal ranges and outputs approximately correspond to their respective aircraft class.

### 2.2.2 Design Space

Conceptual decisions in the analysis of alternatives must be augmented with the *control variables* the teams will use to perform their design space exploration with. Table 2 shows the control variables that will be used and their EDS names. Morphological matrices used in this step are expected to include the control variables listed. Students can simplify and combine multiple variables into a super category, e.g., the thickness to chord ratio could be represented as a single row in the matrix if desired. These control variables define the design space that will be investigated for technical feasibility.

Table 2: Design variables and their EDS names

| **Description** | **Variable** |
|---|---|
| Wing Loading | WSR |
| Thrust to weight ratio | TWR |
| Wing aspect ratio | AR |
| Wing taper ratio | TR |
| Wing thickness-to-chord ratio | TCA |
| Wing quarter-chord sweep | SWEEP |
| Horz. tail aspect ratio | ARHT |
| Vert. tail aspect ratio | ARVT |
| Fan Pressure Ratio | FPR |
| Low-Pressure Compressor Pressure Ratio | LPCPR |

### 2.2.3 Requirements for Step 2

**Morphological Matrix** An analysis of alternatives study must be provided by constructing a morphological matrix. There must be three parts to the matrix: conceptual, design, and mission. Conceptual refers to configuration parameters such as canard vs. tail. Design refers to the variables given in Table 2. Mission refers to requirements such as range and payload. Morphological matrices must be as exhaustive as possible. They are not required to be interactive. The matrix must be included in the report, the JMP journal, and the presentation.

**Number of alternatives** The number of conceptual alternatives must be reported in the report, journal, and the presentation. The report must show the full calculation.

**Identification of the baseline** The baseline must be identified in the matrix by circling or shading the relevant cells of the matrix.

**3-view** Using a CAD software, a 3-view of the baseline must be made. This 3-view does not have to be detailed. Teams are not to spend large amounts of time to add details to it that are not known to them at this stage of the design, e.g., windows, doors, flaps, landing gears. The principal dimensions must be shown on the figure. The baseline must be included in the report, presentation, and the JMP journal.

## 2.3 Step 3: Modeling and Simulation

The modeling and simulation environment used by the teams will be EDS. For the baseline study, teams will run the baseline vehicle input that is provided to them through EDS, and use the output files generated to obtain relevant information. Teams will need to tweak the input/output file(s) and obtain the numbers required to complete the following requirements.

### 2.3.1 Requirements for Step 3

**Mission profile** The mission that is used to size the baseline vehicle must be described and depicted by a graphic. The profile must include altitude, distance, time, Mach number (or velocity if Mach number is unavailable). Briefly comment on the segment profiles used (e.g., you could climb for minimum fuel burn or minimum time). All relevant assumptions associated with sizing and evaluating the vehicle—both from a sizing perspective and an economic perspective—must be clearly stated in the report. The mission profile must be included in the JMP journal as an image or an interactive graphic if preferred.

**Design point** Thrust to weight ratio and wing loading of the baseline must be indicated in the report, presentation, as well as the journal. They can be shown in an appropriate way for each of the three media.

**Weights** The operating, gross, payload, and max fuel weights must be included in the report. In addition to the general weight information a breakdown for the principal weight groups must be included. The weight breakdown must be included in the JMP journal as a JMP graph linking to data in a data table.

**Propulsion** Maximum static sea-level rated installed thrust per engine and a metric for the fuel consumption during cruise must be reported. The journal must also include these information in an appropriate way.

**Aerodynamics** Lift to drag ratios during take-off, cruise, and landing must be included. Investigate how lift to drag ratio varies during cruise on a drag polar. The range of lift to drag ratio must be shown on the drag polar. The aerodynamics information must be included in the JMP journal as a plot linked to a data table that includes the information.

**Airframe manufacturer economics** The manufacturer's cash flow plot and the production schedule must be included. On the cash flow plot all relevant phases and points must be labeled. Separately, the variation of the acquisition cost with respect to production quantity must be shown on a log-log plot. The shape of this curve must be discussed. This plot must be included in the JMP journal as a figure linking to a data table.

**Airline economics** A breakdown of the costs associated in owning and operating the vehicle (e.g., TOC, DOC, IOC) must be shown in a graph. This breakdown must include a study for fuel price fluctuations in the range of 75%–200% of the fuel price today (three pie charts will suffice for the comparisons). A discussion on the effect of the fuel price as a noise variable must be included. Additionally, the ROI for the vehicle throughout its life must be reported by plots of operating cost, interest, depreciation, earnings before tax, net earnings, net cash flow, and discounted cash flow. Each of these terms must be defined in the final report. The JMP journal must include all of these graphs that link to data tables.

## 2.4 Step 4: Design Space Exploration

Before the design space exploration can begin, datum values for all the metrics listed in Table 1 must be established. As discussed in Section 2.2, in order to obtain the actual values for the vehicle under study, each team must use the baseline values provided to them. In this step, surrogate models of the metrics of interest will be created. After the surrogate models are created, a Monte Carlo simulation will be used to explore the design space.

