COMPOSITE AIRCRAFT LIFE CYCLE COST ESTIMATING MODEL

THESIS

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Abstract

Composite materials are beginning to comprise an ever greater percentage of structural materials used throughout aircraft production. The increased usage of these materials has led several individuals within the Air Force community and the DoD to revisit the life cycle cost models for weapon systems. The current life cycle cost models were developed when metals were the major material used in the production process. A series of affordability initiatives have culminated in significant evidence over the last decade to better quantify the impact of primarily composite structures in aircraft. The Advanced Composite Cargo Aircraft, ACCA, a research effort sponsored by the Air Force Research Lab, attempted to determine the impact of part size and large scale composite components on life cycle cost for cargo aircraft. This research evaluates the data provided by the ACCA program as well as data from aerospace industry partners to modify the existing life cycle cost models. This research finds that a relationship exists between relative part count and touch labor hours for certain cost categories, notably, design, design support, and testing cost. In particular, a percentage reduction in part count drives a corresponding percentage reduction in these select cost categories. These findings suggest that reduction in part count filter through most of the major cost categories in development and production. The findings in this research suggest that the current life cycle cost models require modifications in the current cost estimating relationships to capture these impacts.

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I dedicate these pages to my beautiful wife and two children. Without their support, I would never have completed this endeavor.

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Without the support of loving wife, who was always willing to make sacrifices of her time to allow me to work on this project, it would have never been completed. Without my wonderful son who was always willing to provide me with the proper insights into life that only a nine year old can provide, would I have had the determination to complete this work. I am also grateful to my darling daughter, who made me realize that it is possible to work on a thesis and play with dolls simultaneously; the magnitude of work would have been unbearable.

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Daniel Lambert

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I: Introduction

Background

The emphasis on reducing defense related funding has been growing over the past twenty years, since the end of the Cold War. Though there was a spike in defense related funding after the September 11th terrorist attacks, a renewed focus has emerged from top congressional leaders that defense spending must decrease. This reduction in funding has caused military leaders to place a greater priority on the cost of major weapon systems. A leading philosophy behind many military scientists and aerospace officials is that composite materials can help lower the life cycle cost of military weapon systems.

Composite materials are beginning to comprise a greater percentage of materials used in aircraft production. The increased usage of these materials has led several individuals within the Air Force community to revisit the life cycle cost models that estimate the cost of weapon systems. The current life cycle cost models were developed when metals were the major material used in the production process. A series of affordability initiatives have culminated in significant evidence over the last decade to better quantify the impact of primarily composite structures in aircraft.

The current life cycle cost models and procurement strategies do not take into account the different manufacturing techniques for composite materials. With the increased use of composite materials in aircraft production and the corresponding decrease in aircraft part count, the current cost models do not account for this potential cost savings due to reduced touch labor hours. Lack of research on the potential savings associated with reduced part counts and the integration of large scale composite materials into aircraft production has led consumers and industry officials to perceive composite use as more risky compared to use of traditional metallic materials. This perception has meant that the majority of composite use has been focused on component structures. Continuing research is leading prime contractors to investigate the possibilities of an increase usage in composite materials.

Composite materials are combinations of two dissimilar materials where each material remains identifiable, but the mechanical properties of the composite differ from the properties of the original materials. Composites are not a new phenomenon and biological composites have been in existence as long as the Earth has existed. Common examples of biological composites include wood, bone, and teeth. These are biological composites that contain complex internal structures specifically designed to perform certain requirements (Hull and Clyne, 1996: 1). One of the defining features of biological composites is that they are compromised of two components: mineral and organic. For example, bone is comprised of hydroxyl apatite, a mineral, and collagen. This material structure allows bone to be a multifunctional material, providing structural support for the body and allowing blood cell formation. The mineral component in bone provides the strength for structural support whereas the organic component contributes to the ductility (Meyers and others, 2006: 35). The mechanical properties that are exhibited in biological components such as strength and ductility are also important to aircraft production. Aerospace researchers are continually striving to construct materials that can achieve the greatest level of strength and ductility to meet the demands of present day flight. The first truly modern day composite material was fiberglass and it was first used in production processes in the late 1930's (Strong, 2008: 4). Since the 1930's, research has led to the development of advanced, filamentary, and laminated composites. Each of these composites has specific applications throughout aircraft production.

Although the primary use of composite materials has been for component parts, there are several arguments for large structural assemblies comprised of composite materials. Composites have several advantages over conventional aircraft production materials, including reduced weight, reduced number of fasteners, corrosion resistance, and an extended product life.   In addition, composites can be designed specifically for certain aircraft parts to achieve desired stiffness and strength. This ability to custom design aircraft sections, key in the context of this research, reduces touch labor hours related to aircraft production and development. The main disadvantage and largest criticism of using composite materials is the raw materials cost. As was previously stated, the current life cycle cost models do not take into account various aspects of composite manufacturing techniques and this lack of consideration has placed composite materials at a disadvantage compared to metallic materials. Current models treat an increase in raw materials as an increase in total life cycle cost.   These models do not take into consideration the potential cost savings based on reduced part count and a reduction in touch labor hours in aircraft production through the use of composites. This lack of consideration leads to an inflated estimated life cycle cost when composites are incorporated into aircraft structures. This inflated estimated life cycle cost negatively impacts the average procurement unit cost (APUC), the procurement unit cost (PUC), and the cost per flying hour (CPFH) for structures containing a large percentage of composite materials. These estimated cost-ratios are one of the most important tools that decision makers use in determining whether to continue or start production of a new weapon system.

The current literature relating to estimating the cost of aircraft comprised of composite materials is limited. The most comprehensive report on building cost estimating relationships and cost estimates is a RAND study (R-4016) performed by Susan Resetar in 1991. The study attempted to build cost estimating relationships for several of the main cost drivers for aircraft that would be comprised of composite materials. Since 1991, the Air Force has initiated two programs, the Cost Affordability Initiative and the Advanced Composite Cargo Aircraft, to demonstrate the technical feasibility and cost affordability of aircraft comprised predominately from composite materials. These three sources provide the majority of the background information for this research.

Purpose of This Study

The purpose of this research is to improve the method for evaluating life cycle cost of predominately composite material aircraft to accommodate more realistic labor costs related to part count reductions. The goal of this research is to modify the current life cycle cost model used by the Air Force community, which will better characterize the benefits and tradeoff’s associated with composite aircraft development and production.

