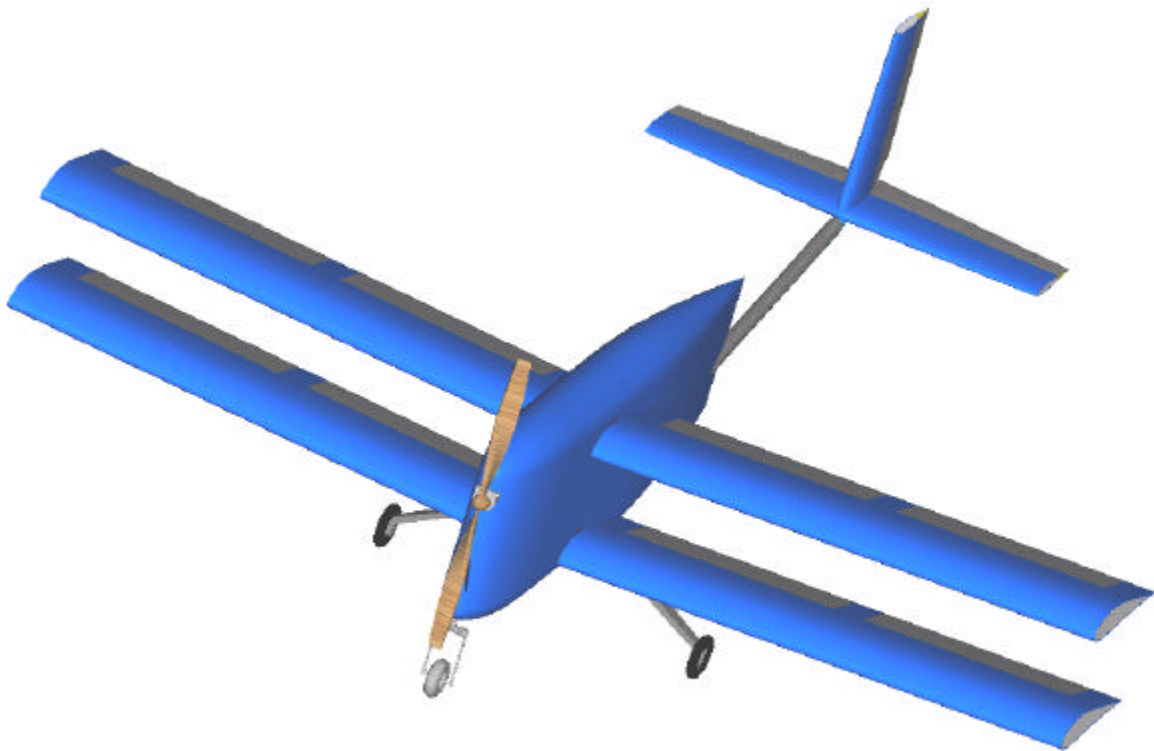

*1999/2000 AIAA Foundation
Cessna/ONR Student Design Build Fly
Competition*

Design Report - Addendum Phase



“Wing and a Prayer”

Utah State University
March 2000

Table of Contents

	<u>Page #</u>
1. Executive Summary.....	3
2. Management Summary.....	6
3. Conceptual Design Phase.....	9
3.0 Introduction.....	9
3.1 Design Parameters – Initial Phase.....	9
3.2 Figures of Merit – Initial Phase.....	13
3.3 Design Parameter Results – Initial Phase.....	13
3.4 Numerical Analysis – Optimization Phase.....	14
3.5 Analytical Methods – Optimization Phase.....	14
3.6 Results.....	18
4. Preliminary Design Phase.....	31
4.0 Introduction.....	31
4.1 Optimization of Wing Area.....	31
4.2 Optimization of Wing Spacing.....	31
4.3 Tail Optimization.....	31
4.4 Landing Gear Optimization.....	31
4.5 Design Refinement.....	32
4.6 Airfoil Analysis.....	33
4.7 Results.....	34
5. Final Design Phase.....	44
5.0 Introduction.....	44
5.1 Detailed Aerodynamic Analysis.....	44
5.2 Structural Analysis of Tail Boom.....	47
5.3 Handling Qualities & Dynamic Stability Analysis.....	47
5.4 Flight Performance Analysis.....	50
5.5 Error Considerations.....	52
5.6 Results.....	52
6. Manufacturing Plan.....	63
6.0 Introduction.....	63
6.1 Main Wing.....	63
6.2 Tail.....	64
6.3 Fuselage.....	65
6.4 Landing Gear.....	66
6.5 Power Plant.....	66
6.6 Figures of Merit - Manufacturing Plan.....	67
6.7 Results.....	67
Appendix 1 -References.....	71
Appendix 2 – Nomenclature.....	72
Detailed Drawing Package.....	73
7. Lessons Learned.....	112
7.0 Introduction.....	112