### 2.4.1 Requirements for Step 4

**Design of Experiments** In this step, each team must provide a representative design of experiments using aircraft design variables (see Table 2) with appropriate ranges for each (see Appendix, Table A). The DoE must contain the baseline, corner points, face-centered points, min and max points, and a suitable number of random points. This DoE will be evaluated by the TAs before being run through EDS by respective teams.

**Regression** Using results obtained from EDS, response surface equations (RSE) or artificial neural net (ANN) models for each metric in Table 1 must be created. The independent variables of the surrogates must be the variables provided by the teams in the DoE. Links to data tables must be created in the journal.

**Goodness of fit** The regressions must be checked for goodness. The material covered during class describes multiple goodness of fit checks. All checks must be applied on the regressions obtained, and regressions must be modified by transformation and/or addition of higher order terms if necessary. The discussion of the goodness of fit metrics as well as the steps taken must be included in the report with necessary plots (e.g., distributions) and tables ($R^2$, *MFE*, *MRE*, as well as maximum and minimum percent error, mean and standard deviation of the errors) for results. **Once this step is performed, a teaching assistant must approve the fits before any further work**. The journal must include links to scripts that run these analyses and show appropriate plots.

**Prediction profiles** A sensitivity analysis for each metric must be performed via prediction profile plots. The report must include the profiler plots. Because there are a large number of them, the teams are encouraged to use only the plots for influential variables for each metric. Discussion of the sensitivities must accompany the plots. The journal must include a link to a script that runs the analysis and show appropriate plots.

**Stepwise fit** A separate stepwise fit is also required. This fit will not be used later for project purposes; however, the advantages and the disadvantages of it must be discussed in the report. The stepwise fit will include up to the fourth-order terms (pure powers of factors and pure interactions). The stepwise fit must also be diagnosed and compared to the previously obtained RSEs. Teams will continue their work with the surrogate models created before and discard the stepwise fit. This step is not required to be shown in the journal.

**Contour plots** The reviewers will look for two contour plots with thrust to weight ratio and wing loading as vertical and horizontal axes respectively. One plot will contain the performance metric constraints, the other one will contain the constraints for the economic metrics. The contour plots must be included in the JMP journal in an appropriate way.

**Feasible space** The teams will observe that there is no feasible or viable space given the stringent requirements. A discussion on how much to relax each requirement and the expected consequences of the relaxation must be included. Step 5 adds more rigor and detail to this part. A summary of this discussion must be included in the JMP journal.

**Monte Carlo** A Monte Carlo simulation with 10,000 cases must be run with the RSEs obtained earlier. Using the Monte Carlo data, teams will create cumulative distribution function plots to assess feasibility and viability. The journal must include links to scripts that run the Monte Carlo simulation and produce appropriate plots.

## 2.5 Step 5: Determination of System Feasibility/Viability

Once all the response CDFs are obtained, students need to determine how feasible and viable their design space is. If there is an unacceptable probability of success, new technologies will need to be added to the vehicle later in Step 6. In this step, the necessary improvements to achieve feasibility and viability will be assessed.

### 2.5.1 Requirements for Step 5

**Visualizing feasibility** A line representing the requirements can be added to the CDF plots created earlier with proper shading to determine the *probability of success*. The value can be read from the vertical axis where the requirement crosses the CDF line. CDF graphs with requirement cutoffs must be included and commented on in the report (including the actual probability of success measured either on the plots or in a separate table). CDF plots must be included in the JMP journal but do not need to be annotated.

**Optimized baseline** Once the design space exploration is complete a new *optimized baseline* can be selected. **This baseline will serve as the vehicle the technologies are added onto**. Note that the optimization problem is multi-objective in nature. Teams must justify their selection of the optimized baseline from multiple possible non-dominated solutions. This will be the team's second model, referred as the "Optimized Baseline" model.

**Comparison between baselines** Similar to Step 2, the optimized baseline must be described via a 3-view and a table summarizing the design. Overlaying the optimized baseline on the original baseline to highlight the differences in geometry can be useful before commenting on the differences. A discussion on why the changes make sense is expected. An image of the new baseline as a comparison to the old must be included in the presentation and the journal as well.

**Other options** Next step will infuse technologies to the optimized baseline. However, a justification of why technologies are needed must be provided. A brief discussion on other ways to reach feasibility must be included in the report.

## 2.6 Step 6: Specify Technology Alternatives

If the design space is completely closed for a given set of requirements, one way to reach feasibility is adding new technologies. There are three steps in specifying technology alternatives. The first is compiling a list of relevant technologies, i.e., that are expected to help making the vehicle meet requirements. Later, compatibility rules must be established between technologies. For example, drilling tiny holes in composite structures is not a good idea; therefore, active boundary layer control technologies are usually incompatible with composite wing skins. The last step is to determine the impacts—both improvements and degradations—to the optimized baseline for each technology.