The following are the research questions that this research will attempt to answer.

Research Questions

1. Does a relationship exist between reduced part counts and design, design support, tooling, and testing costs?
2. If a relationship exists, how do we quantify that relationship?
3. If a relationship exists, how can the relationship be incorporated into current life cycle cost models?
4. How did the manufacturing process for the Advanced Composite Cargo Aircraft compare to the original manufacturing process in terms of touch labor hours?
5. What additional information is required?

II: Literature Review

Cost Estimating Methodology: RAND Basis

One of the earliest and most comprehensive attempts to quantify and develop a methodology for estimating composite material cost in aircraft production is the RAND report R-4016-AF, *Advanced Airframe Structural Materials*, by Susan Resetar, J. Rogers, and Ronald Hess published in 1991. The objective of this report was to quantify the cost effects of the incorporation of composite materials in aircraft structures. The authors relied on a survey based methodology in lieu of a traditional statistical analysis. The survey methodology was utilized in 1991 due to the lack of actual data at the time of the study. As the authors discussed in the report the industry survey approach was chosen rather than a statistical analysis of historical data because:

- There are only a half dozen historical data points (military aircraft programs) encompassing all composite material types
- The range of material types is limited. Materials such as aluminum-lithium and graphite/thermoplastic, have not been incorporated into production aircraft; as a result, no historical data, except for data based on developmental experience, exist for these materials.
- Projected levels of usage are far beyond what has been attained by existing production aircraft (Resetar and others, 1991:15)

The RAND study received survey responses from the main prime contractors, several of which have consolidated since the time of the study. The study considered two time frames: the late 1980's and the mid-1990's. The underlying assumption of the report was that the data for the late 1980's reflected the company's current experience, whereas the data collected for the mid-1990's would reflect the company's best estimate regarding the future of the technical knowledge of the materials as well as design and manufacturing techniques. Since 1987 numerous technical innovations have occurred in the field of composite research. The anticipated data of the mid-1990's that the surveyed companies reported is obsolete or immaterial and not useful in current research.

The section of the RAND report that is of most interest to this research is Section IV which addresses the cost data responses from reporting companies. This section outlines the nonrecurring cost elements as well as the recurring cost elements in hours per pound ratios for the most common materials used in aircraft production. The nonrecurring cost elements analyzed are engineering and tooling costs, while recurring cost elements included: engineering, tooling, manufacturing, and quality assurance costs. The study reports each material type and time period for each recurring and nonrecurring cost element. The average, minimum, and maximum values are reported for each material type with aluminum serving as the baseline (1.0). Each of the six additional materials is given a cost factor for both the late 1980s and the mid-1990s. The cost elements that are of particular interest to this current research are nonrecurring and recurring engineering hours, nonrecurring and recurring tooling hours, and recurring quality assurance hours. Table 1 is the nonrecurring engineering hours per pound ratio.

Table 1: Non-Recurring Engineering Hours Per Pound Ratios (Resetar et al, 1991)

	Late 1980s			**Mid-1990s**	
Material Type	**Average**	**Min/Max**		**Average**	**Min/Max**
Aluminum	1.0	1.0/1.0		1	0.8/1.0
Al-lithium	1.1	1.0/1.3		1	0.9/1.3
Titanium	1.1	1.0/1.3		1	0.9/1.3
Steel	1.1	0.9/1.3		1.1	0.9/1.3
Graphite/epoxy	1.4	0.9/2.5		1.2	0.7/2.0
Graphite/bismaleimide	1.5	0.9/2.5		1.3	0.7/2.0
Graphite/thermoplastic	1.7	0.9/3.0		1.4	0.7/2.5

Nonrecurring engineering hours are the engineering hours spent designing the airframe and include wind-tunnel models, laboratory testing, drawings and schematics as well as process and materials specifications. The RAND report found that on average nonrecurring engineering hours per pound in the 1980s were 40% to 70% higher for composites than for metals (Resetar and others: 58). The study received multiple responses from participating companies detailing possible reasons for this drastically higher hours per pound ratio. The reasons included unfamiliarity with the composite material and little to nonexistent experience in designing with these new materials. Another reason given for the higher hours compared with metallic materials is that there were not universal material standards and safety margins with composite materials during the 1980s. The study did cite one consideration that may actually reduce nonrecurring engineering hours and therefore reduce the cost of composites. Industry officials predicted that design unitization will reduce the part count and simplify the overall design process (Resetar and others, 1991: 58-59).

Nonrecurring tooling was the next major cost element that is of interest to the current research. Nonrecurring tooling refers to the tools designed solely for use on a particular airframe program. Industry ratios for nonrecurring tooling hours per pound are presented in Table 2.

Table 2: Nonrecurring Tooling Hours Per Pound Ratio (Resetar et al, 1991)

	Late 1980s			Mid-1990s	
Material Type	**Average**	**Min/Max**		**Average**	**Min/Max**
Aluminum	1.0	0.9/1.0		1	0.9/1.0
Al-lithium	1.2	1.0/1.7		1.1	0.9/1.7
Titanium	1.4	0.9/3.7		1.4	0.9/3.4
Steel	1.1	1.0/1.4		1.1	1.0/1.4
Graphite/epoxy	1.6	0.7/2.5		1.4	0.5/2.0
Graphite/bismaleimide	1.7	0.7/2.5		1.5	0.5/2.3
Graphite/thermoplastic	2.0	0.7/3.0		1.6	0.5/2.5

The RAND report cited several reasons for the increased cost of tooling for composite materials compared to standard metallic materials. The foremost reason is the exposure to high temperatures and pressures in the autoclave, which is the current method of manufacturing composites structures. The higher temperatures and pressure will increase the tool design effort due to designers having to consider the relationship of the thermal expansion between the tool and the processed material. Since current metallic tools are not able to withstand the higher heat and pressure, tools will be constructed of steel, graphite, and electroplated nickel materials thereby increasing the cost of the tools compared to common aluminum based tools. However, one industry official stated that non-recurring tooling hours may actually decrease due to unitized design reducing the overall quantity of tools required (Resetar and others, 1991: 59-61).

Recurring engineering hours is an aspect of the RAND study that is of interest to this research; however the report was limited in the actual data received from industry respondents’ to the RAND survey. Table 3 is the RAND summary of the recurring engineering hours.

