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An Aircraft Design Project for the High School Level*

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An aircraft design project has proven to be very popular with both students and teachers and an effective tool for generating interest in science education in general and design in particular at both the high school and junior high school level. The project is a very abbreviated yet technically correct preliminary design of a business jet. It is presented to the students as a nine-page booklet containing a set of four worksheets, followed by a menu-driven, user-friendly BASIC computer program which checks the calculations and draws a top view of the aircraft. If the students so desire, and they always do, the program rapidly iterates modifications of the calculations to provide a rudimentary introduction to design optimization employing computer-aided design.

INTRODUCTION

A DESIGN project can have several beneficial effects on pre-college students and their teachers. The two which were the primary reasons for developing the business jet design project described in this paper were aimed at opposite ends of the academic performance spectrum. The original goal was to demonstrate to low performance level junior high school students that science and mathematics can actually be used to do interesting and fun things. The second was to give high school students with good academic performance a taste of engineering at work in order to provide them with career choice guidance. Both of these effects were found achievable to a very satisfying level as long as the project level of sophistication is well thought out and carefully delivered at the appropriate pace.

The project was so well received that it was subsequently presented at teacher training workshops. There it had a third effect which was not expected in advance. It was not clear, at least not to the author, that many elementary level teachers have had minimal exposure to math and science and are easily intimidated by serious discussions of either. Mixed groups of elementary and secondary teachers have been led through this design project on several occasions in three different parts of the state. The sense of accomplishment voiced frequently by elementary teachers seems sure to have a favorable impact on all their future students, who need to have their teachers give them the attitude that science and technology are manageable parts of everyday life.

A bit more specifically, the project was originally created in 1990 by the author at the request of the local Volusia County school system. The initial objective was to motivate 'at risk' junior high school students, those who were performing poorly in spite of high scores on IQ and similar tests. A week-long summer science camp program was set up on the Embry-Riddle campus which included the design project integrated into a broad introduction to aviation. Students who were not at risk responded vigorously to announcements of the program, so more sessions were added. The project was sufficiently popular that a slightly more sophisticated project was created for two FAA-sponsored high school Aviation Career Education programs later in the summer. By January, 1994, the project has been delivered 16 times by the author, about evenly split between students and science/aerospace education teachers. And it has been presented at least nine times by other colleagues at ERAU. It has always proven to be a great success. Students at all levels show a high level of interest and enthusiasm, and very apparent pride of ownership in the finished product. Feedback from their teachers and parents has been frequent and highly complimentary. The second time the program was offered it was featured on the evening news by a major Orlando television station, which students and public relations offices were all very pleased about.

PROJECT DETAILS

A general introduction describes briefly why design is important and how it relates to the overall world of scientific careers. This description is tied in with the formal definition of the scientific method, adapted by the instructor to whatever terms are appropriate to the grade level of the project participants. Then the four primary forces acting on an aircraft in level flight are introduced: lift in equilibrium with weight, and

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drag in equilibrium with thrust. Presented pictorially these forces provide such a clear rationale for the calculations which must be done to complete the design of an aircraft that there are never questions about how to proceed. The worksheets are organized to follow the order of determination of those forces.

Worksheets

Each of the four worksheets is a fill-in-the-blanks format. As mentioned above, two slightly different versions have now been developed and used: the original one for students at the junior high school level and a minimally more complex one for high school students. Students are issued calculators and work in pairs. Each worksheet takes 45 minutes to an hour, with the instructor talking the class through the process using overhead projector slides. It should be noted that this time period taxes the limits of the attention span of junior high students and considerable effort must be expended toward making the presentation entertaining.

The first worksheet estimates the weight of the aircraft. It is shown in reduced form in Fig. 1. The primary variables are number of people on board, baggage allowance for each person, and range of the aircraft. The meaning of each variable is discussed with the students along with some typical reasons for choosing a particular value for each.

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                                  Name____________________________

WORKSHEET 1 - WEIGHT ESTIMATE

     The first step in the design process is defining the
mission of the airplane.

     N=number of passengers plus crew.  For a business jet the
crew is usually 2 (pilot and co-pilot) and 4 to 8 passengers
are carried.

     N=__________

BAG=weight of luggage each person can bring on board.  It is
usually at least 30 lbs. and could be as high as 100.