The compatibility matrix shows whether each technology can be used together with other technologies. Incompatibilities reduce the number of possible technology combinations. If there were no incompatibilities, the number of possible technology sets for 10 technologies would be $2^{10} = 1024$. Although not a very large number in this project, in realistic industry examples that number becomes very large due to the large number of technologies investigated. In a compatibility matrix a *1* indicates compatibility, and a *0* indicates an incompatibility. A technology is always compatible to itself, and the compatibility relationship works both ways; therefore, the compatibility matrix is presented as an upper-triangular matrix missing its diagonal terms.

Finally, once the compatibility matrix is determined, the potential system and sub-system level impacts of each technology must be established. The impact should include benefits and degradations to the entire system to be accurately assessed. For example, a composite technology may decrease structure weight but may increase some cost metrics. This information is presented in a *Technology Impact Matrix (TIM)*. The values in the impact matrix represent the impacts of the technology if it were matured to the point of full-scale production to the system under investigation. The values are deterministic, they do not represent means, variances, maximums, minimums, or medians. An example TIM is shown in Table 3.

Table 3: Sample Technology Impact Matrix

| Impact | Variable | T01 | T02 | T03 | T04 |
|---|---|---|---|---|---|
| Wing Wt | FRWI | | | | -0.10 |
| Fus. Wt | FRFU | | | | |
| H.T. Wt | FRHT | | | | |
| V.T. Wt | FRVT | | | | |
| Ind. Drag | FCDI | | -0.10 | -0.043 | |
| Prof. Drag | FCDO | | -0.05 | 0.01 | |
| Ldg. Gear Wt | FRLG | | | | |
| Avionics Wt | WAVONC | | | | |
| Hydraulics Wt | WHYD | | | | |
| Furn.&Equip. Wt | WFURN | | | | |
| V.T. Area | SVT | | | | |
| H.T. Area | HVT | | | | |
| Engine Wt | WENG | -0.05 | | | |
| Fuel Consump. | FACT | -0.10 | | | |
| RDT&E Cost | AKRDTE | 0.03 | 0.05 | 0.005 | 0.005 |
| O&S Cost | AKOANDS | 0.02 | | | 0.005 |
| Prod. Cost | AKPRICE | 0.02 | 0.02 | 0.005 | 0.02 |
| Utilization | U | -0.005 | | | -0.005 |
| Wing Area | SW | | | | |
| Thrust to Weight | TWR | | | | |

### 2.6.1 Requirements for Step 6

**Researching technologies** At the beginning of the project, teams performed a technology research exercise that consisted in the examination of different technology development programs around the globe and their expected impacts. This set of technologies will be referred to as "LTAG Technologies". Now, teams will be provided with a list of 17 technologies with some background information and potential impacts. Teams must down-select a final set of 10 technologies to be used in the later stages of this project, where there must be at least one technology from the "LTAG" technology set.

**Information on the technologies** All technologies must have a name and impacts listed in the journal. Judgment must be used on how to present this information.

**TIM and Compatibility Matrix** For the final set of 10 technologies, teams will need to compile their impacts in the form of a TIM, and produce a notional compatibility matrix (TCM) for this set.

**Uncertainty in impacts** The values provided in the TIM are deterministic. A discussion on the implications associated with this assumption, particularly regarding technology maturity, must be included in the report.

## 2.7 Step 7: Assess Technology Alternatives

The technologies will be evaluated deterministically in the project. Because this step only investigates the technology impacts, the design parameters must be held constant (**at the optimized baseline values**).

Given a set of $n$ technologies, the number of trials to test every combination of them is equal to $2^n$, which is equivalent to a full factorial design of experiments. In this case, $n = 10$ and number of experiments is $2^n = 1024$. That is a excessive number of experiments; however, there is no other way to reduce this number as the technologies are entirely discrete variables with two levels (i.e., *on* or *off*). In order to reduce this number, the experiments will be performed on the impacts of the technologies, not the technologies themselves. The impacts are continuous variables and a partial factorial design can be used to provide data to create surrogate models. The technology evaluation to be performed is then a metamodel of each system metric as a function of the $m$ vector elements, where $j$ is the number of k factors. The metamodels are second-order RSE as shown in Equation 1.

$$R = \beta_0 + \sum_{i=1}^{m} b_i k_i + \sum_{i=1}^{m} b_{ii} k_i^2 + \sum_{i=1}^{m-1} \sum_{j=i+1}^{m} b_{ij} k_i k_j + \epsilon \tag{1}$$

Note that response surfaces have already been fitted in step 4. This was a function of design variables. Therefore, the same surrogate **cannot** be used to assess the impacts of technologies. For this entire step, the design variables will be held constant at their optimized baseline values, and a new set of surrogates will be created using the k-factors to model the impacts of the technologies.

