Minimization of Payback Period for a Short-Range Commercial aircraft using Multidisciplinary Design Optimization

Zihao Chen*
University of California: San Diego

Shawn Smith†
University of California: San Diego

Yangjia Peng‡
University of California: San Diego

Stephen Yuan§
University of California: San Diego

I. Nomenclature

$alpha$	=	angle of attack
T	=	thrust
M	=	mach number
W_e	=	empty weight
W_0	=	gross weight
C_D	=	drag coefficient
D	=	drag
L	=	lift
m	=	mass flow
TOC	=	total operation cost
$RDT\&E$	=	research, development, testing, and evaluation cost
A	=	thrust ratio modeling constants
n	=	thrust ratio modeling constants

II. Introduction

Commercial air travel is an ever increasing type of transportation in the modern society. With increasing technology and overall welfare, more and more people choose to join the booming economy of air travel. However, as low cost commercial air travel becomes widely available for everyone, congestion in major commercial airports are a problem. John F Kennedy International and London Heathrow airports are the obvious examples. This problem is further amplified when it comes to densely populated countries such as China and India. As a result, a design of an aircraft that focuses on tackling this problem is necessary. This need calls for a high capacity, high fuel efficiency commercial

*Undergraduate Student in the department of Mechanical Aerospace Engineering.
†Undergraduate Student in the department of Mechanical Aerospace Engineering.
‡Undergraduate Student in the department of Mechanical Aerospace Engineering.
§Undergraduate Student in the department of Mechanical Aerospace Engineering.

transport aircraft design optimized for short range flight, which is the fundamental goal of this project. The primary goal of this aircraft design is to provide a low payback period solution to the increasing air travel demand and congested major airports. Therefore, we aimed to create a reconfigurable design with minimized manufacture and total operation cost while retaining a standard of safety. The Aircraft will also be optimized for a range of 700 Nautical Mile with a max range of 3500 Nautical Miles.

III. Background

The design process for modern commercial aircraft is flexible, and the appropriate objective function for the design focus is not clearly defined. Inspired by the article "Valuation Techniques for Commercial Aircraft Program Design"(Markish, 2002) by Jacob Markish from Massachusetts Institute of Technology, that states in the conclusions that an aircraft shouldn't be designed as a machine that only focuses on sets of cost and performance parameters. It should rather be designed as part of the process that generates values for the firm.

Traditionally, the technical parameters of the aircraft and the parameters related to the program, such as the costs and pricing of the aircraft, are taking care of by two separate groups of people. The result of this segregation is that "closing the loop" for the whole design system leads to uncoupling the technical related design analysis and program-related profitability analysis. Each of these analyses is unusually a sub-optimization at their level of design that is not able to consider all of the design variables simultaneously.

An example given by the article is about one typical objective function in the conceptual design stage, the gross take-off weight of the aircraft. The gross take-off weight in this situation is always used to represent costs, the objective function is usually to minimize the gross take-off weight. However, this methodology can lead to many inaccuracies. Since cost is not perfectly correlated with weight, the idea to treat it as a single parameter problem can cause insufficient consideration of the effects of other program-related parameters such as price and production quantity. As a result, a better focus than minimizing the gross take-off weight, or even minimizing the cost of the aircraft for the aircraft design process is to maximize the value that the aircraft would be able to produce.

In the situation that the methodology of determining the value can be agreed by the stakeholders of the program, such as the manufacturers and airlines, the design trade-offs can be made based on the entire system rather than in a small portion of the design. However, the remaining problem with how to define value is something that needs to be addressed before we are able to compose a design matrix that is for the whole design system level. In the case of commercial aircraft, the major consideration for the stakeholders would be the profitability that the aircraft can perform after it begins its life cycle. An intuitive way to measure the profitability of an aircraft from the airlines' perspective is to analyze the break-even point in the operation of the aircraft. Because the shorter the payback period is, the sooner the aircraft would be able to generate value from the investment. Therefore, motivated by this modified perspective, we are looking for optimizing the profitability of the aircraft by taking care of the design process and the profitability as a whole system to optimize the value that this designed aircraft can bring via minimizing the payback period.

IV. Modeling and Methods

The primary goal of this aircraft design was to provide a low payback period solution to the increasing air travel demand and congested major airports. Therefore, we aimed to create a design with minimized manufacture and total operation cost while retaining a standard of safety. The Aircraft will also be optimized for a range of 700 Nautical Mile with a max range of 3500 Nautical Miles.

To minimize manufacturing cost, the development and procurement cost of aircraft must be optimized. Wing area and maximum velocity are variables that heavily impact the DAPCA (development and procurement cost of aircraft) and hence must be optimized.

To minimize total operation cost, maintenance and fuel burn become primary concerns. Maintenance cost is heavily associated with engine cost and the number of engines while fuel burn is heavily associated with lift to drag ratio as well as the engine type. As a result, angle of attack, wing area, chord length, and altitude will be primary variables to be optimized to minimize fuel burn.