     BAG=_________ lbs.

     WPEOPLE=weight of people on board, each assumed to weigh
170 lbs.

     WPEOPLE=N*170=__________*170=_________ lbs.

     WBAG=total baggage weight

     WBAG=N*BAG=__________*__________=__________ lbs.

     WPAYLOAD=WPEOPLE+WBAG=__________+__________=_________ lbs

     Total weight of the airplane depends on the weight of fuel
in its tanks (the tanks are much larger than those in cars).
The fuel weight depends on how far the airplane flies, called
range.  Choose a range by looking at the attached map to see
where you might want to go.  1500 miles is a typical range, but
you are the designer, so pick what you want.

     WMAX=total weight of the airplane=WPAYLOAD+WFUEL+WEMPTY

     WEMPTY=weight of the airplane without fuel or payload on
board.  It is a factor, EWF, times total weight.
     EWF=.50 is typical for this type of aircraft, so
     WEMPTY=EWF*WMAX=.50*WMAX

     WFUEL=fuel fraction*WMAX=FF*WMAX
Typical values are: FF=.333 for 750 mile range
                    FF=.375 for 1500 mile range
                    FF=.40  for 2250 mile range
     FF=________

     Algebraically rearranging the equation for WMAX we get

     WMAX=WPAYLOAD/(1-EWF-FF)=WPAYLOAD/(.50-FF)

     WMAX=_________/(.50-________)=__________lbs.