Table 3: Recurring Engineering Hours/Pound (Resetar et al, 1991)

Cumulative Average Hours for 100 units for 1000 lb of Structure				
Time Period/Material Type		**Average Value**	**Min/Max Value in Cluster**	**Min/Max Value in Sample**
Late 1980s				
Aluminum		1	0.4/1.0	0.4/2.3
Al-lithium		1.1	0.5/1.1	0.4/2.5
Titanium		1.4	0.7/1.5	0.6/2.3
Steel		1.1	0.6/1.0	0.5/2.3
Graphite/epoxy		1.9	0.8/2.5	0.4/4.2
Graphite/bismaleimide		2.1	1.2/2.8	0.4/4.5
Graphite/thermoplastic		2.9	0.9/3.2	0.67.5
Mid-1990s				
Aluminum		0.9	0.3/1.0	0.3/2.1
Al-lithium		1	0.4/1.0	0.4/2.2
Titanium		1.2	0.7/1.5	0.6/2.1
Steel		1.1	0.5/1.0	0.5/2.3
Graphite/epoxy		1.5	0.6/1.9	0.3/3.6
Graphite/bismaleimide		1.6	1.0/2.3	0.3/3.6
Graphite/thermoplastic		1.4	0.6/2.2	0.3/3.6

While Table 3 shows that in the late 1980s recurring engineering hours for composite materials were two and three times the hours required for aluminum, several industry officials did not expect any change at all in recurring engineering hours for composite materials.

Recurring tooling is the second recurring cost category discussed in the RAND report that is of interest to the current project. Recurring tooling is the required effort to maintain and repair production tools and is a function of the nonrecurring tool element. Table 4 is a summary of the responses that the RAND authors received from industry officials regarding recurring tooling hours (Resetar and others, 1991: 63).

Table 4: Recurring Tooling Hours/Pound (Resetar et al, 1991)

Cumulative Average Hours for 100 units for 1000 lb of Structure				
Time Period/Material Type		**Average Value**	**Min/Max Value in Cluster**	**Min/Max Value in Sample**
Late 1980s				
Aluminum		1.6	0.6/1.7	0.3/5.2
Al-lithium		1.7	0.5/1.9	0.3/4.6
Titanium		3	0.5/2.9	0.5/9.7
Steel		2.3	0.6/2.5	0.4/7.3
Graphite/epoxy		3.6	0.6/6.7	0.6/9.3
Graphite/bismaleimide		3.7	0.6/6.8	0.6/9.3
Graphite/thermoplastic		3.9	0.7/7.1	0.7/10.5
Mid-1990s				
Aluminum		1.5	0.5/1.7	0.3/4.5
Al-lithium		1.7	0.5/1.9	0.3/4.6
Titanium		2.6	0.6/2.8	0.5/8.2
Steel		2.3	0.6/2.3	0.4/7.3
Graphite/epoxy		3.2	0.4/6.0	0.4/8.6
Graphite/bismaleimide		3.3	0.5/6.1	0.4/8.5
Graphite/thermoplastic		3.8	0.6/7.0	0.4/10.5

Industry officials cited numerous reasons for the significantly higher hours for composite materials compared to aluminum. The most compelling reason given for the higher tooling hours required for composite materials is the additional wear on the tools because of the thermal cycling in the autoclave.

The final cost element that the RAND study examined that is significant to this research is recurring quality assurance. Industry average, minimum, and maximum recurring quality assurance hours per pound are shown in Table 5.

Table 5: Recurring Quality Assurance Hours/Pound (Resetar et al, 1991)

Cumulative Average Hours for 100 units for 1000 lb of Structure					
Time Period/Material Type			**Average Value**	**Min/Max Value in Cluster**	**Min/Max Value in Sample**
Late 1980s					
Aluminum			1.7	0.7/2.7	0.3/3.8
Al-lithium			1.8	0.8/2.8	0.4/3.5
Titanium			2.7	1.0/4.4	0.5/6.0
Steel			2.4	0.9/3.9	0.5/5.3
Graphite/epoxy			4.1	0.8/7.4	0.7/10.9
Graphite/bismaleimide			4.3	0.8/7.8	0.8/11.8
Graphite/thermoplastic			4.4	1.0/7.8	0.8/10.6
Mid-1990s					
Aluminum			1.5	0.6/2.4	0.3/3.3
Al-lithium			1.7	0.8/2.6	0.4/3.3
Titanium			2.4	0.9/3.9	0.5/5.2
Steel			2.4	0.9/3.9	0.5/5.3
Graphite/epoxy			3.1	0.5/5.8	0.5/9.2
Graphite/bismaleimide			3.6	0.6/6.6	0.6/10.4
Graphite/thermoplastic			3.4	0.7/6.1	0.6/9.1

In the late 1980s, industry officials stated that quality assurance hours for composite materials would be significantly greater than metallic structures due to the unproven nature of composites and additional testing would be required. At that time of the survey, there were no set testing procedures or guidelines and defense companies were just beginning to develop a standard set of testing procedures for these materials. Quality assurance hours are also dependent on the criticality of the component to the overall system.

While hours per pound is an important aspect of identifying the greatest cost drivers affecting aircraft acquisition, material cost is often one of the key drivers in determining which type of manufacturing material to incorporate into the aircraft design. The RAND study identified the three elements that determine total material cost: raw material cost, buy-to-fly ratio, and the material burden rate. The element of total material cost that is notable for composite materials is the buy-to-fly ratio. The buy-to-fly ratio is the amount of material purchased to complete a pound of finished part that "flies" away (Resetar and others, 1991: 65-66). Composite materials have a much lower buy-to-fly ratio due to composite manufacturing techniques that eliminate scrap material and allow custom manufacturing of parts. Table 6 shows the buy-to-fly ratios for the common materials used in aircraft manufacturing.