If the reference point for a k factor is 0, meaning no change, then a negative value represents reduction of the k factor value and a positive value represent an increase. If the reference point is 1, k factor is a multiplier in front of a number. The direction of improvement can vary between k factors (i.e., some are beneficial if they are smaller, some are beneficial if they are larger).

A technology combination matrix must be created in JMP by the teams to evaluate the impact of the technologies via the RSEs. The first set of columns will represent technologies, the next set will represent the k factors of technology combinations, finally the last set will be the metrics calculated via the RSEs. As an example, the metric values obtained for an aircraft with two arbitrary technologies $T_X$ and $T_Y$ is depicted in Equation 2. A unique k vector is associated with each technology—here $\overrightarrow{k_X}$ and $\overrightarrow{k_Y}$—and since the impact of the various technologies is assumed to be additive, an alternative with T3 and T9 is simulated by adding each element of the vector resulting in a new vector $\overrightarrow{k_{X+Y}} = \overrightarrow{k_X} + \overrightarrow{k_Y}$. The new vector is then fed into the RSEs and the metrics calculated. This is performed for every compatible combination and every metric.

$$\overrightarrow{k_{X+Y}} = \overrightarrow{k_X} + \overrightarrow{k_Y} = \begin{Bmatrix} A\% \\ B\% \\ C\% \\ D\% \\ E\% \\ F\% \\ G\% \\ H\% \\ I\% \\ J\% \\ K\% \\ L\% \\ M\% \\ N\% \\ O\% \\ P\% \\ Q\% \\ R\% \\ S\% \\ T\% \end{Bmatrix} + \begin{Bmatrix} a\% \\ b\% \\ c\% \\ d\% \\ e\% \\ f\% \\ g\% \\ h\% \\ i\% \\ j\% \\ k\% \\ l\% \\ m\% \\ n\% \\ o\% \\ p\% \\ q\% \\ r\% \\ s\% \\ t\% \end{Bmatrix} = \begin{Bmatrix} A+a\% \\ B+b\% \\ C+c\% \\ D+d\% \\ E+e\% \\ F+f\% \\ G+g\% \\ H+h\% \\ I+i\% \\ J+j\% \\ K+k\% \\ L+l\% \\ M+m\% \\ N+n\% \\ O+o\% \\ P+p\% \\ Q+q\% \\ R+r\% \\ S+s\% \\ T+t\% \end{Bmatrix} \tag{2}$$

### 2.7.1 Requirements for Step 7

**Identification of variables** The EDS variables corresponding to the k factors must be listed as well as the actual minimum and maximum of the variable. For example, if the baseline engine weight is 1,000 lbs for a subsonic vehicle, then the actual minimum is 980 lbs (-2%) and the maximum is 1,150 lbs (+15%). The table must be included in the report as well as a data table that is linked from the journal. Also consider adding the scaling variables (T/W and W/S) to the design space. Minimum and maximum range of the scaling variables must be picked based on the design feasibility.

**Explanation of the step** The motivation for generating the k factor surrogate models must be explained briefly in the report. Students can refer to the discussion above and lecture material to write this part. How a technology is represented with a k-vector and how it is rapidly modeled through a surrogate model must be explained.

**Regression diagnostics** The goodness of fit for k factor surrogates must be investigated and reported. This is similar to the design variable surrogate step (Step 4). A table of the MFE and MRE statistics, including max and min percent error, mean and standard deviation of the errors must be included. The report must have the full details, the presentation may include only important/interesting cases for brevity, and the journal must have a link or button to run the analysis from the appropriate data tables and generate the plots on the fly.

**Profiler** A prediction profiler for the metrics as a function of the k factors must be included in the report and journal. The presentation may include only a subset of these plots to highlight interesting cases and support design decisions.

**Monte Carlo** A 10,000 case Monte Carlo simulation must be run using the surrogates. Uniform distributions must be used for each k factor. The cases that concurrently satisfy *all* the constraints must be separated from the rest using filters in JMP. These *good* points must be investigated for repeating k factor values. The mean values for each k factor that results in a feasible design must be calculated and commented on. The gap that exists between the optimized baseline and the feasible vehicle must be calculated. This filtered Monte Carlo exercise must be included in the JMP journal.

**Technology profiler** Technology combinations must be assessed via a profiler plot. The technologies must be on the horizontal axis and the metrics must be on the vertical axis. The technologies are discrete variables (on/off) and the plot must be setup to reflect that characteristic. See Figure 1 for an example. A script that generates this plot must be included in the journal.

**Infusion on a fixed geometry** The reason for evaluating technologies on a fixed geometry must be discussed. Additionally, the extra steps necessary to evaluate technologies and design variables at the same time must be laid out. A reason on why that is impractical must be argued in the report.

**Probabilistic technology impacts** A discussion on how to evaluate the impact of technologies in a probabilistic manner must be included in the report. There are several good answers for this problem but they must not be attempted in this project. A discussion on one idea will suffice.