  Great work! Now you know that your jet weighs __________ lbs.
```

Fig. 1. High School Worksheet No. 1.

The page in the booklet which precedes this worksheet is a map of the Northern Hemisphere with range circles drawn centered on Daytona Beach, Florida, home base for most of the presentations. Discussions usually center on vacation ideas, visits to far flung relatives, parent's business travels, or reporters in a hurry to get to places currently in the news.

It is here that teachers doing the project are reminded that interdisciplinary side projects would fit in neatly, particularly if a larger-scale map were used. Geography and social studies topics are natural extensions of the choice of range: things like climate, food, currency, language, local customs and other cultural differences at potential landing sites.

In the junior high version gross weight is simply a range-dependent factor times the payload weight. In the high school version range is related to fuel weight fraction and students are coached on selecting an empty weight fraction, which are then used to calculate gross weight.

The second worksheet calculates size and geometry of wing (the main lift producer), tails, and fuselage. Figure 2 is a replica of Worksheet 2. This is a little more complex and is sometimes done in two sittings if the attention of the students is wearing thin. Junior high students are asked to select a landing speed based upon the size of the airports they picture their jet using. And they are asked to pick an aspect ratio and sweep angle after a discussion of how these factors relate to speed and range. A page with three typical aspect ratio wings drawn to scale is included to help the class make this choice. A typical maximum lift coefficient and taper ratio are assumed without discussion and the wing area and dimensions are calculated. The high school students are told about force coefficients and are asked to select a maximum lift coefficient based on what type of flaps they are willing to commit to. They then calculate wing geometry using the form of equations more familiar to aeronautical engineers.

Horizontal tail and vertical tail are briefly described as other lifting surfaces similar to the wing except with smaller aspect ratios, and calculations are continued with a minimum of discussion.

The third worksheet, shown reduced in Fig. 3, estimates drag and selects an appropriate engine (the thrust producer). Students are asked what speed they want to cruise at, after being warned not to get too close to the speed of sound. A cruise altitude of 30,000 feet is assumed without discussion. In the junior high project a drag coefficient is assumed without discussion, but in the high school version the students are asked to select a drag coefficient from a brief table of typical values related to the sophistication of the shape streamlining. Drag is then calculated, corrected to a reasonable approximation of an equivalent sea-level value, and presented to the students with a reminder that drag equals thrust required. With this information they select the lightest engine

Name______________________

WORKSHEET 2 - WING AND TAIL DESIGN

First, you need the total weight of the airplane from Worksheet 1. WMAX=_________ lbs.

The size of the wing, called planform area, depends on how fast the airplane is flying when it lands. The faster it lands the longer the runway must be. But if the landing speed is low to keep the runway requirement short, the planform area will be large and the airplane will need big engines to overcome drag at high speed.

The planform area also depends on lifting ability of the wing, described in the form of maximum lift coefficient, CLMAX. This depends in turn on the complexity of the flaps used. Flaps can vary from a simple downward bending of the trailing edge (similar to ailerons) to very complex downward movement on both the leading and trailing edges.

These choices are among the most important ones in the whole design process. Typical choices are:

VLDG=landing speed=85 MPH for small private airports
100 MPH for medium size airports
120 MPH for large commercial airports
CLMAX=1.8 for the simplest, least expensive flaps
2.0 for slotted flaps, typical on business jets
2.4 for very complex leading and trailing edge flaps

Choose VLDG=_________ MPH
CLMAX=_________

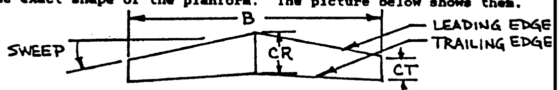
Then you can calculate planform area, S.

S=473*WMAX/(CLMAX*VLDG^2)=473*_______ /(______*________^2)
S=_________ square feet

Now design the shape of the wing planform. The main choice is called aspect ratio, AR. High aspect ratio gives a long skinny wing, while low aspect ratio gives a short stubby one. Which you choose depends partly on what you think looks good---a little of the artist's sense of proportion. Also, fast airplanes have low aspect ratios, like 4 to 6. Slower but longer range airplanes have high aspect ratio, like 7 to 10.

Choose AR=________

Now we can calculate several other variables which define the exact shape of the planform. The picture below shows them.



Span, B=distance from left wing tip to right wing tip.

B=√(AR*S) =√(________*________) =________ ft.

Chord is the distance from the leading edge to the trailing edge. Root chord, CR, is measured at the center of the wing. Tip chord, CT, is measured at the wing tip, and is usually half of the root chord.

CR=1.33*S/B=1.33*________ /________=________ ft.

CT=.5*CR=.5*________=________ ft.

Last, choose the sweep angle, SWEEP. The choice depends on how fast the airplane will cruise. Use SWEEP=10 degrees if the cruise speed is below 400 MPH, and about 30 degrees if the cruise speed is above 400 MPH.