7.1 Wings.....	112
7.2 Fuselage.....	113
7.3 Landing Gear.....	113
7.4 Estimated Weight vs. Actual Weight.....	113
7.5 Second Generation Improvements.....	114
8. Aircraft Cost Model.....	119
8.0 Introduction.....	119
8.1 Manufacturers Empty Weight (MEW).....	119
8.2 Rated Engine Power (REP).....	119
8.3 Manufacturing Man Hours (MFHR).....	119
8.4 Results.....	120

7.0 Introduction

Once the design team began to manufacture and test components of the airplane, several lessons were learned that were not apparent during the design process. A number of these challenges were met by improved manufacturing techniques. However, in certain instances the components were redesigned to simplify the manufacturing process or to decrease the total weight of the airplane.

7.1 Wings

A number of items affected the final outcome of the wings. The alternatives were analyzed based on performance, weight, and manufacturability to determine the best solution for the encountered problems.

7.1.1 Wing Construction The design team planned to build the wings using a foam core with central load carrying spar and 1/32-inch balsa sheeting. To cut the foam core, two aluminum templates were cut to match the desired airfoil geometry of the wing. It was determined from the design phase that the wing chord would be 10.5 inches. Therefore, the templates were cut for an airfoil with a 10.5 inch chord length and a 1/32-inch offset all around the template. The 1/32-inch offset was made to account for the sheeting that would cover the foam wing. With the templates fixed to the sides of foam blocks, the team began to hot wire the foam wings. However, after a number of wings had been cut, the team noticed that all the foam wings had a wing chord of 10.375 inches. The team determined that the hot wire melted an extra 1/32 of an inch of foam along the cutting surface. This extra 1/32 of an inch that was melted decreased the wing chord to 10.375 inches, which was too small. Therefore, a second set of aluminum templates was cut for the airfoil shape. The templates were cut with a chord length equal to 10.5 inches and no offset was included. Using the second set of templates and accounting for the melting, the foam wings had a chord length equal to 10.4375 inches. This was desired so that with the balsa sheeting applied, the wing chord was exactly 10.5 inches.

7.1.2 Wing Dihedral During the design phase it was determined that the wing spars deflected less than one inch. However, after the construction and testing of the wing spars, it was determined that the spars deflected approximately four to five inches at the tips of the spars under a load of ten pounds. The design team determined that if the wings were mounted to the fuselage with zero dihedral, under normal flight conditions the deflection in the wing spars would provide approximately two to three inches of dihedral. Also, after further discussion with the selected pilot, an airplane that was very neutral in roll was preferred. By decreasing the total dihedral the airplane became more neutral in roll. Therefore, the team decided that to decrease manufacturing time, the dihedral in the main wings was eliminated.

7.1.3 Control Surfaces on Bottom Wing Originally the design team designed the wings with ailerons and flaps on both the top and bottom wings. The team over designed the airplane for a high roll rate during the design phase by placing ailerons on both the top and bottom wings. Therefore, to decrease the designed roll rate, the team decided to remove the ailerons on the bottom wing and build one complete flap. The extra flap length provided extra lift for takeoff. Also, by removing the ailerons on the bottom wing, the design team was able to decrease the total number of servos by two, which decreased the total rated aircraft cost.

7.1.4 Wing Spar The manufacturing process for the composite spar changed three times during the manufacturing process as experience was gained working with composite materials. First, in order to remove the steel mandrel from the cured composite spar, Teflon tape was applied longitudinally along the mandrel as a release agent. However, this resulted in a difficult release. It took about two hours to remove the first spar from the steel mandrel and the second spar could not be removed from the mandrel. The mandrels would not come out of the carbon fiber spars because the ridges of Teflon (that formed as a result of tape overlap) were not perfectly straight and parallel. Therefore, it was determined that the Teflon tape would not be used during the manufacturing process. Second, instead of using Teflon tape, the mandrels were smoothed with Emory cloth. Carnauba base car wax was also applied very liberally to the mandrel before winding. The wax was still wet when wound. After curing, the mandrels came out of the spars with little effort. Figure 7.1 shows microscopic pictures of a cross section of one of the spars. For the most part the lay-up was satisfactory, but because of the liberal application of wax, voids were present in the carbon fiber lay-up as can be seen in picture B of Figure 7.1 as the dark spots. Third, to eliminate the voids, the mandrels were smoothed with Emory cloth, only a small amount of carnauba wax was applied to the

steel mandrels, and the wax was allowed to dry before winding. The result was satisfactory in ease of manufacturing and product quality for the wing spars. Therefore, the same process was used to wind the tail boom.