**Additivity** An explanation of the assumption of *additive technologies* must be provided in the report. A discussion about what else can be done if the assumption is not valid is to be included in the report. An example for a non-additive technology may help.

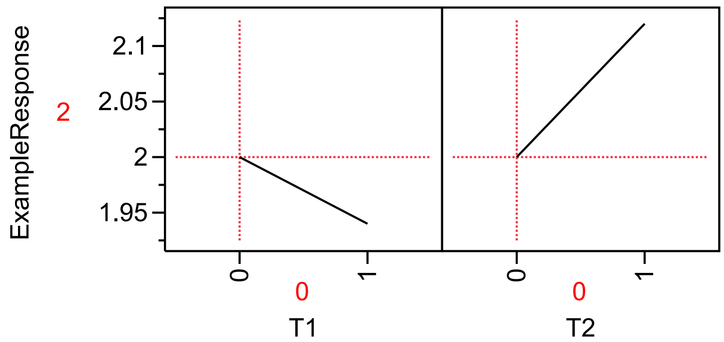


Figure 1: Example profiler plot that links technologies to a metric

**Decision matrix** A *decision matrix* for the compatible combinations must be created. In a decision matrix, the rows are the technology alternatives denoted as $T_x + T_y + T_z$ (e.g., T3+T5+T11) and the columns are the metrics. This is a very large matrix as the number of all possible technology combinations is extremely large and must not be included in the report; however, it must be in the journal as a link to the data table.

## 2.8 Step 8: Select Best Family of Alternatives

In this step the *best* mix of technologies to satisfy the system level metrics is selected. For any multi-attribute, -constraint, or -objective problem, the selection of the best family of alternatives is inherently subjective and no single answer will fulfill all customer requirements. Three approaches are proposed to account for the subjectivity of the problem:

1. Multi-attribute decision-making (MADM) techniques in the form of TOPSIS
2. Technology space constellations
3. Technology sensitivities: one-to-one technology comparison

Teams should refer to Reference 4 for a detailed description of how to do this part of the project. A spreadsheet that implements TOPSIS will be provided to the teams as a project resource on the class website. This spreadsheet must be modified to fit the specific needs of each team. The final spreadsheet must be able to calculate the sensitivities. This step should be completed roughly 2–3 weeks after step 5 is complete.

### 2.8.1 Requirements for Step 8

**Using many methods** A brief explanation of why different decision making approaches are necessary for technology family selection must be included. Each method used must also be described (how it works, what are the steps, etc.). A very brief summary of this discussion must be included in the journal and presentation as well.

**Scenarios** For the TOPSIS step, at least ten different weighting scenarios should be used to select the top 10 technology mixes. An explanation of why scenarios must be used with TOPSIS and how this method helps with robustness must be included in the report. If there are technologies that appear under significant number of scenarios, they must be reported and discussed. It is possible to perform TOPSIS in JMP as well as other environments. If the calculations are done within JMP, a link or a button that can rerun the analysis can be included in the journal. Otherwise, a link to a data table with the results is enough to receive full credit.

**Filtered constellations** A technology constellation by plotting all technology combinations in a Response A vs. Response B plot must be generated. The constellations need to be filtered by the constraints to leave only the feasible alternatives. This process must be repeated until only the combinations that satisfy all constraints are left. A series of plots must be included in the report depicting the filtering process (one response pair is enough). In the JMP journal, the same process must be doable with a number of button clicks.

**Sensitivities** The influence of each individual technology to the baseline metrics obtained from your geometric optimal design must be compared for technology sensitivities (i.e., what percent change from the baseline metrics do the technologies have on the baseline vehicle). A plot for each metric must be included. Figures 5 or 13 in Reference 4 are two examples teams can refer to. Buttons that can generate these plots must be included in the journal.

**Probabilistic sensitivities** A paragraph must be included in the report about whether the results might change if the sensitivities were calculated probabilistically. A notional example can be included to help with the explanation. Creative thinking is desired in this step.

**Select the best set** Based on the three approaches, key technologies and technology combinations that improve the system characteristics in terms of the metrics of interest must be identified. The final selection must be supported thoroughly in the report and presentation but briefly in the journal.

**Missing element** One major element is missing in the selection or identification of the best technology combination. This element must be identified and the report must entail how it can be used in the selection process. Notional examples and plots can help convey the idea. In order to do so, teams must perform economic studies on changes in cash flow diagrams to simulate the addition of new technologies and compare it to their baseline vehicles' cash flows. Questions regarding business aspects must be answered here. The data for performing these studies can be obtained by running the aircraft economics module within EDS called ALCCA.