SWEEP=________ degrees

The tails are designed next. Their size and their distance behind the wing determine how easily the pilot is able to fly the airplane and to perform maneuvers. The design calculations are almost like those done for the wing. The tail which sticks straight up is called the vertical tail. The one which extends from side to side is called the horizontal tail. Their size is a fraction of the wing planform area, S. Precise calculation of this information requires knowing the center of gravity position, which is beyond the scope of this project.

Horizontal tail area, SHT=S/4=________ /4=________ sq. ft.

Horizontal tail span, BHT=√(3*SHT) =√(3*________)=________ft.

Root chord, CRHT=1.25*SHT/BHT=1.25*_______ /_______=______

Tip chord, CTHT=.6*CRHT=.6*________=________ ft.

Vertical tail area, SVT=S/6=________ /6=________ sq. ft.

Vertical tail span, BVT=√(1.5*SVT) =√(1.5*_______)=_______ft.

Root chord, CRVT=1.25*SVT/BVT=1.25*_______ /_______=______

Tip chord, CTVT=.5*CRVT=.5*________=________ ft.

SWEEP of the tails is the same as SWEEP for the wing. The leading edge of the tail is behind the trailing edge of the wing by a DISTANCE of 1.5*CR=1.5*________=________ ft.

Now you have enough information to draw the wing and tails. The last data you need is the width of the fuselage. Decide how many seats you want across each row in the passenger compartment. It is usually two across. The fuselage width, WF, is 2.5 feet times the number of seats across each row.

WF=2.5* no. of seats per row=2.5*________=________ ft.

Finally done! This is the longest set of calculations. But you now have all the data you need for WORKSHEET 4, which will guide you through drawing your design.

Fig. 2. High School Worksheet No. 2

which has sufficient thrust from a table of the five currently available engines likely to be found on a business jet. A detailed diagram of a typical small turbofan engine is included in the booklet so that they can interpret the dimensions of their chosen engine, which are provided in the selection table. At this point the calculations are finished, and congratulations are enthusiastically provided.

The fourth worksheet is a step-by-step process for drawing the side and top view of the aircraft. It is admittedly a bit tedious, and has never actually been fully completed in a group session. We actually go through the steps one by one, and I have always done the plotting on an overhead projector slide in order to help the class interpret the instructions. Typically about half way through this is about as much plotting/drafting as a large group can maintain interest in. I do always insist on getting as far as plotting out the leading edge sweep of the wing. The reason for this is to make the point (only after they have done it) that they have just used trigonometry, the tangent function, and it has not left anyone bloody or with a headache. They are surprised by this point and I truly believe that it makes a confidence-boosting impression on them.

The computer program

Completion of the worksheets is followed by a trip to the computer lab to run the design program. This program duplicates the worksheet calculations exactly in order to minimize the time needed to adapt to it. It is menu driven and the menu selections are the same four-step breakdown of the project as the worksheets. Familiarization is usually accomplished by having each student team repeat and check their hand calculations by entering data directly off the worksheets. Then the students are free to investigate other sets of variables to see the influence on their design. It takes only a minute or so to re-enter a new set of variables and see a new picture of the design, providing a very informal but nonetheless effective example of the benefits of computer-aided design.

The top view drawing which the program draws, shown in Fig. 4, is a relatively rudimentary one, but one which actually uses the dimensions just calculated. The scale is fixed so that size comparisons are intuitively apparent. Forward swept wings are allowable. The graphics routine written into the program was intentionally left fairly simple in order to keep the focus on technical observation of the design. A more sophisticated drawing is certainly possible, but the tendency for the student activity to degenerate into a video game is very real and seemed more likely to be a problem if the picture were anything more than a geometry definition plot.

Name________________________________

WORKSHEET 3 - DRAG CALCULATION AND ENGINE SELECTION

The drag of the airplane determines the thrust required from the engines. Drag depends on how fast you fly, going up in proportion to speed squared. It also is proportional to wing planform area, S. It also depends on air density, which goes down as altitude increases---we'll assume flight at 30,000 feet.

Recall S=________ sq. ft., from Worksheet 2.

Choose a cruise speed, in MPH. Do not try to fly faster than about 90% of the speed of sound. The speed of sound is about 680 MPH at the altitudes typically used by bizjets.

Choose cruise speed, VMPH=________ MPH

The other big factor in drag is the drag coefficient, CD. It is the hardest design data to estimate accurately. You can get a rough idea of its value by comparing the design you have in mind to some existing airplanes, in the table below. Keep in mind that a sleek, aerodynamically clean airplane is more expensive to build and does not easily provide room for the payload. This is another one of the really tough decisions in the design process.