Table 6: Material Cost Factors (Resetar et al, 1991)

Cumulative Average Hours for 100 units for 1000 lb of Structure				
Time Period/Material Type		**Buy-to-Fly Ratio**	**Raw Material $/lb (FY90$)**	**Material $/lb (FY90$)**
Late 1980s				
Aluminum		2.5	11	27
Al-lithium		4.2	17	72
Titanium		3	26	76
Steel		2.1	8	18
Graphite/epoxy		1.9	69	130
Graphite/bismaleimide		1.9	78	146
Graphite/thermoplastic		1.9	91	173
Mid-1990s				
Aluminum		2.2	10	22
Al-lithium		2.7	9	25
Titanium		3	24	72
Steel		2.1	8	18
Graphite/epoxy		1.8	57	102
Graphite/bismaleimide		1.8	61	111
Graphite/thermoplastic		1.8	66	119

The lower buy-to-fly ratios for composite materials reflect one of the advantages of using composite materials versus metallic materials. This lower ratio coupled with weight savings and reduced part counts has led to increased research by both the government and industry into how to incorporate composite materials into aircraft production in a cost effective manner.

As was mentioned several times early in this report, the RAND study referred to several considerations that may reduce the cost of composites. The overwhelming reason that composite costs may be reduced for several of the cost elements is that design utilization will reduce part count and simplify the overall design process (Resetar and others, 1991: 59-63). Furthermore, two overarching trends factor into the higher composite cost for each cost element: the impact of autoclave curing and the lack of experience that engineers have with composite materials.

The cost estimating relationships (CERs) that RAND developed were applied to two hypothetical aircraft, both fighter aircraft. The baseline aircraft was manufactured with aluminum while the second aircraft was split 55% aluminum to 45% composite materials. Considering that the RAND report predicted higher cost for every recurring and nonrecurring cost element, it is not a surprise that the composite fighter had a projected four percent increase in nonrecurring cost and a thirty-five percent increase in recurring cost. While the RAND study is the best product that addresses the CERs of composite materials it is lacking in several aspects. The hypothetical aircraft were both fighters, which are considerably more structurally demanding than a military transport or cargo aircraft. Also, the report was produced in 1991 and since that time considerable research has been conducted on composite materials that indicate that the CERs developed by RAND may lack some validity.

Boeing 787

Boeing Corporation has long been a leading company in traditional commercial and military aviation manufacturing but with the new Boeing 787 Dreamliner, the company has become a leader in composite aircraft manufacturing. Boeing reports that the new 787 Dreamliner will be composed of 80% of composite material by structure and 50% of composites by weight, including the fuselage and wing (Boeing, 2010). The decision by Boeing to incorporate composites into a significant portion of the 787 structure was based on economic rational. With petroleum prices increasing in the first half of the new century, Boeing made a tactical decision that new aircraft would need to be more fuel efficient. The favorable weight to strength ratios of composites was one of the most compelling reasons for Boeing to incorporate composites into a significant percentage of the structure of the 787 Dreamliner. Looking at Figure 1 it is evident that Boeing is investing heavily in composite use.

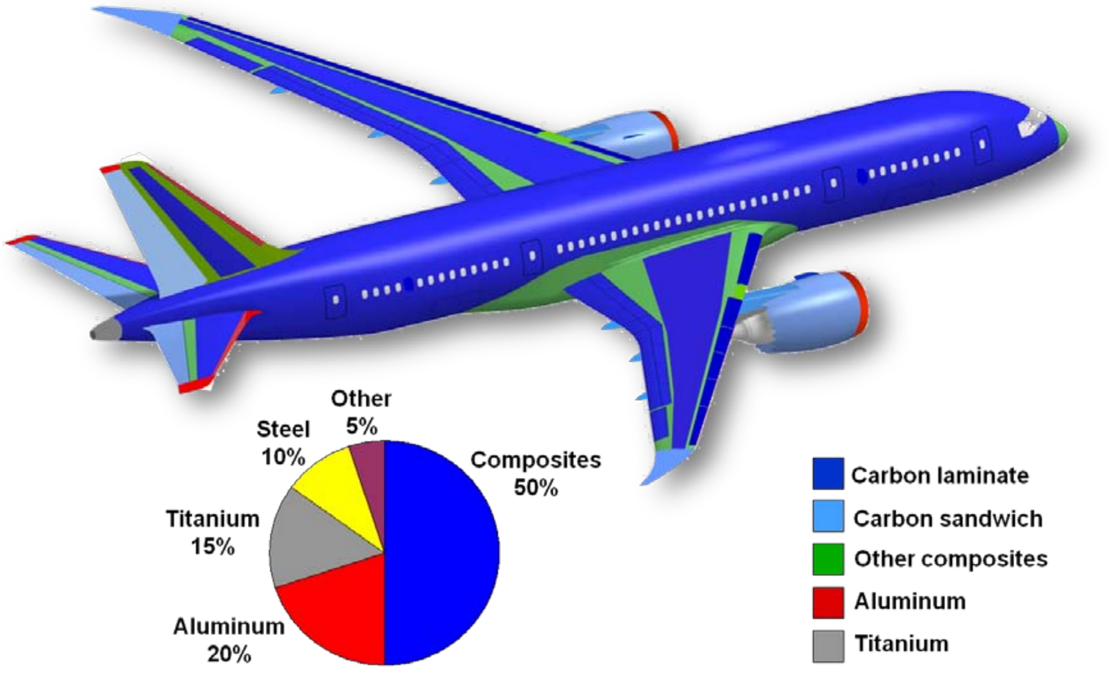


Figure 1: Boeing 787 Dreamliner External Skin Makeup (Boeing, 2010)

The 787 is designed to fly at a speed of Mach 0.85, which is similar to today's fastest wide body aircraft, the Boeing 777 and 747. Moreover, the 787 series will be 30,000 to 40,000 pounds lighter than its comparably sized competitor, the Airbus A330-200 (Walz, 2006). What is significant to this project is that by using large structural pieces, Boeing was able to eliminate 1,500 aluminum sheets and 40,000 to 50,000 fasteners in the fuselage section alone. This is an 80% reduction in fasteners compared to a non-composite barrel structure and reduces the number of holes drilled in the fuselage from one million to fewer than 10,000 (Boeing, 2010).

In order for Boeing to achieve efficiency in manufacturing large composite structures, the company relied on fiber placement machines in the production process. These precise systems can automate the building of laminates made of combinations of ply angles other than the conventional 0 degrees, 90 degrees and 45 degrees and can achieve this at a consistent cost per unit of production. Boeing is not the first entity to use this process, but it is the first company to attempt to build a large scale composite commercial aircraft. While the internal rates of returns and profit projections for the Boeing 787 are not known at this time, the company is undergoing this innovative manufacturing process with profits as the overarching motive.