## 2.9 Step 9: Closing the Loop (Final Step of TIES)

The design of any complex, multi-attribute system is highly subjective, especially in the early phases of the development. Thus, the selection of a single concept alternative is highly dependent on the decision-maker's judgment and relative importance of the evaluation criteria. Because of this, the family of alternative concepts that have been identified through the execution of TIES should be carried through the design process to retain design freedom as long as possible (similar to the cost-knowledge-freedom curves). This process entails a re-investigation of the design space with the various technology alternatives that were deemed as the most significant from the selection step results. Subsequently, Steps 4 and 5 are repeated to determine if a different geometry will further increase the feasibility of the system for the family of technology alternatives. This iteration also deals with the robustness of the final design against the impact of a few noise variables. It is important that TIES is viewed as an iterative process with each go more detail about the design and its performance can be gained.

### 2.9.1 Requirements for Step 9

**The chosen combination** The best technology combination from Step 8 must be identified in a table that provides the technology combination, the combined tech vector values, and the associated system-level metric values. A copy of this table must be linked to the journal as a data table or something similarly appropriate.

**New model** A final case containing the values of design variables and k-factors for the chosen design must be run in EDS. Note that this will be your third model, referred as the "technology-infused" model (the 2nd was the "optimized baseline" model).

**Technology impact study** A table comparing the performance metrics of the technology infused vehicle, the optimized baseline (produced during Step 5), and the original baseline (provided to you by the TAs) must be provided in the report and the journal appropriately. Note that these comparisons must be made with respect to the outputs produced by EDS, not the surrogate models.

**Final design iteration and robustness analysis** As discussed during the lecture, quality is understood in this context as a design that is robust against noise. The goal of this step is to perform a new iteration on the design variables. Now we are in the "technology-infused" design space, and therefore there might be room for improvement with respect to the original design variables. Additionally, this step will include a set of noise and economic variables to study their impacts on the optimal design. Table 4 contains the new variables to be included:

Create a DoE that includes all of the design variables (the same used in Table 2)[2], and the variables in Table 4. Vary the fuel price between 75%–300% of its baseline value.

[2] It is possible that some of your design variables were affected by a technology. In such case, make sure to limit their variability in this study

Table 4: Design and Robustness Variables

| Variable | EDS Name | Baseline | Type |
|---|---|---|---|
| Operational vehicles demanded | NV | 800 | Economic |
| Utilization (hours/year) | U | 5325 | Economic |
| Fuel price ($/gal) | COFL | 1.70 | Noise |
| Engineering labor rate ($/hr) | RE | 89.68 | Noise |
| Tooling labor rate ($/hr) | RT | 54.86 | Noise |
| Airframe learning curve factor (%) | LEARN1 | 82.0 | Noise |

Use a +/- 50% bounds for the two labor rates, and a 60%–100% range for the learning curve. Run this DoE through the EDS environment and create surrogates of its main performance metrics. Observe the impact that noise and economic variables have on the outputs.

**Assessing the feasibility of the advanced concept** A Monte Carlo study must be performed for the technology-infused design space. CDF plots including the targets for each metric must be shown in the report. Additionally, a filtered Monte Carlo study must be performed using scatterplots. The constraints must be applied as filters and the resulting space must be visualized. Discussion on the filtered Monte Carlo results, especially where the feasible design is in relation to the design variable ranges must accompany the figures. The journal must be updated with this last step of the exploration of the technology-infused design space. Each of the substeps must be easily executable with a button click in the journal. Descriptions around the buttons may help users navigate the journal.

**Robustness analysis** Select a combination of parameters that is the most **robust** against noise variables. This is going to be the fourth and final design. Analyze the trends between the performance metrics and variability in the noise variables. Justify your reasoning behind the final design. Make sure to run this final design through the EDS environment to obtain the exact performance metrics.

**Comparing the baseline to the final design** The report must contain a discussion of the differences between the baseline and final design CDFs, particularly referring to how feasible the design is at this point. A few sentences that summarize this discussion are adequate for the journal.

## 2.10 Step 10: Uncertainty and Business Case

In this step, the effect of multiple sources of uncertainty on a system-level metric will be investigated. Some sources of uncertainty contribute more than others to the total uncertainty in system-level metrics. As discussed in the lectures, there are irreducible and reducible uncertainties. Technology development programs aim to reduce specific sources of uncertainty so that the vehicle integrator faces less risk when technologies are transitioned to an aircraft program. Teams will quantify the sensitivities to rank sources of uncertainty and simulate the reduction of uncertainty due to technology maturation.

In addition, teams are to conduct business case analyses of their final aircraft. These will examine the impact of "noise" variables such as fuel cost or labor rates on the system-level economic parameters and determine robust solutions.

#### 2.10.1 Requirements for Step 10

**Robustness to Critical Technology** Select one technology that the team would be willing to recommend as the best option for technology development investments. In justifying this choice, consider the performance, schedule, and budget risk associated with developing this technology. Create a design of experiments for this technology's properties. Identify the robustness of your design to this technology's capability use the range $-25\%$ to $+10\%$ for its performance effects and the range $-10\%$ to $+25\%$ on the nominal values. In this process, teams will need to run ALCCA several times and explore the impact that uncertainty in the technology has on cashflow diagrams, ROI, and RPM. Discuss the results in the report. Link to every JMP data table and script inside the journal with a brief explanation.