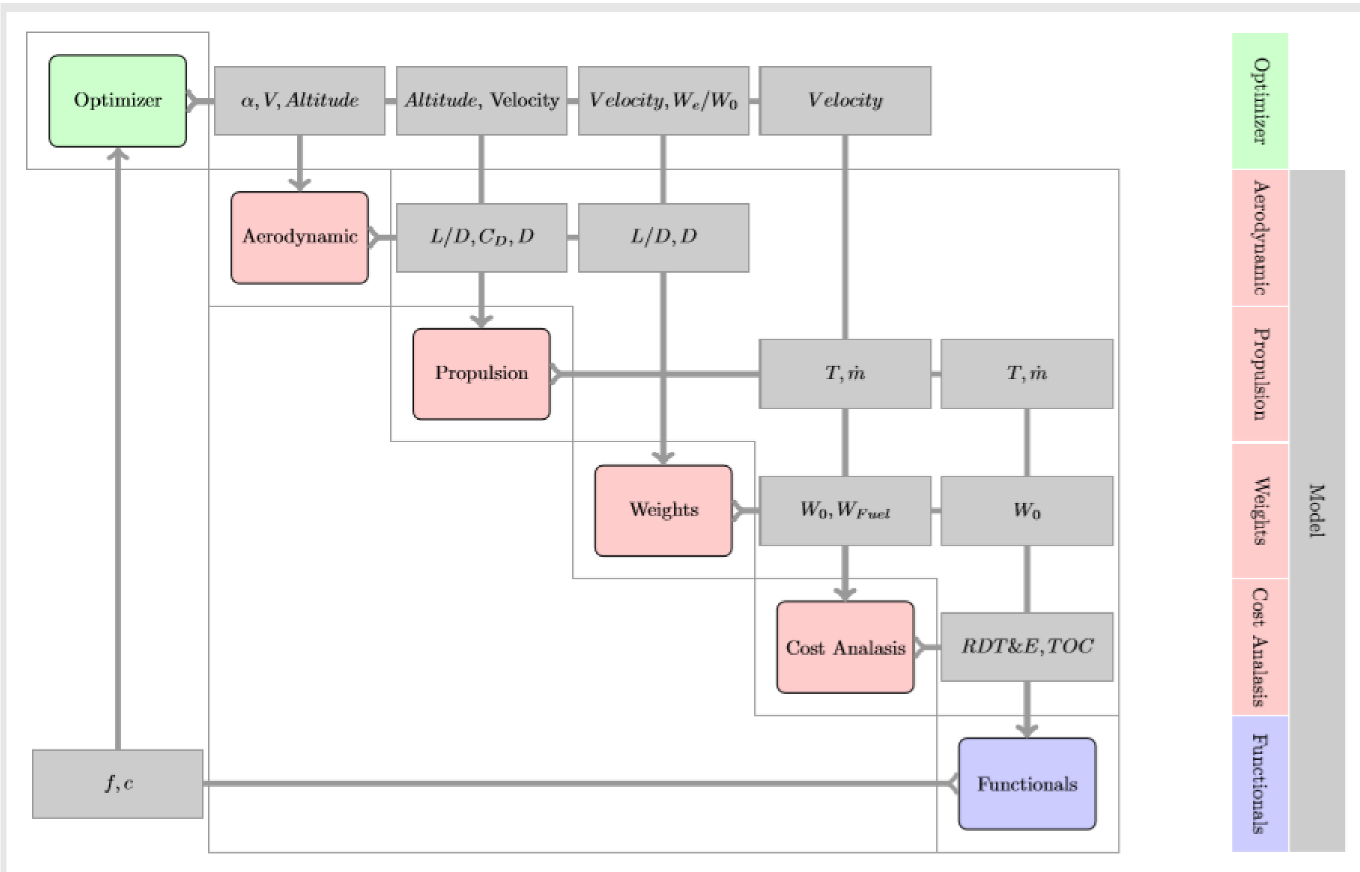

Fig. 1 Design structure matrix (DSM) diagram.

The model that we used includes the lattice vortex method(LVM) and parasite drag build up for aerodynamics and DAPCA model for manufacturing cost analysis. LVM will be valid for our program because it is built on the assumption that the flow is inviscid, incompressible, irrotational. The aircraft of our project is aimed to function at a speed below from which air becomes incompressible. While, LVM often struggles when it comes to computing skin friction drag, it could be supplemented with the implementation of parasite drag build up which sums up the individual drag forces produced at various components of the aircraft This is particularly convenient for our project because we aimed to compute the lift and drag forces for each component of the aircraft, such as wing and tail, independently and use these values to optimize our desired variables, lift to drag coefficient and fuel cost, as described in the software development. DAPCA is relevant because our design aimed to minimize not only the total operating cost, but also manufacturing cost to minimize the payback period. Aside from the aerodynamics and cost analysis, we decided to adapt a turbofan model for the engine and thrust analysis. The turbofan model is chosen because the operation regime of our aircraft is subsonic, below a Mach of 1, specifically between 230 m/s and 350 m/s, a region where turban provides a splendid fuel efficiency. As one of the goal of the our project was to minimize fuel cost, we chose a turbofan model with high bypass ratio, which leads to a model with thrust computed by the following equations:

$$\frac{T}{T_{V=0}} = AM^{-n} \tag{1}$$

Finally, the pressure and temperature and their relative gradients would be obtained from the atmospheric model which assumes temperature to be piecewise linear and pressure to be hydrostatic.

Building off of these ideas, we constructed a hierarchy of OPENMDAO groups and components. The problem will attempt to minimize one variable, that is the payback period of the plane and there will be three major groups: aerodynamics, propulsion, and cost analysis. The group of aerodynamics will consist of three subgroups: the tail, wing, and fuselage. The components will have the global variables of desired lift to drag ratio and various speeds of speeds of the plane, such as the cruising and take off speeds, and the local variables of their relative area as input and return their relative lift coefficients as outputs. The optimization variables are: angle of attack, chord length, total lifting surface area, altitude, velocity, and empty weight fraction as seen in table 1:

Table 1 Optimization problem statement.

	Variable	Description	Quantity
minimize	P	Payback Period	
with respect to	$200m^2 \leq A_W \leq 1000m^2$	Lifting Surface Area	1
	$0^\circ \leq \alpha \leq 7^\circ$	Angle of attack	1
	$4m \leq MAC \leq 12m$	Mean Chord Length	1
	$6km \leq\leq 12km$	Altitude	1
	$200ms \leq V_{max} \leq 300ms$	Cruising velocity	1
	$0.40 \leq W_e f \leq 0.60$	Empty Weight Fraction	1
		Total design variables	6
subject to	$L - W = 0$	Vertical equilibrium	1
	$C_L \leq 1.$	Coefficient of Lift	1
	$V_{stall} \leq 75ms$	Stall Speed	1
		Total constraints	3

A. Aerodynamic Modeling

The modeling first starts off by estimating the geometry, location, aspect ratio of both wing and tail through constants, total lifting surface area, etc. It then dives deep into calculating and estimating both lift coefficients and drag coefficients for the three main parts of the aircraft: wing, tail, and fuselage, resulting in three sub groups.

1. Wing Group Modeling

With the final goal of calculating lift coefficient and drag coefficient wing group modeling computed through 10 components: area computation, cos sweep computation, lift, induced drag, Skin friction, form factor, interference factor, parasite drag coefficient, critical mach number, and wave drag coefficient.

The modeling starts with estimating the wing area and sweep using inputs such as reference lifting surface area, etc.

It then computes the lift coefficient of the wing through modified lift curve slope (which is calculated from lift curve slope), angle of attack, and incidence angle.

Drag is also needed for modeling the propulsion. Wing drag coefficient calculation is split into four parts: induced drag, skin friction drag, wave drag, and parasitic drag coefficients. By using lift coefficient, aspect ratio, and Oswald efficiency calculated with estimated sweep and aspect ratio, induced drag coefficient was calculated Skin friction drag coefficient (viscous drag coefficient) was also modeled through first estimating the reynold's number as well as its cut off value, and then estimating the viscous coefficient for laminar and turbulent flow scenarios based on the estimated reynold's number. By summing the skin friction coefficient from laminar flow and turbulent flow, the viscous drag coefficient is calculated.