7.2 Fuselage

Only two changes were made to the fuselage. The team wanted to decrease the total weight of the airplane by as much as possible while maintaining the necessary structural strength. The floor of the fuselage was one item that weighed considerably more than necessary. It was determined that the team could use a better grade plywood that maintained the structural strength required for the fuselage floor, while at the same time decreasing the total airplane weight. Therefore, the team built the fuselage floor using aircraft grade plywood that was 1/4-inch thick. Second, the team decided to manufacture the fuselage without the curved top and bottom fairings. The fairings increased the total weight of the airplane by approximately half a pound, while only slightly reducing the total drag on the fuselage. Therefore, to decrease the total weight of the airplane, the team eliminated the fairings.

7.3 Landing Gear

A number of problems occurred with the initial construction of the landing gear. After the landing gear was constructed using the composite layup, it was placed in an oven for five hours so that the carbon fiber could cure. When the landing gear was removed from the oven it was completely twisted as can be seen in Figures 7.2. Upon analyzing the construction, cure, and result, a number of problems were found.

First, the laminate layup was not symmetric. This means that there was not a mirror image about the midplane of the laminate. Initially the gear tapered from two inches in width at the root to approximately $\frac{3}{4}$ inch at the tip. The problem occurred during the lay up of the unidirectional laminates (fibers were in one direction). The team wanted to use unidirectional laminates to provide a maximum strength through a symmetric pattern. However, the taper proved to be too difficult to layup using unidirectional laminates and the resulting laminate was non-symmetric. As can be seen in the Figures 7.2, the non-symmetric layup resulted in a twisted unusable landing gear.

To solve this problem the taper in the landing gear was removed. A constant cross section width of two inches was used creating a rectangular planform. This greatly simplified the layup of the unidirectional laminates that provided the strength. After the layup a symmetric laminate was achieved and no twisting occurred during the curing process.

Second, during the cure process shrink tape was used to aid the landing gear. The shrink tape acts as a compression agent to force a good bond between the laminae. Due to the shape of the gear (rectangle, long sides vs. really short sides), good compression of the shrink tape was only achieved on the two short sides of the gear. The long flat sides where bending stresses will be the most critical, did have equal compression during the cure.

The team determined that the only way to achieve a constant pressure around the entire landing gear during the curing process was to use a vacuum bag. The shrink tape method was eliminated and the entire landing gear was placed in a vacuum bag and allowed to cure. The vacuum bag provided a uniform compression on the entire landing gear a better bonding of the individual fibers was achieved. Figure 7.3 shows the new landing gear after the problems were solved.

7.4 Estimated Weight vs. Actual Weight

Perhaps the largest lesson learned during the entire design and build of the airplane was the variances in weight from estimated design weight to the actual completed weight. Table 7.1 provides a breakdown of the major components of the airplane with estimated and actual weights. It can be seen that every component of the airplane, except for the landing gear, weighed slightly more than the estimated weight. The design team realized during the manufacturing process that the weight of the glue, epoxy, and mounting hardware was neglected during the design phase. The wings were weighed before the epoxy was applied to the 1/32-inch balsa wood that was used to sheet the wings. The weight of the wings was almost nearly equal to the weight estimated during the design phase. However, after the epoxy was used for the balsa sheeting and the wings were sheeted with the monokote, each wing weighed approximately six ounces more than predicted. The other major difference in weight from the estimated to actual weight was encountered in the weights of the motor, propeller, controller, and batteries. Estimated weights for these components of the power plant were taken from published values of weight from the respective manufacturers. However, each component of the power plant was slightly heavier than the published weight values. Each component, excluding the propeller, was built by the manufacturer after the order was placed. Because of the fabrication process, the weights of the motor, controller, and batteries were not identical to the published weights for the components.