Composite Affordability Initiative

In the mid-1990's, the Air Force Research Laboratory (AFRL) realized that the aircraft industry was hesitant to significantly incorporate advanced composite materials into new aircraft even though advanced composites were proving to be beneficial. Composites have been utilized in multiple fighter aircraft such as the F-15, F-16, and F-

18 in small percentages. However, data shows that composite applications have reached a plateau with the F-22 being a good example of this phenomenon. Early projections for the F-22 airframe detailed that the aircraft structure be 50% composite by weight but the structure was eventually settled back to 25% composites by weight (Russell, 2006: 3). Due to this consistent lack of willingness by both the Air Force and industry partners to embrace composite materials in aircraft structures, AFRL launched the Composites Affordability Initiative (CAI) to address the perceived risks and barriers of using composites.

More specifically, the CAI was established to significantly reduce cost, development cycle time, and weight of military aircraft. The vision of the CAI team was to "develop the tools and technologies necessary to enable aircraft designers to confidently design an all-composite airframe utilizing revolutionary design and manufacturing concepts, enabling breakthrough reductions in cost and weight (Russell, 2006: 3-6)." The CAI team was a joint effort by both the Department of Defense (DoD) and the aerospace industry. Specifically, the CAI team included personnel from AFRL Materials and Manufacturing Directorate (AFRL/ML) and Air Vehicles Directorate, the Office of Naval Research-ManTech, Bell Helicopter Textron, The Boeing Company, Lockheed Martin Corporation, and Northrop Grumman Corporation (Russell, 2006: 3-4).

The CAI was broken down into phases with Phase I designated as the "Concept Design Maturation activity." The goal of Phase I was to determine the critical issues preventing the full utilization of composites and provide an evaluation to demonstrate the feasibility of the established goals. Phase I of the CAI included seven tasks that were undertaken over a six month time frame. The tasks were predominately technical reviews analyzing the barriers encountered in using composites in large structural components during aircraft manufacturing. The final product of Phase I was the top level design definition of an affordable airframe concept. The idea was to develop a product that would demonstrate state-of-the-art capabilities that would be demonstrated during a fast track demonstration during Phase II of the CAI (Baron, 1997: 18-20). The Phase II "Pervasive Technology" effort was the second phase of a multi-phase program to achieve the CAI goal and vision. The main goal and vision for Phase II was to reduce the acquisition cost of composite structures by 50% (Koury, 1998).

Phase II was divided into 10 tasks; Task 1was the management task for the program and Tasks 2 through 10 were the specific activities that would allow CAI to achieve the Phase II program objectives. These tasks developed design concepts, matured affordable manufacturing processes and developed cost, structural, and quality analysis tools. Each task had specific objectives to achieve the overall goal of reducing the cost of composite structures. A number of items were identified and these formed the basis for the approach and development work for the Phase II Pervasive program. The majority of objectives for each task was technically oriented and will not be discussed in detail in this report. However, the overarching approach that the CAI team took to reduce composite aircraft cost was to reduce part count, reduce/standardize fastener count, reduce touch labor hours, and reduce manufacturing support labor hours per unit. The manufacturing support labor hours included: industrial engineering, manufacturing engineering, and quality assurance. Also the CAI team attempted to reduce tooling hours and reduce indirect cost (Koury, 1998).

Cost trade studies were conducted in 1999 to develop a new Configuration 140 structural concept based on the developments and lessons learned from the first two years of Phase II. The Configuration 140 was the baseline aircraft that was used as the benchmark for the CAI and provides the baseline against which the CAI developed design and manufacturing technologies. The Configuration 140, shown in Figure 2, is a modified version of the LM advanced design configuration 140 aircraft.

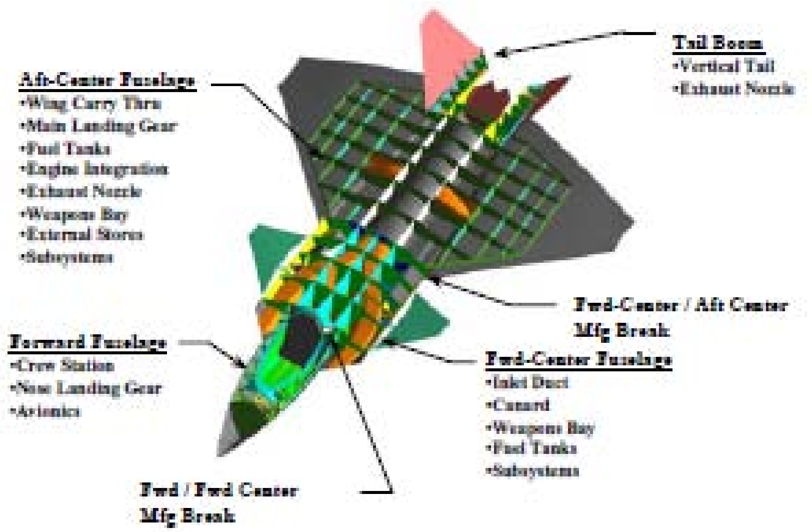


Figure 2: CAI Baseline Aircraft--LM Configuration 140 (Koury, 1998)

The cost trade study resulted in the configuration for the "Concept C" aircraft, shown in Figure 3. The Concept C aircraft was compared and evaluated with the baseline aircraft, the LM Configuration 140.