After the form Factor computation was estimated using mach number and sweep, parasite drag coefficient was computed with skin friction coeff, form factor, interference factor, estimated wetted area, and total lifting surface reference area. To estimate the wave drag, a critical mach number is needed to correctly model wave drag coefficient. After all, wave drag is heavily dependent on whether the incoming air near the lifting surface exceeds the speed of sound. Critical Mach Number computation was computed with sweep and lift coefficient while wave Drag Coefficient computation was computed using both cruising mach number, and critical mach number.

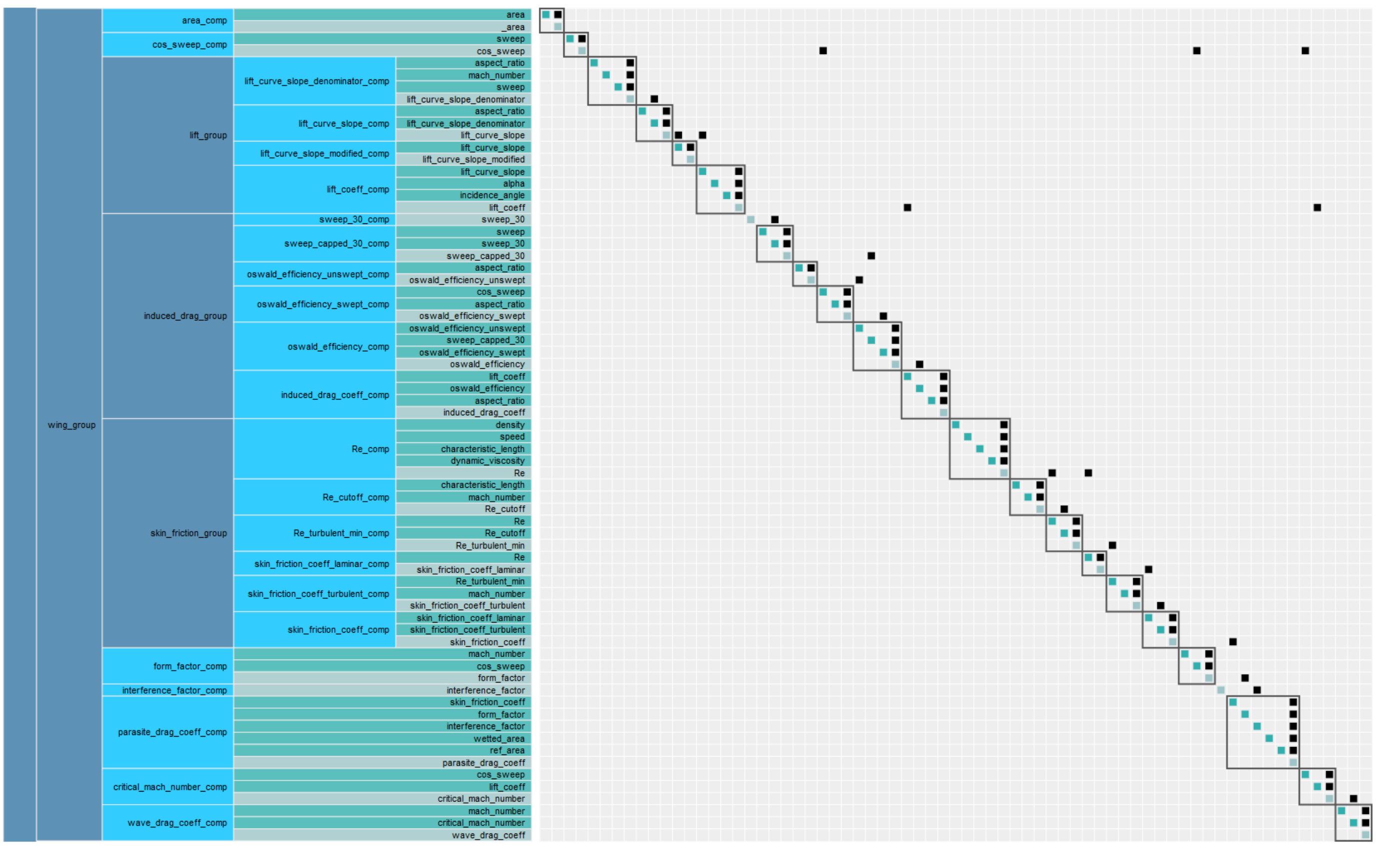

Fig. 2 Wing n2 diagram

2. Tail Group Modeling

Modeling the tail group also follows a similar process as modeling the wing group. With geometry inputs first determining its aspect ratio, etc. The tail group first estimates the lifting coefficient, then induced drag, viscous drag, parasitic drag, and wave drag coefficient using lift coefficient, reynold's number, mach number, critical mach number, total lifting surface reference area and estimated wetted area.