Weight (lbs.)	Estimated	Actual
Wings	3.01	4.53
Horizontal & Vertical Surfaces	0.46	0.55
Fuselage, Tail Boom, Nose Gear, Receiver & Receiver Battery	4.43	4.47
Landing Gear	1.2	0.96
Motor, Propeller, Controller, & Batteries	6.61	7.48
Total Airplane Weight	15.71	18.0

Table 7.1 Estimated Airplane Weight vs. Actual Airplane Weight

The table list the estimated and actual weights for the different components of the airplane.

7.5 Second Generation Improvements

After the airplane was designed, built, and tested, the design team determined that a number of improvements were possible during the entire design and build process. Many of the improvements were simple and could save time in the design and construction of the airplane.

7.5.1 Design Improvements After reevaluating the design phase of the airplane, the team determined that two improvements could have been made. First, the weight calculations should have been more conservative. The team found that it was difficult to build the airplane to meet exact weight estimates. Because much of the performance of the airplane depended on the total weight, it would be better to build an airplane that weighed less than estimated rather than build an airplane that weighed more than estimated. The team decided that placing small factors of safety in all of the weight calculations during the design phase would help remedy the extra weight encountered during the manufacturing process. Second, after the airplane was completely constructed, team members noticed that a number of bottle configurations were possible in the fuselage. The design team limited the bottle orientation in the fuselage to laying down or standing up during the design phase. By analyzing more bottle configurations a more efficient fuselage could be designed.

7.5.2 Manufacturing Improvements The construction of the airplane was difficult but for the most part the airplane built was very nearly the airplane designed. Two improvements could have been made during the manufacturing of the airplane. First, placing the carbon fiber spars in the wings was a very difficult process because the angle of the spar relative to the upper surface of the wing varied from wing to wing. The team determined that to improve the carbon fiber placement in the wing, a jig would be used to hold the wing spar parallel to the upper surface of the wing. Second, a more efficient construction of the hot wire apparatus would provide better tolerances in the airfoil geometry across the span of the wing. The hot wire device that was used during the construction of the airplane worked well; however, by better maintaining the tension in the wire closer tolerances could have been achieved.

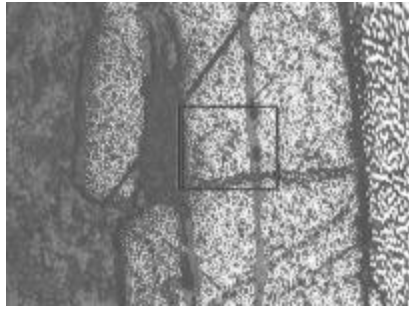
7.5.3 Weight Savings

After analyzing the final constructed airplane, the team decided that the airplane could have been built to weigh less than the actual weight. The fuselage floor weighed nearly a pound and the team felt that by using materials other than wood, the total weight of the fuselage could have been decreased. The wing support also could have been built to weigh less. By using a combination of wood and composite materials this could be accomplished. However, by using other materials, the difficulty in manufacturing would also increase. The airplane was designed so that the fuselage floor would be six inches plus the radius of the wheels off the ground. It was difficult to find a lightweight nose wheel support that provided the necessary fuselage floor height off of the ground. Therefore, by building a custom nose wheel support, weight could be saved. Finally, the team determined that weight could be removed from the wings by drilling holes in all of the control surfaces and then applying monokote over the control surface. Weight was a critical design issue throughout the design and build process. By decreasing weight wherever possible, the airplane would require less power and the rated aircraft cost would decrease.

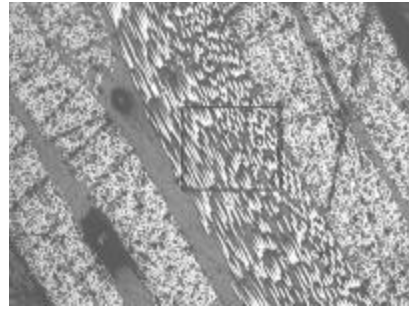
7.5.4 Sponsorship

One of the challenges for the design team during the entire design process was that of sponsorship. The design team was required to raise funds for the entire cost of the airplane. Therefore, it was imperative that the team seek sponsors that would contribute to the airplane design. Members of the design team found that it was difficult to find individuals and companies that would sponsor the project. The team found that the companies that were contacted at the beginning of the design phase were more willing to contribute to the project. Where as companies and individuals that were contacted toward the end of the project were less willing to donate. Based on the experience in gathering sponsors for the project, the team determined it would be best to contact potential sponsors as early in the design process as possible.