**Economic Robustness** Create a Monte Carlo study for the impact of the economic and noise variables shown in Table 4 on the main economic metrics of interest. That is, Acquisition price, DOC, RDTE, and RPM (see Table 1). Use the same surrogates generated in Step 9. The team should consider different aleatory uncertainty scenarios. Use prediction profilers to show the sensitivity of the economic metrics with respect to these variables and include in the report a discussion about these trends.

**Uncertainty reduction** Determine which inputs' uncertainties are the most important to reduce. Reduce the uncertainty of your choice of two of the nominal values and justify why reducing them is beneficial. What kind of activities would be required to reduce these uncertainties? Simulate the reduction by shrinking the input range on these variables. Describe how this affects your sensitivity analyses. Discuss the results in the report. Link to every JMP data table and script inside the journal with a brief explanation.

**Conclusion** A conclusion section must be provided that includes the final design choices and summarizes the team's efforts and findings. A three-view drawing of the final design is required in this section of the report. Final design must also be included in the journal and the presentation appropriately.

# A Aircraft Data

Table 5: Design space definitions for each aircraft

| **Aircraft** | | **WSR** | **TWR** | **AR** | **TR** | **TCA** | **SWEEP** | **ARHT** | **ARVT** | **FPR** | **LPCPR** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Low | 100.0 | 0.33 | 7.50 | 0.26 | 0.100 | 24.0 | 4.00 | 1.000 | 1.55 | – |
| **50pax** | BL | 112.9582 | 0.341202 | 8.289 | 0.2813 | 0.109 | 26.99 | 4.59 | 1.107 | 1.744 | – |
| | High | 120.0 | 0.35 | 9.00 | 0.295 | 0.120 | 29.0 | 5.00 | 1.500 | 1.85 | – |
| | Low | 115.0 | 0.290 | 8.50 | 0.260 | 0.10 | 23.0 | 5.50 | 1.700 | 1.60 | 1.600 |
| **150pax** | BL | 124.1458 | 0.312178 | 9.741 | 0.284 | 0.109 | 25.717 | 6.266 | 1.918 | 1.72 | 1.89 |
| | High | 130.0 | 0.330 | 10.50 | 0.300 | 0.120 | 27.0 | 7.00 | 2.200 | 1.80 | 2.200 |
| | Low | 122.00 | 0.290 | 7.0 | 0.230 | 0.10 | 29.0 | 4.0 | 1.60 | 1.550 | 1.40 |
| **210pax** | BL | 129.0805 | 0.296576 | 8.091 | 0.2458 | 0.1095 | 30.73 | 4.5 | 1.82 | 1.645 | 1.5265 |
| | High | 135.00 | 0.310 | 9.0 | 0.260 | 0.12 | 32.0 | 5.0 | 2.00 | 1.700 | 1.80 |
| | Low | 122.000 | 0.290 | 7.500 | 0.160 | 0.100 | 28.000 | 4.000 | 1.500 | 1.500 | 1.300 |
| **300pax** | BL | 128.7726 | 0.306566 | 8.810 | 0.1759 | 0.109 | 30.940 | 4.620 | 1.840 | 1.548 | 1.420 |
| | High | 135.000 | 0.315 | 9.500 | 0.185 | 0.120 | 34.000 | 5.000 | 2.000 | 1.700 | 1.700 |
| | Low | 137.500 | 0.255 | 7.000 | 0.270 | 0.100 | 36.000 | 3.000 | 1.000 | 1.600 | 1.800 |
| **400pax** | BL | 140.740 | 0.260 | 7.609 | 0.2867 | 0.1095 | 39.700 | 3.600 | 1.260 | 1.710 | 1.982 |
| | High | 142.500 | 0.265 | 8.500 | 0.290 | 0.120 | 44.000 | 5.000 | 1.500 | 1.800 | 2.100 |

Table 6: Constraints for each aircraft

| **Aircraft** | **50 pax** | **150 pax** | **210 pax** | **300 pax** | **400 pax** |
|---|---|---|---|---|---|
| **Wing Span** | <= 82 ft | <= 118 ft | <= 171 ft | <= 214 ft | <= 262 ft |
| **Nacelle Diameter** | <= 70 in | <= 90 in | <= 150 in | <= 175 in | <= 140 in |