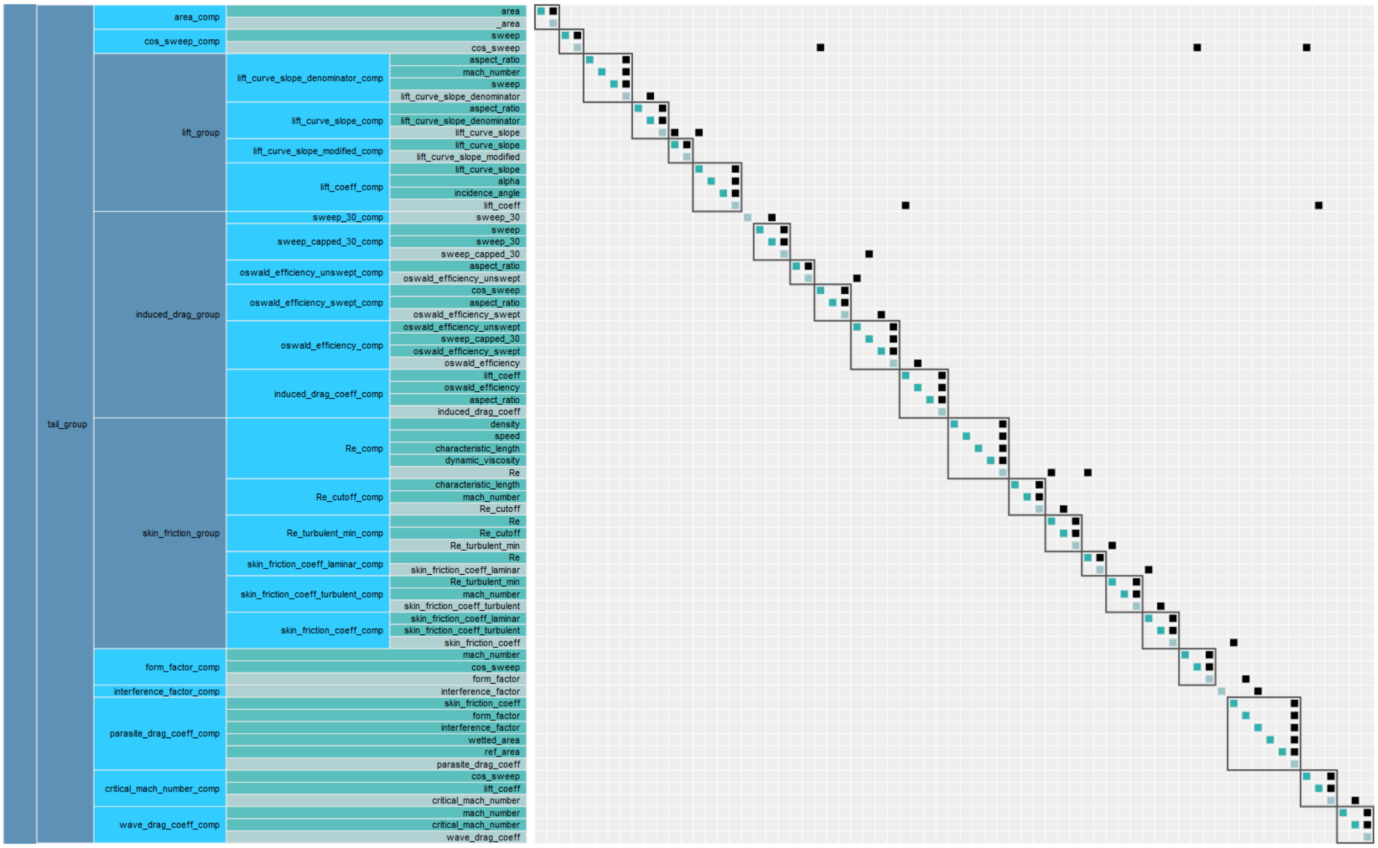

Fig. 3 Tail n2 diagram

3. Fuselage Group Modeling

Because the fuselage does not provide any lift, while the fuselage group follows very similar procedure as tail and wing group, no lift coefficient was calculated for this group and is assumed to be zero for the group when calculating drag coefficients for the fuselage.

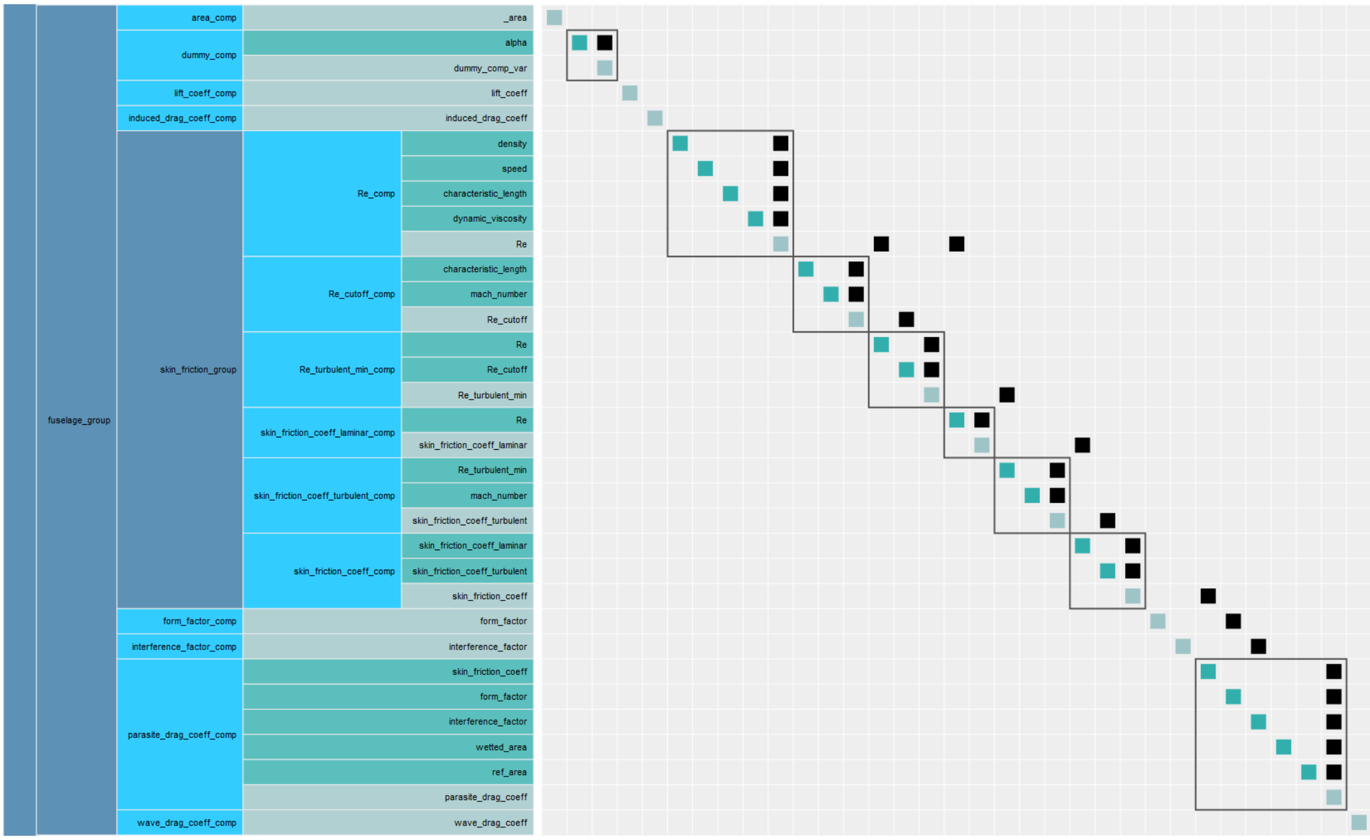

Fig. 4 Fuselage n2 diagram

4. Final Aerodynamic modeling

By using the lift and drag coefficient of all of the parts above, in addition to the total surface area of each part (wetted area, etc) the final lift and drag coefficient is calculated, which is then used along with speed and air density to calculate the final total lift and drag forces.