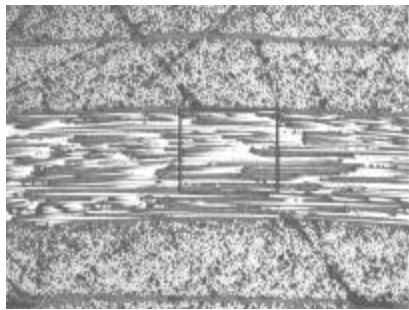
Microscopic View of Carbon Fiber Composite Lay Up for Airplane Spar



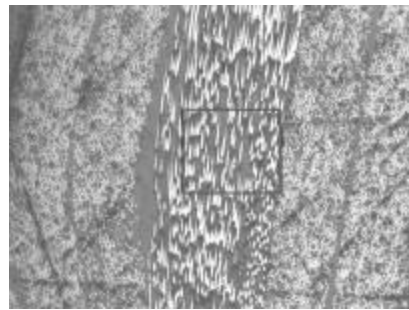
A.10X



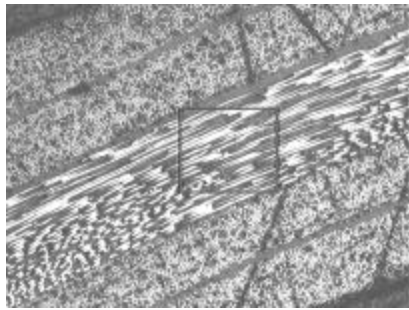
B.10X



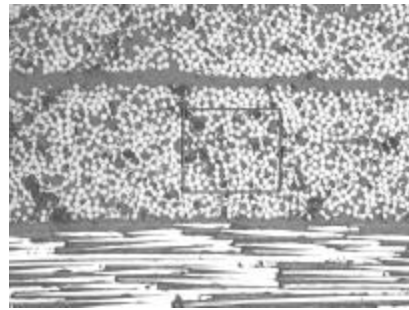
C.10X



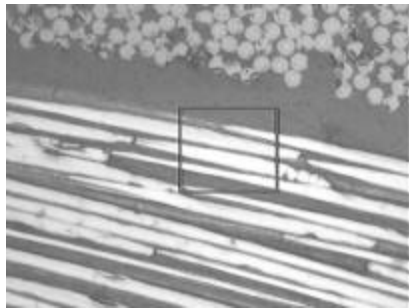
D.10X



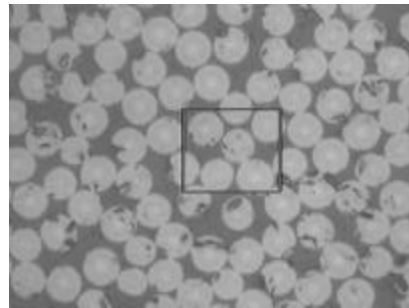
E.10X



F.20X



G.50X



H.100X

Figure 7.1 Microscope Pictures of Carbon Fiber Spar

Microscopic pictures of one of the tested wing spars show voids in the cross section.

Initial Landing Gear



Figure 7.2 Initial Landing Gear

The initial landing gear was built with taper. The landing gear twisted during the curing process.

Modified Landing Gear



Figure 7.3 Modified Landing Gear

This landing gear did not have any taper. This is the landing gear that the team will use at the competition.

8.0 Introduction

The total score that could be obtained at the competition this year was based on three items: the written report score, the total flight score, and the rated aircraft cost. The total score was calculated as follows:

$$\text{Total Score} = \frac{\text{Written Report} * \text{Total Flight Score}}{\text{Rated Aircraft Cost}}$$

To obtain the maximum possible score it was critical to maximize the written report score and the total flight score while minimizing the rated aircraft cost. During the conceptual, preliminary, and final design phases, the team iterated the total flight score and the rated aircraft cost simultaneously to determine an optimum airplane configuration. By iterating the two parameters simultaneously, it was determined that the optimum airplane did not have the best total flight score possible nor did the airplane have the lowest possible rated aircraft cost. However, the optimum airplane achieved the highest possible score. It was determined that there was a tradeoff between total flight score and rated aircraft cost. Generally as the total flight score of the airplane increased, the airplane was capable of carrying more liter bottles of water around the course, but the rated aircraft cost also increased causing the total score to decrease. As the rated aircraft cost decreased, the airplane was less capable of carrying the liters of water and the total score decreased. Therefore, it was important to optimize simultaneously the total flight score and the rated aircraft cost to determine the optimum airplane.