supersonic fighter	CD=.015-.018
commercial airliner	CD=.018-.022
business jet	CD=.018-.025
retractable gear lightplane	CD=.022-.028
fixed gear lightplane	CD=.030-.035

Estimated CD=________

Calculate drag, D = CD*(VMPH)^2*S*.000958

D=_______*_______ 2*_______ *.000958 = _______ lbs.

Air at sea level is much heavier than air at high altitude, so we need to multiply drag by 2.5 to get the approximate drag at sea level, DSLS.

DSLS=2.5*D=2.5*_______=_______ lbs.

We need drag at sea level because this is the simplest way to select an engine which is powerful enough. Thrust required from all the engines together is equal to drag. And the engine makers tell us thrust measured at sea level.

Business jets usually have two engines, but it could be one or three if you want. Divide DSLS by the number of engines you want. Then pick the lightest engine which has enough thrust from the table on the next page.

THRUST REQUIRED=DSLS/(no. engines)=_______/_______=______ lbs

Engine	Thrust (lbs)	Weight (lbs)	Length (ft)	Diameter (ft)
Williams FJ44	1800	420	3.9	2.0
Pratt & Whitney JT15D	2500	557	5.1	2.2
Garrett TFE731	3700	747	3.9	3.3
General Electric CF700	4500	737	4.5	3.1
Avco-Lycoming ALF502	6700	1270	4.7	4.2

Write your choice here:________________________________

Its dimensions will be needed when you draw your airplane, using Worksheet 4.

This part is done! Now you can draw your design.

Fig. 3. High School Worksheet No. 3.

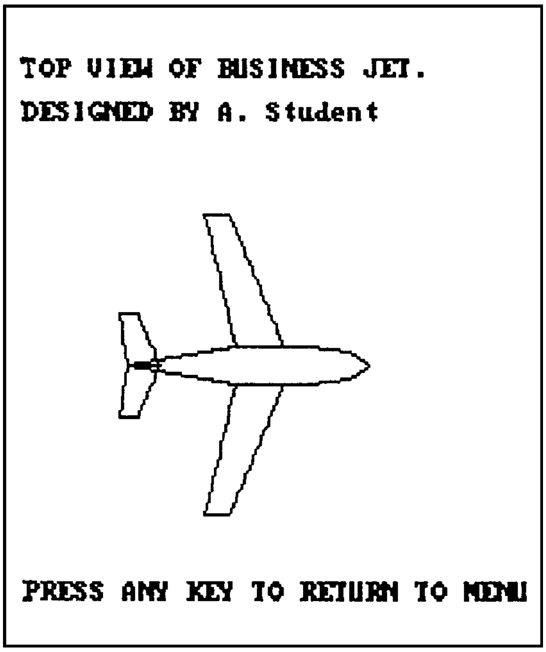


Fig. 4. 'Design' program output plot.

CONCLUSIONS

Presenting the project to students at lower levels is definitely an exercise in patience and in explaining concepts simply! But the author has successfully done so with low achievement level sixth graders, probably the realistic lower edge of the applicability envelope. Some of these students needed to be taught how to use a calculator, and quite a few did not know what a square root was. But we all persevered, moved a little more slowly, and it was very heartwarming to see the frowns of confusion turn into the smiles of satisfaction as we progressed. There seems to be little doubt that at least a few of them were convinced that math and science are not beyond them.

High school students have a predictably more mature reaction to the project, and repeatedly express satisfaction at having had the opportunity to get a taste of what engineering is like. The career education objective for this group has been clearly accomplished.

One other bit of data that the author considers to be a strong indicator of the motivation value of the project is the number of students who wanted to keep a copy of the computer program disk. The worksheet booklet is, of course, theirs to work in and then keep. In the first offering of the project (7th graders) so many students asked for permission to copy or keep the disks that in succeeding sessions extra copies of the disks have always been made available. Almost everyone wants a copy of the disk when they are told at the conclusion of the project that they may keep one. This is true even among the lower economic level, lower achievement level groups in which, based on their own statements, few have access to a computer. No attempt was made to keep an accurate count, but a reasonable estimate is that 400–500 disks have been given away over a three year period.

Presentations to teachers have included the entire range of kindergarten through 12th grade. The main vehicle for doing this has been summer or weekend science institutes which provide teachers part of the in-service training required for renewal of their teaching certificates. It has been especially rewarding to see elementary teachers, who on the whole have little confidence in their math and science ability, complete the project successfully and feel that they can understand a little of the 'magic' of engineering.

In conclusion, when the idea for a junior high school level design project first came up at a science education advisory committee meeting, it was not at all clear that the concept was even workable. It was with significant uncertainty that the author volunteered to try to create such a project. But, based on the experience described above, it now appears clear that it is possible to use a carefully tailored and structured design project to implant interest in design education at quite an early level. This project used aircraft design only by coincidence since that is the author's area of expertise. It seems highly probable that similar design projects could be worked out in almost any field.

A final note. Copies of the worksheets and disks are available for the asking from:

Teacher Resource Center
Embry-Riddle Aeronautical University
600 S. Clyde Morris Blvd.
Daytona Beach, Florida 32114–3900, USA

and

NASA/Universities Space Research Association
3600 Bay Area Boulevard
Houston, Texas. 77058–1113, USA

Charles Eastlake has 13 years experience as a design engineer in the aircraft industry prior to beginning his teaching career. He has taught aircraft design at Embry-Riddle Aeronautical University since 1979, and has spent summers working at NASA and at McDonnell-Douglas Aircraft to stay in touch with industry. He also teaches aerodynamics, aircraft stability and control, composite materials, wind tunnel testing, and helicopter dynamics. Professor Eastlake is an avid pilot and aircraft owner. He has also done extensive outreach work with several Florida school systems involving aircraft and spacecraft design, and has assisted dozens of students from all around the US with science fair projects.