B. Propulsion Modeling

Propulsion was modeled through 6 components: mach number, zero speed thrust, thrust ratio, available thrust, throttled thrust, and mass flow. Zero speed Thrust was computed using max thrust attained from engine data, as well as air density. While zero speed thrust accounts for the loss of thrust with the decrease of air density (caused by increased altitude), the thrust does not take into account the loss of thrust as velocity increases. As a result, the thrust ratio is needed to estimate the loss of thrust as velocity changes. To estimate the thrust ratio, mach number is computed. Thrust ratio was then estimated using mach number and two imperial constants: A and n through the following equation 1. Final available thrust was then computed through thrust ratio and zero speed thrust, which takes into account not only loss of thrust due to altitude, but also loss of thrust due to velocity. To ensure leveled flight with constant speed, final total thrust must be equal to drag. This is where throttle is needed. By calculating the ratio of drag over available thrust, the ratio for throttle can be calculated. Final throttled thrust was then computed by multiplying throttle with available thrust, and mass flow can be estimated through specific fuel consumption (constant provided by the engine) and final throttled thrust. Many of these variables calculated are not only the inputs to the final cost and weight models, but also serve as constraints (such as drag = throttled thrust) to ensure that the model does not exceed reasonable values during the optimization process.

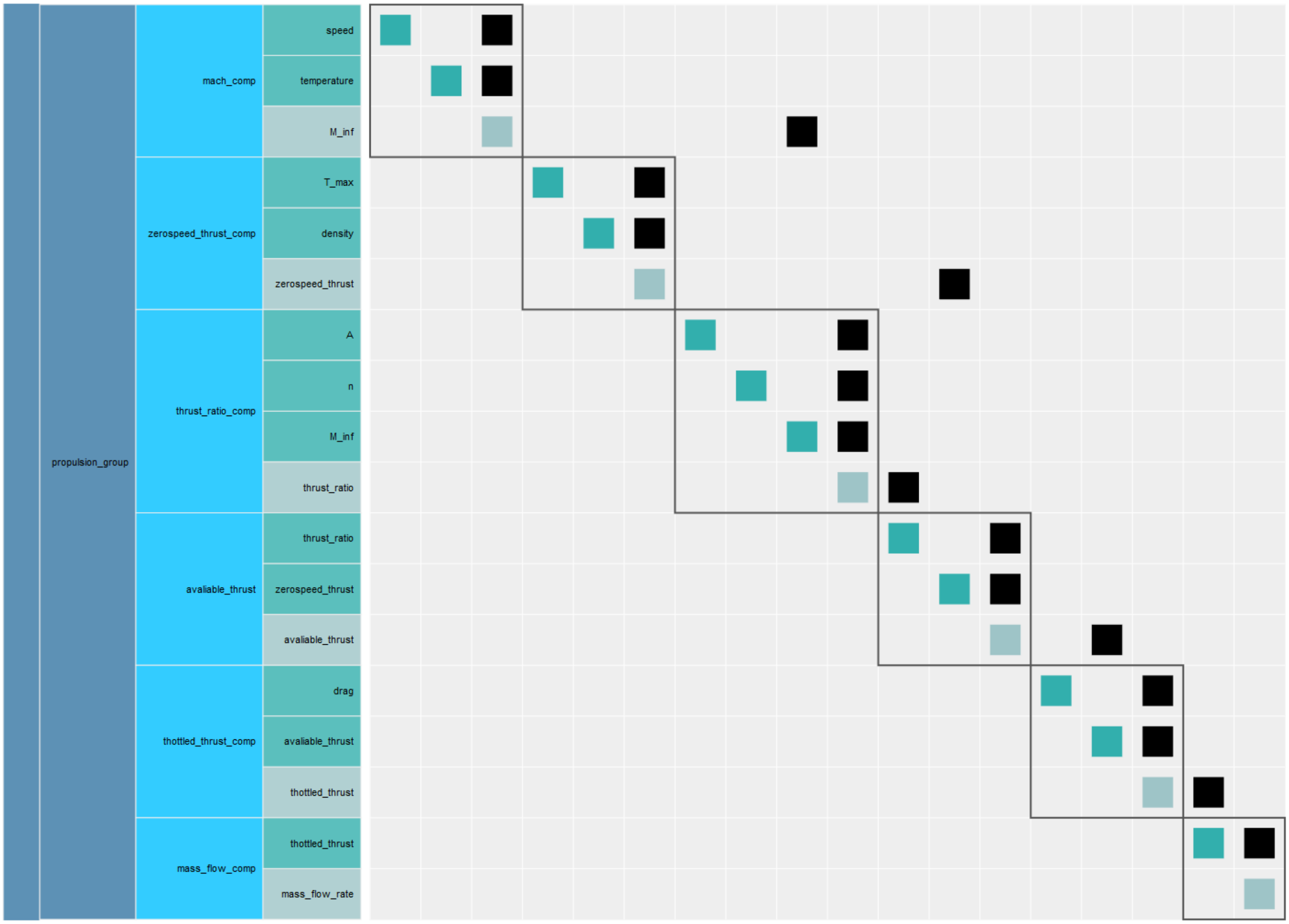

Fig. 5 Propulsion n2 diagram

C. Weights Modeling

Weight ratio was then modeled through 3 components that calculates fuel weight ratio, gross weight, and empty weight. Using range, specific fuel consumption, lift to drag ratio, and speed provided by both constants and the aerodynamic group, fuel weight ratio was estimated .By using the estimated payload weight, crew weight, in addition to the empty weight ratio and previously calculated fuel weight ratio, gross weight and empty weight was then estimated. All of these values will be critical to cost analysis modeling, which is based on DAPCA