The aircraft cost model was used as a means to determine approximately the cost of the airplane in dollars. Although the model was not entirely accurate, it presented an important and necessary insight into the design process. The rated aircraft cost was computed using the following formula:

$$\$(\text{Thousands}) = \frac{A * \text{MEW} + B * \text{REP} + C * \text{MFHR}}{1000}$$

A detailed description of the variables is provided below.

8.1 Manufacturers Empty Weight (MEW)

MEW was the manufacturers empty weight, which equaled the entire weight of the airplane in pounds without the payload and batteries. To determine a dollar value for the MEW, A represented the manufacturers empty weight multiplier and was assigned a value of \$100 per pound. For every pound, the rated aircraft cost increased by 0.1. It was important to design an airplane that was as lightweight as possible for this reason. However, even more difficult, was the building of the designed airplane. It was critical that the airplane weight did not exceed the designed airplane weight and it was important if possible to cut weight during the manufacturing process. The MEW or total empty weight of the airplane without the payload or batteries was 13.1 pounds.

8.2 Rated Engine Power (REP)

REP was the rated engine power and was calculated using the following formula:

$$\text{REP} = \# \text{ of engines} * 50\text{A} * 1.2 \text{ V/cell} * \# \text{ of cells}$$

REP returned a number with the units of watts. B represented the manufacturers rated engine power multiplier and was given the value of \$1 per watt. It can be seen that the rated aircraft cost increased as more engines and cells were used to power the airplane. The design team used 36 cells to power just one motor. The REP was calculated for the designed airplane as follows:

$$\text{REP} = 1 * 50\text{A} * 1.2\text{V/cell} * 36 \text{ cells}$$

The calculated value for the REP was 2160 watts.

8.3 Manufacturing Man Hours (MFHR)

MFHR or manufacturing man hours was used to approximate the number of hours that were required to build the designed airplane. The MFHR was broken down into different groups described by the Work Breakdown

Structure (WBS). The total manufacturing man hours were then computed by summing all the hours from the WBS. The multiplier C was used to convert the number of manufacturing hours required into dollars and was assigned a value of \$20 per hour. The total number of manufacturing man hours (MFHR) predicted by the cost model for the designed airplane was 129 hours. Table 8.1 shows the MFHR for the entire airplane broken down into the different categories of the WBS.

WBS		Airplane Characteristics	Number of Assigned Hours	Total Number of Hours
Wings	# of Wings	2	5	10
	Projected Area (ft*ft)	11.5	4	46
Fuselage	# of Bodies	1	5	5
	Total Length (ft)	6	4	24
Empenage	Basic	-	5	5
	Vertical Surface	1	5	5
	Horizontal Surface	1	10	10
Flight Systems	Basic	-	5	5
	# of servos	9	1	9
Propulsion System	# of engines	1	5	5
	# of propellers/fans	1	5	5
Total Hours				129

Table 8.1 Work Breakdown Structure for the Designed Airplane

This table shows the total number of manufacturing hours assigned to each component of the airplane.

8.3.1 WBS Wing(s) It was given that five manufacturing man hours per wing plus an additional four hours per square foot of projected wing area were used in the calculation of the WBS for the wings. Therefore, the total rated aircraft cost increased with multiple wing configurations and larger wing areas.

8.3.2 WBS Fuselage and/or Pods Each body required five hours of manufacturing time plus an additional four hours per foot of total fuselage or pod length to compute the WBS for the fuselage.

8.3.3 WBS Empenage The WBS for the empenage was computed using a given five hours of manufacturing time plus five hours of manufacturing time for the vertical surface plus ten hours of manufacturing time for the horizontal surface.

8.3.4 WBS Flight Systems Five hours of manufacturing time plus one hour per servo provided the total manufacturing time for the flight system.

8.3.5 WBS Propulsion Systems Five hours of manufacturing time per engine plus an additional five hours per propeller or fan were used to calculate the WBS of the propulsion systems.

8.4 Results

It can be seen that several key factors affected the total rated aircraft cost. For the airplane that was designed and built, the total rated aircraft cost is calculated below:

$$\text{Rated Aircraft Cost (Thousands of \$)} = \frac{\$100/\text{lbs.} * 13.1 \text{ lbs.} + \$1/\text{watts} * 2160 \text{ watts} + \$20/\text{hours} * 129 \text{ hours}}{1000}$$

$$\text{Rated Aircraft cost (Thousands of \$)} = 6.05$$