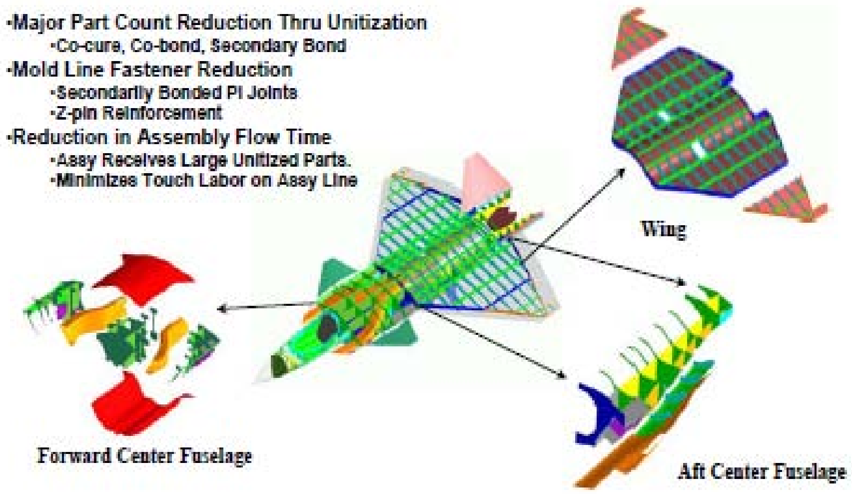
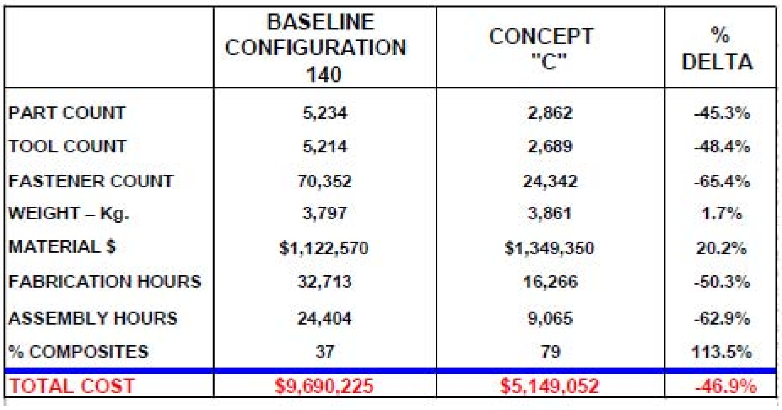


Figure 3: CAI Concept C Aircraft (Koury, 1998)

Table 7 shows the comparison of the Baseline and the Concept C data for the measurable data metrics. The data is based on cumulative average cost for 2,000 delivery vehicles and all cost are in FY94 dollars.

Table 7: Concept C and Baseline Metrics Categories (Butler et al, 2002)



	BASELINE CONFIGURATION 140	CONCEPT "C"	% DELTA
PART COUNT	5,234	2,862	-45.3%
TOOL COUNT	5,214	2,689	-48.4%
FASTENER COUNT	70,352	24,342	-65.4%
WEIGHT – Kg.	3,797	3,861	1.7%
MATERIAL $	$1,122,570	$1,349,350	20.2%
FABRICATION HOURS	32,713	16,266	-50.3%
ASSEMBLY HOURS	24,404	9,065	-62.9%
% COMPOSITES	37	79	113.5%
TOTAL COST	$9,690,225	$5,149,052	-46.9%

Consistent with the goal of the CAI, the Concept C structural configuration shows a substantial increase in the percentage of composites incorporated into the aircraft structure (Butler, 2002: 22).

With the increased percentage of composites used in the aircraft structure, it is not surprising to see the 45.3% decrease in the total part count. The majority of the metrics decreased for the Concept C aircraft compared to the baseline except for weight and material costs. The material cost increased by 20.2% and this increase is consistent with previous studies that show the price of composites to be significantly greater than standard metallic materials. Overall, the cost trade study predicted a 46.9% cost savings and this is close to the CAI Phase II program goal of 50% cost reduction or cost savings for composite aircraft.

The cost trade study for the CAI Phase II also examined cost savings by cost categories as visually represented in Figure 4.

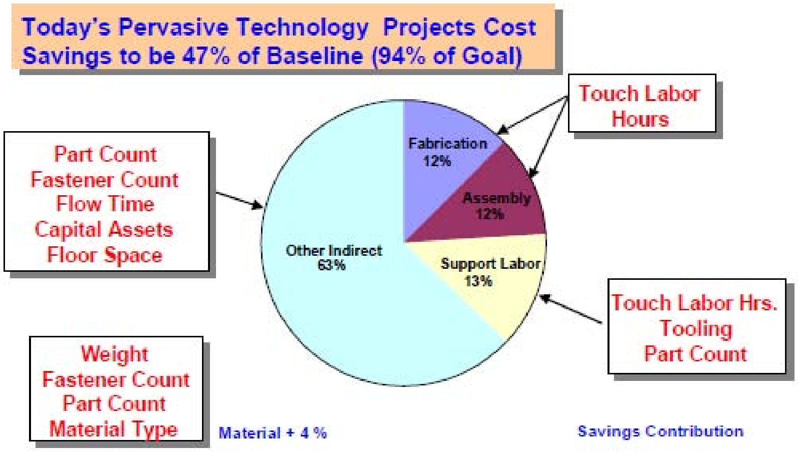


Figure 4: Projected Cost Savings by Cost Category for Concept C (Butler et al, 2002)

The projected reduction in cost demonstrated by the CAI Phase II program is due to a concentrated effort to use composite materials more effectively in aircraft design. These projections will only become reality if there is a significant paradigm shift in composite use which combines affordable design with affordable process at the system level (Koury, 1998).

Advanced Composite Cargo Aircraft (ACCA)

ACAA Production Study was a joint effort between AFRL and Lockheed Martin and is the direct result of the lessons learned in the CAI program. ACAA was established to determine how composite technologies and composite design techniques would work in a low production quantity military transport aircraft (Zelinski, 2010). The ACCA Production Study also identified the technologies that have the most impact on the weight and cost of the air vehicle. The study affirms that the technologies used in the ACCA program are still immature; however, the study identifies roadmaps for each immature technology that will bring the Technology Readiness Level (TRL)/Manufacturing Readiness Level (MRL) to a TRL/MRL of 5 by 2013. Figure 5 is the “program flow” that the ACAA team took in meeting the program goals. The focal point for this research is Task 2 but an explanation of the program is needed to gain a better understanding of the ACCA process.