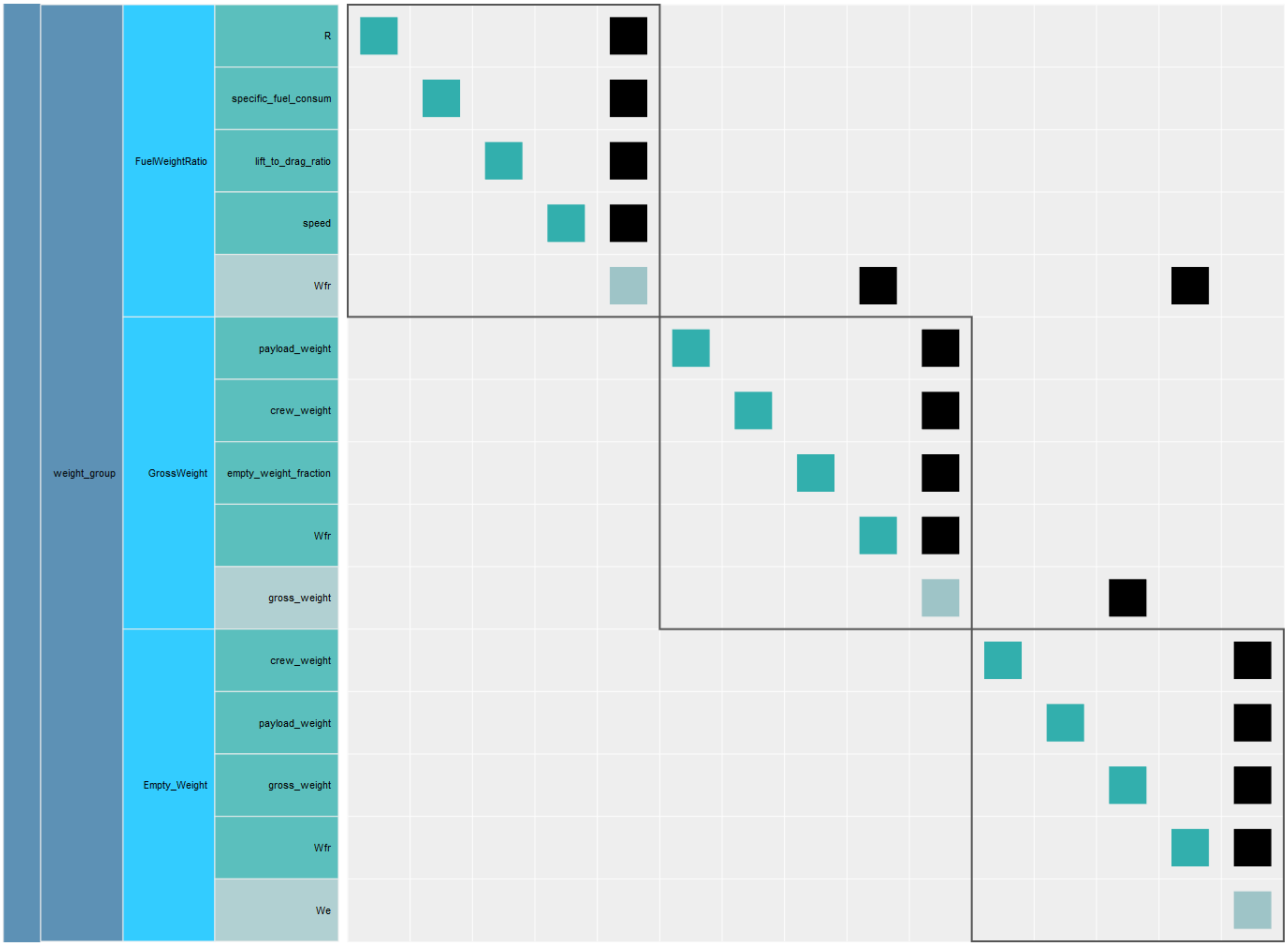

Fig. 6 Weight n2 diagram

D. Cost Analysis Modeling

The model we used for cost analysis is mainly based on the DAPCA (Development and procurement costs of aircraft) model*. More specifically, the cost group of the model we built mainly contained five components, RDTE costs, Flyaway costs, Fuel costs, Maintenance costs, and Payback Period analysis. With RDTE costs and Flyaway costs obtained via the implementation of DAPCA modal, we would be able to determine the listing price of the aircraft that satisfies general production and profit requirements from the manufacturer's perspective. From the airline's perspective, in order to minimize the payback period, the two major components of the total operational costs that are in close relationship with the aircraft design are Fuel costs and Maintenance costs, and other costs such as crew salaries, depreciation, and insurance are going to be included only in the payback period analysis via coefficients from historical data.

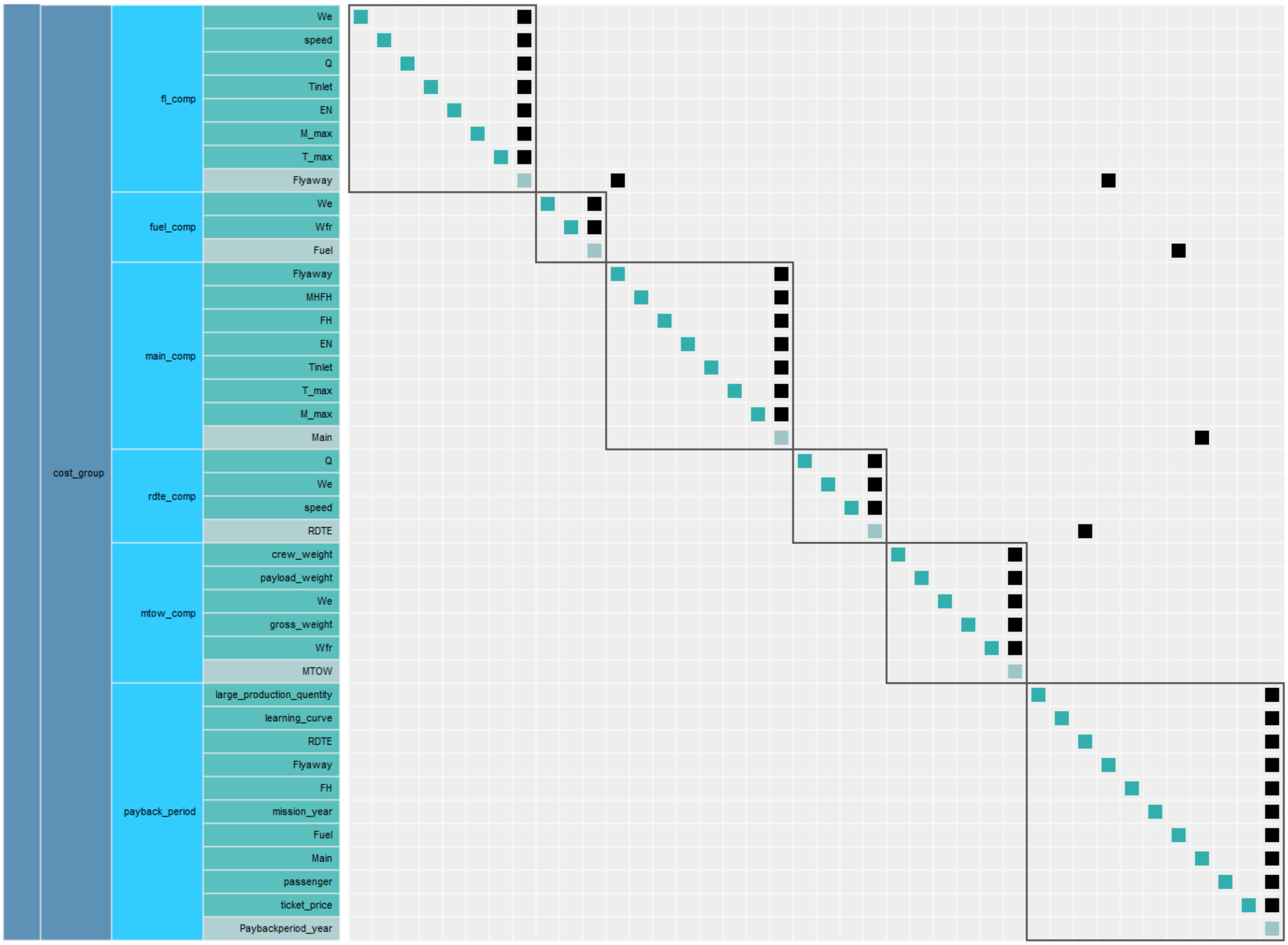

Fig. 7 Cost n2 diagram

1. RDTE Costs

The first component is for rdte computation representing the RDTE (Research, development, testing, and evaluation) costs of the aircraft. This set of costs includes the following elements:

- Flight test costs:

$$CF = 2498We^{0.325}V^{0.282}FTA^{1.21} \tag{2}$$

- Development support costs:

$$CD = 91.3We^{0.630}V^{1.3} \tag{3}$$

- Engineering costs:

$$He = 4.86We^{0.777}V^{0.894}Q^{0.163} \tag{4}$$

- Tooling costs:

$$Ht = 5.99We^{0.777}V^{0.696}Q^{0.263} \tag{5}$$

These four elements are merged into one equation that takes care of the total RDTE costs analysis with We and V as design variables for partial derivatives and the rest of the inputs for the equations as constants.

2. Flyaway Costs

The second component is flyaway representing the flyaway cost (cost of producing one aircraft). This set of costs includes the following elements:

Manufacturing costs:

$$Hm = 7.37We^{0.82}V0.484Q^{0.641} \tag{6}$$

Quality control costs:

$$Hq = 0.133Hm \tag{7}$$

Engine production costs

$$Ceng = 31120.043Tmax\ 243.25Mmax\ 0.969TturbineInlet - 2228 \tag{8}$$

Manufacturing material costs

$$CM = 22.1We^{0.921}V0.621Q^{0.799} \tag{9}$$

These four elements are merged into one equation that takes care of the total RDTE costs analysis with We and V as design variables for partial derivatives and the rest of the inputs for the equations as constants.

3. Fuel Costs

One of the components for analyzing the operational cost is fuel costs. Fuel costs are simply calculated incorporating the fuel weight fraction obtained from the Breguet range equation and associated with the per-gallon price of the fuel to get the final fuel costs. The design variables implemented in this component are W0 and Wfr fuel weight fraction.

4. Maintenance Costs

The maintenance costs component consists of both maintenance labor costs and maintenance material costs. The equations for these elements are:

Maintenance labor

$$MMH = \frac{MMH}{FH} * FH \tag{10}$$

Material cost

$$MC = 3.3\frac{Ca}{10^6}\ 14.2\ 58\frac{Ceng}{10^6} - 26.1Neng * FH \tag{11}$$

5. Payback Period

Finally, the payback period component gathers all outputs from the previous analysis to estimate the years needed for the airline to break even with predetermined flight hours and ticket prices. When determining the price of the aircraft, the learning curve effect is taken into account. With the expected 15 percent revenue from the manufacturer's perspective, the final price of the aircraft is therefore determined and ready to be applied to the analysis of the payback period. The fixed direct operational costs of the aircraft include depreciation and insurance. The insurance is 1 percent of the direct operational cost. If the resale value is 10 percent of the purchase price and the depreciation period is 20 years:

$$Depreciation_{yearly} = Airframe * Cost * \frac{0.9}{20} \tag{12}$$

The variable direct operational costs include maintenance costs, fuel costs, and crew costs. Since the flight hours and missions per year of the operating route are predetermined, together with the previous components regarding the operational costs, the break-even units formula is simply:

$$PaybackPeriod = \frac{0.9 * AircraftPrice}{(TicketRevenue - TOC)} \tag{13}$$

Where the total operational cost TOC consists of direct operational cost DOC and indirect operational cost IOC that is determined as of the DOC from historical data of commercial airline operations.

6. Final Cost Summary

All in all, with the intention of providing a low investment solution to remediate the increasing air travel demand, we seek to minimize the payback period by minimizing manufacturing cost and total operation cost. As a result, wing area, angle of attack, chord length, maximum velocity, altitude, empty weight fraction are primary variables for optimization design structure.