# B Schedule

Table 7: Project Deliverables and Milestones

| Part | Canvas Submission |
|---|---|
| Project Release | – |
| Steps 1–3 Write-up | Yes |
| **Step 0: Scouting Presentations** | Yes |
| Step 4: DoE Submission for Approval | Yes |
| Step 4: Obtain Data from Design DOEs | – |
| Steps 4–5 Write-up | Yes |
| Step 7: K-factor DoEs Submission for Approval | Yes |
| Step 7: Finish K-factor DoEs | – |
| Step 8: Steps 6-8 Write-up | Yes |
| Step 9: Final Design DoEs Submission for Approval | Yes |
| Step 9: Finish Final DoEs | – |
| Steps 9 Write-up | Yes |
| **Project Presentations** | Yes |
| **Final Report Submission** | Yes |

Table 8: Condor Schedule for Step 4

| Date | Teams |
|---|---|
| October 6 | 1-4 |
| October 7 | 5-8 |
| October 8 | 9-12 |
| October 9 | 13-16 |
| October 10 | 17-19 |
| October 11 | 20-22 |
| October 12-13 | Extra Dates for Required Reruns |

Table 9: Condor Schedule for Step 7

| Date | Teams |
|---|---|
| October 27 | 1-4 |
| October 28 | 5-8 |
| October 29 | 9-12 |
| October 30 | 13-16 |
| October 31 | 17-19 |
| November 1 | 20-22 |
| November 2-3 | Extra Dates for Required Reruns |

Table 10: Condor Schedule for Step 9

| Date | Teams |
|---|---|
| November 13 | 1-4 |
| November 14 | 5-8 |
| November 15 | 9-12 |
| November 16 | 13-16 |
| November 17 | 17-19 |
| November 18 | 20-22 |
| November 19-20 | Extra Dates for Required Reruns |

As presented in Section 1.5, one of the final deliverable for this project is a complete report that documents each step of the work. The writing of the report is something that should be done throughout the process. The same can be said about the presentation and the development of the JMP journal.

To aid in this process, individual submissions have been created in Canvas, where teams need to submit individual portions of the final report and show that they are making enough progress towards the final result. This submissions do not need to be the final versions. That is, the “Step 1” write up in the final submission might be different from the one submitted for the first write up assignment.

# C Technology Quad Charts

The following figure represents the information contained in a notional technology quad chart document. As seen, quad charts are used as a visual aid to summarize relevant information about a technology as follows:

- Description of the proposed technology and how it works
- Visual aids to represent the expected improvements or the way these can be introduced into the system
- Technology development status, potential impacts, incompatibilities, technology readiness level, and modeling approach
- References and/or relevant points of contact

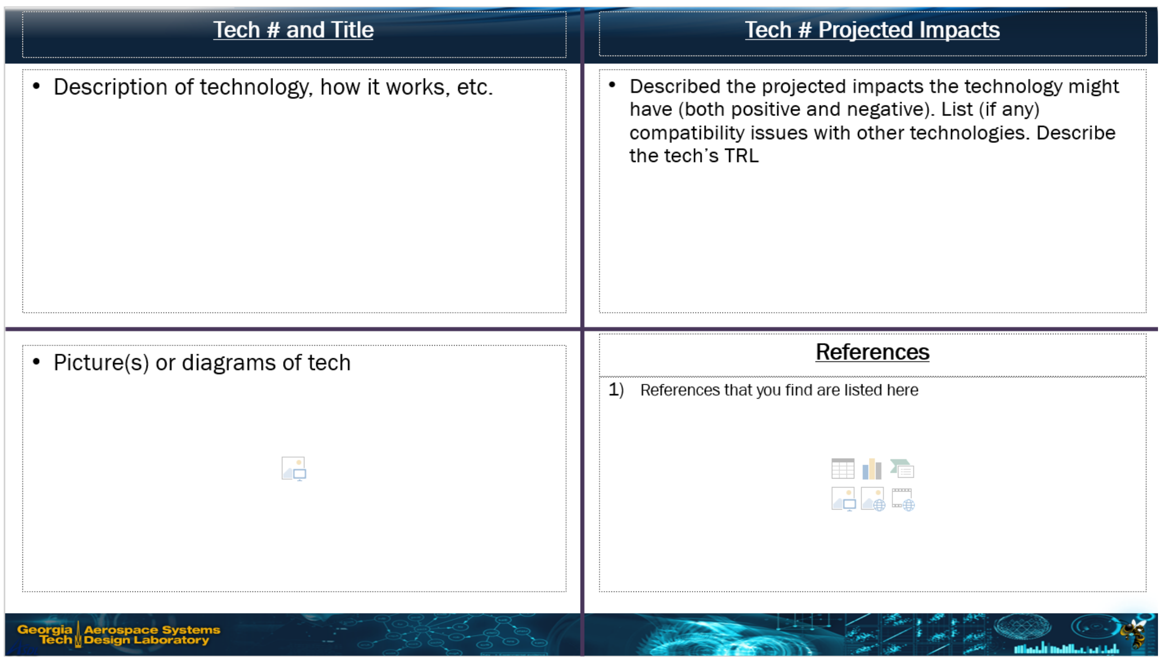


Figure 2: Notional Quad Chart Template