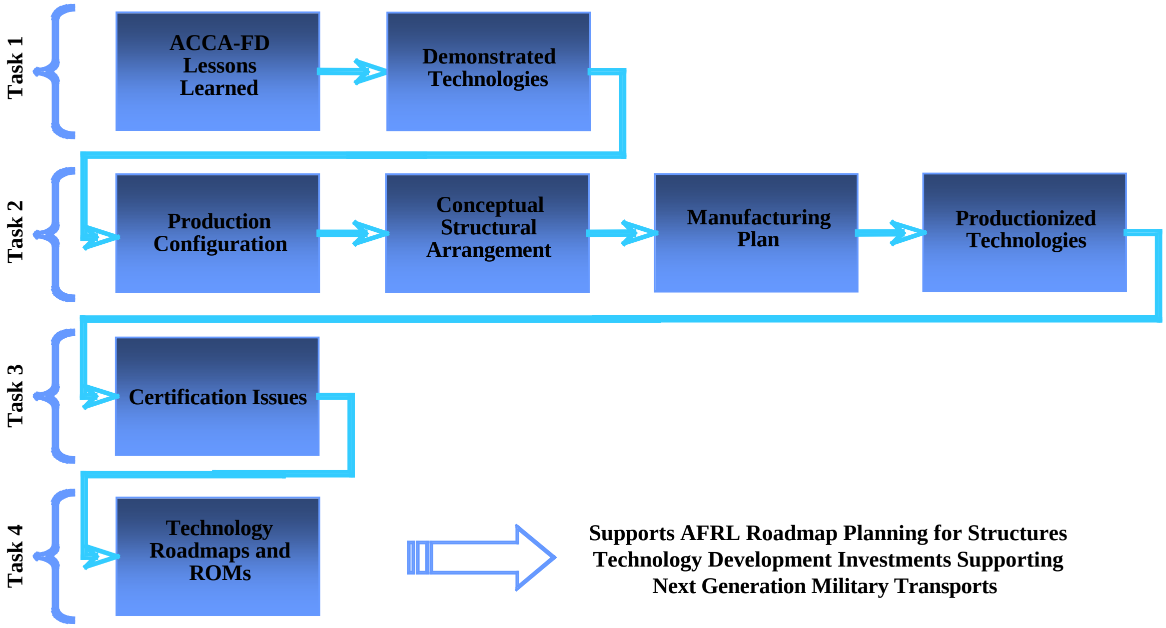


Figure 5: ACCA Task Flow (Neumeier et al, 2009)

The ACCA or X-55 is a single production aircraft intended to demonstrate the use of advanced composite materials in the fuselage and the vertical tail of a conventional high-wing transport aircraft, a Fairchild Dornier 328J (DO-328J). This approach replaced approximately 40% of the total vehicle structure with unitized/integrated composite structures. Figure 6 is a visual representation of the major structural components for ACCA. In order to transform the DO-328J into a military cargo aircraft, certain modifications that addressed military utility interests were incorporated into the reconfigured design of the X-55. The most noticeable modifications included enlarging the fuselage to accommodate a 463L pallet and modifying the aft cargo door.

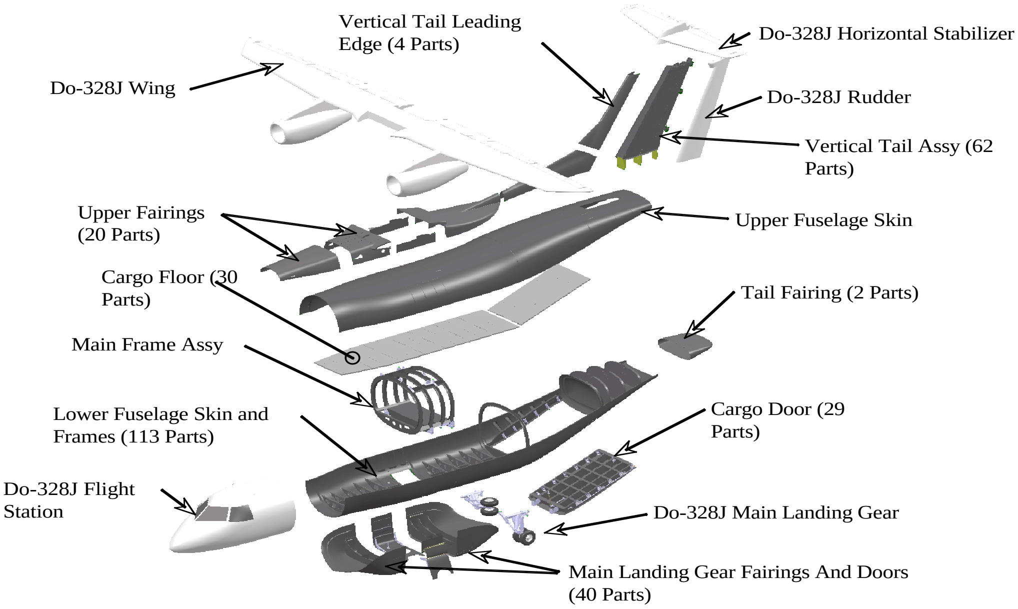


Figure 6: ACCA Major Structural Components (Zelinski, 2010)

Figure 7 illustrates a detailed breakout of the fuselage assembly modifications that was replaced with an advanced composite design.

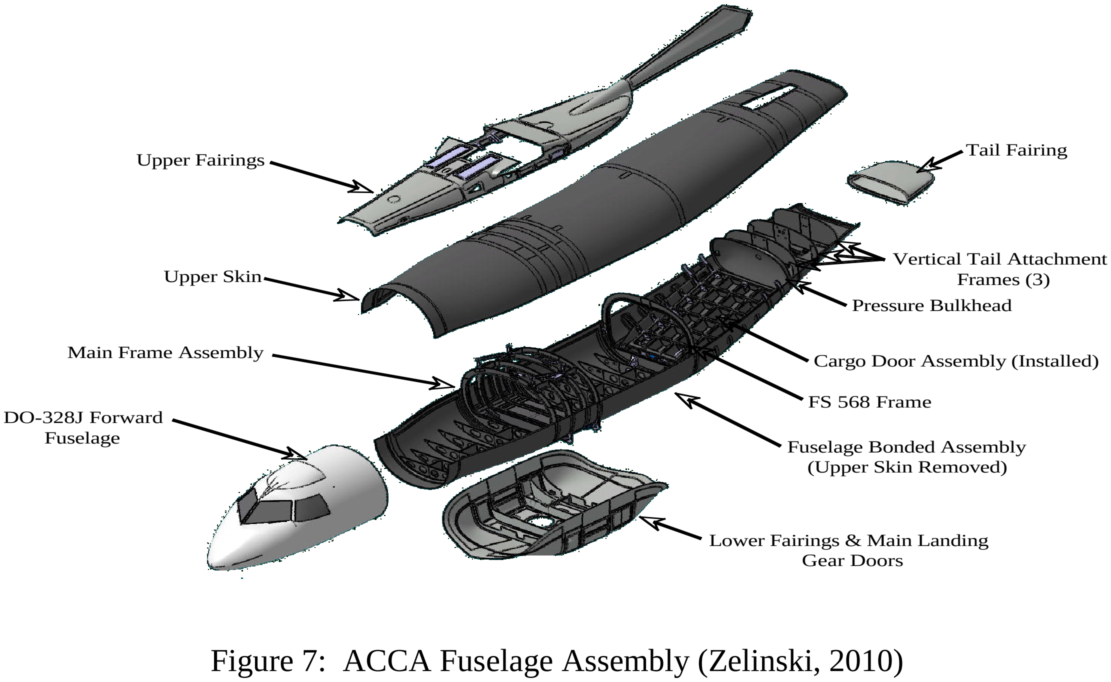


Figure 7: ACCA Fuselage Assembly (Zelinski, 2010)