E. Overall N2 Diagram

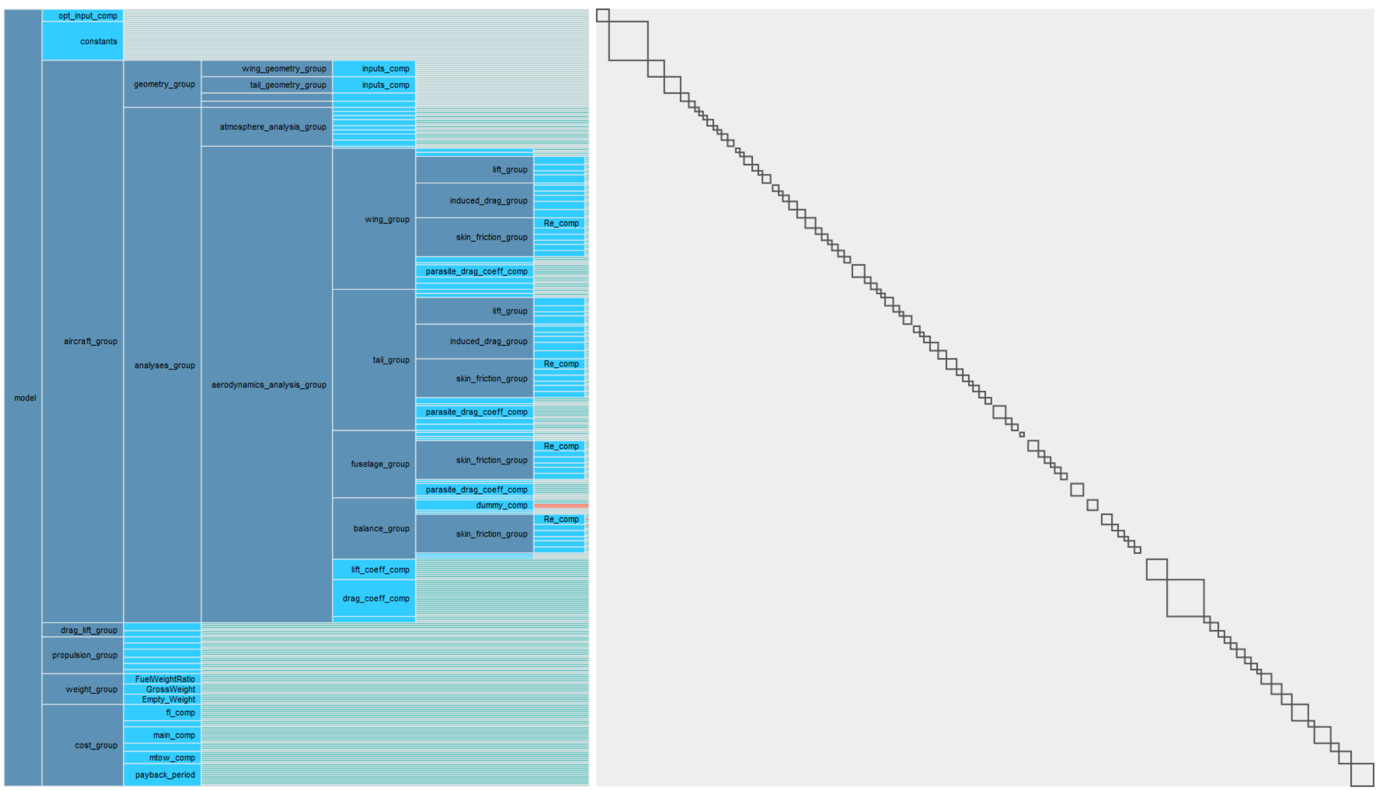

Fig. 8 n2 Diagram for over code

V. Results

After thorough consideration, it was decided to use General Electric CF6-80E1 for engine model and NACA 747A415 for the airfoil design. Using the optimization with our input values for the aircraft, it was able to calculate the gross weight as 274,042 lbs, empty weight as 137,522 lbs, and maximum takeoff weight as 275,021 lbs. These values were used to calculate the flyaway, RDTE, and fuel cost resulting in costs of \$30,070,991, \$3,793,237,470, and \$51,864, respectively. The flyaway cost was used to calculate the maintenance cost, resulting in a cost of $2,592,000. Using the overall aircraft price, the payback period was able to be calculated as 4.4 years. Evaluating the results, we were satisfied with the payback year being the value that it was. However, we noticed the large cost in the RDTE which brought confusion. Noticing that, it was concluded that the results were not entirely what we had expected.

Parameter	Value
Gross Weight	275,042 lbs
Empty Weight	137,522 lbs
Maximum Takeoff Weight	275,021 lbs
Flyaway Cost	$30,070,991
RDT&E Cost	$3,793,237,470
Maintenance Cost	$2,592,000
Fuel Cost	$51,864
Payback Period Year	4.4

Fig. 9 Final Optimizied Results

VI. Conclusion

Our initial goal of the project we decided to take on was to create a high capacity, short-range, and easily reconfigurable conventional aircraft that would remedy the ongoing problem of air traffic and airport congestion. Taking on this challenge, the team decided to put a heavy focus on minimizing the payback period of the aircraft while maximizing the lift-to-drag ratio. The approach the team decided to take in order to achieve this goal is by designing a code that is able to optimize the cost of the plane based off of a desired lift-to-drag coefficient. With our goal and approach set, we created a design structure matrix to assist in the progression of our code and give us an understanding on how the different components of the code would connect with one another. The model consisted of four groups that are interconnected with one another: structural, aerodynamic, propulsion, and cost analysis. The values calculated from these four groups would be inputted back into the code further optimizing the process.

Using the parameters chosen to input to the code, the group was able to get a resultant gross weight of 275,042 lbs with an empty weight of 137,522 lbs and maximum takeoff weight of 275,021 lbs. In regards to the cost analysis, the resultant values for the cost group gave a flyaway cost of $30,070,991, RDTE cost of $3,793,237,470, maintenance cost of $2,592,000, fuel cost of $51,864, and a payback period of 4.4 years. These values raised concerns for the group since they did not make sense considering the value of the RDTE was substantially large. With this being said, it raised concerns with the structuring of the formulas used within the code and how they connected with one another.

From a financial point of view, the code the group produced would provide a perspective on creating an aircraft that would be able to reach a break-even point in a short period of time. The cost of a commercial aircraft is a significant amount which limits the capabilities of airlines when it comes to combating the issue of congestion in both the air and on ground. Since a majority of flights across the globe were less than 3500 Nautical Miles in distance, most international aircrafts were not used to their utmost potential since they were designed for a maximum range of 7000 Nautical Miles. Smaller aircrafts would not be an optimal solution considering they carry roughly 200 passengers while larger aircrafts carry around 400 passengers. With the development of the code, there would be an insight on how to deal with this issue. Not only would high capacity and short-range aircrafts help alleviate the problem through reduction in congestion and increase in passenger capacity, they would also be produced while keeping the payback period to a minimum.

There are definitely improvements that can be made in the code that the group has developed. Major obstacles became apparent while developing the optimization code. The most noticeable obstacle was the inability to optimize the payback period correctly. The structuring of the code caused an issue where the optimization would not complete in a way that would satisfy the goal of the project. The best improvement that could be made to the code would be having each of its components connect to one another more sufficiently. A way to do this would be to ensure that all the formulas used were able to connect to one another more appropriately. There were times where variables in the overall code were misnamed and did not match one another which resulted in errors when the code was ran. Overall, an improvement to the method used in creating the structuring of the code was needed. Being on the same page when it came to using variables and which metric system the formulas used were important to the code and having a more thorough discussion on this matter would have been beneficial for its advancement.

VII. Statement of Contribution

1. Zihao Chen

Zihao was mainly responsible for modeling the propulsion and aerodynamic portion of the codes in addition to creating the final run file that links up all the groups and components in addition to debugging all the components and assisting with implementing the optimization progress. Zihao was also responsible for creating and updating design flowchart and optimization problem statement. Moreover, Zihao wrote the modeling portion of the paper (cost modeling portion excluded) in addition to editing the final latex research document with Shawn.

2. Shawn Smith

Shawn created the GitHub repository the team used to collaborate and upload files to. He would be the one to merge files when pull requests were made and assist in the bug fixing process when there were errors pointed out by the continuous integration tool that was connected to the repository. He would produce the n2 diagrams for the group and assist in finding solutions to unconnected variables found through the diagram. He also assisted in the creation of the structure, weight, and geometry components as well as grouping them. Lastly, he helped with the implementation of the optimization portion of the code and the creation of the LaTex files.

3. Yangjia Peng

Yangjia was primarily in charge of developing the cost analysis module for the optimization code. The cost analysis group includes components such as RDTE costs, flyaway costs, fuel costs, maintenance costs, and payback period analysis. He also created the design structure matrix as an intuitive guideline for optimization code development and establishing the connection between different parts of the models for optimization. Finally, he also took part in debugging the code, background research from existing papers, and writing cost modeling in the model section.

4. Stephen Yuan

Stephen created the initial design flow chart structure for the project. He also worked on some components and group for weight modeling. In addition, he contributed by writing the introduction.

References

1. "The GEnx Commercial Aircraft Engine". Retrieved 18 February 2020.