The success of the ACAA program in meeting the program goals of reducing the part count by at least one order of magnitude and reducing the number of drawings and inspection requirements was possible through four key technologies: Large integrated sandwich structures, Out of Autoclave Materials, Pi Preforms, and Fiber Placement (Zelinski, 2010). While none of these technologies are revolutionary, taken together in a concerted effort these technologies allowed the ACCA program to achieve its program goals.

Of particular interest to this project is how the use of composites affected the cost of the ACCA. The ACCA production study addressed cost throughout the program and offers several insights into how large integrated composite structures affect cost. As noted in previous studies, part count plays an important role for in house cost. The study indicated that fewer, larger parts will cost less on both a non-recurring and recurring basis (Zelinski, 2010). The ACCA study estimated that the redesigned fuselage was able to achieve a 90% reduction in part count while the vertical tail reconfiguration achieved an 80% reduction in part count compared to the original DO328 aircraft (Zelinski, 2010). While these findings are a confirmation of early predictions by previous studies, an area of interest is how these findings can be utilized in the current cost estimating community. The current CERs that are used to forecast LCC for composite aircraft are not reflective of the cost reductions due to reduced part count. This research will address this deficiency in current LCC models.

III. Data Collection and Methodology

Introduction

This chapter will examine the dataset used for our analysis and the methodology used to incorporate the actual Advanced Composite Cargo Aircraft touch labor hours into the dataset. Furthermore, this chapter will detail how we intend to perform our analysis and utilize any relationship that is discovered.

Data Sources

The data for this research came predominately from the Advanced Composite Cargo Aircraft (ACCA) program work breakdown structure and a leading aerospace company. The ACCA is funded entirely by the Air Force Research Laboratory and the data is entirely accessible to the Department of Defense (DoD) and DoD contractors.

As was referred to in the preceding paragraph, a leading aerospace company temporarily provided data in support of this research. This aerospace company will be referred to as “Company X” for the remainder of this research to protect the company’s proprietary information. This research along with previous research on this topic done by Captain Aaron Lemke in 2009 and 2010 seeks to respect Company X’s proprietary information and not compromise any competitive advantage that Company X has in this field. Company X’s dataset consist of aircraft production and development manufacturing and cost data for a variety of metallic and composite military aircraft. Company X’s data set is subdivided into various cost categories including manufacturing, design, design support, testing, tooling, logistics, and quality assurance touch labor hours. The dataset also contains various aircraft weights, part counts, and average part sizes.

While the data set has numerous potential research uses, we are primarily interested in the touch labor hours for design, design support, tooling, and testing. This dataset combined with the ACCA data will provide a sufficient sample *n* for statistical analysis.

This analysis will rely on a cost model built by Company X that predicts whole aircraft structure values. Company X has done considerable research on the relationship between the air vehicle weight taken from the Defense Contractor Planning Report (DCPR) and the whole structure values of the aircraft (part count) using traditional manufacturing methods. DCPR is the “in house” weight or the amount of the air vehicle built by the prime contractor.

Using the DCPR CERs, Company X has developed an extensive cost model designed for first unit predictions for prototype aircraft. Company X’s model incorporates all costs factors that are relevant to predicting the first unit cost for prototype aircraft, however, this research will only examine the variables related to design, design support, tooling, and testing hours. As was indicated in the preceding paragraphs, Company X uses the DCPR as one of the fundamental basis for their model. The model also incorporate several other variables (18 in total) into their model including a state-of-the-art (SOA) factor as well as stealth presence, quantity, max velocity, aspect ratio to capture the broadest cross-section, and status as a military or civilian aircraft (Lemke, 2010: 15).

These variables are consistent with the RAND generated CERs that are currently used by AFRL in their Life Cycle Cost (LCC), with the exception of the RAND CER using empty weight versus the DCPR. The modification of the RAND CERs is the goal of this study, with the variable of interest being a respective percentage to be applied as an additional factor to the RAND CER for design, design support, tooling and testing touch labor hours. To complete this analysis, this research will need to complete two data collections. This research will need to obtain an adequately large set of actual first unit touch labor hours and the respective part counts for the vehicles examined.

As was outlined earlier, Company X provided a dataset of aircraft touch labor hours; the next section will detail the inclusion of the ACCA data into this dataset.

Incorporating ACCA into Existing Data Set

One of the challenges of including the ACCA data into Company X’s data set was the issue of ACCA being a modification of an existing aircraft and not a whole new structure design. ACCA was an anomaly in aircraft manufacturing in the sense that the contractor who was awarded the contract to modify the DO-328J was not the original manufacturer and had limited knowledge of the original aircraft. The ACCA program was only a partial modification consisting primarily of fuselage and vertical tail modifications (40% of the vehicle structure by weight). In order to include the ACCA data into Company X’s dataset, certain calculations had to be performed to extrapolate a “whole structure” data point. We relied heavily on the expertise of Company X to project the systems and structures weights from the partial modification of the DO-328J as if the entire aircraft is a new production. The assumption with this methodology is that the DO-328J and the vehicles used for comparison are analogous. We relied on Company X and the ACCA manufacturer’s expertise in this area to make this assumption; however, we were unable to validate this assumption statistically and realize this is a limitation in the research. We also relied on these sources to determine the accuracy of the vehicle complexity, state-of-the-art factors, and other factors that we will utilize in the initial predictive model.

Once we determined the modified portions empty weights, we were able to generate ratios for the remaining cost elements that are of interest to this research: design hours per pound, design support hours per pound, tooling hours per pound, and test hours per pound. A major assumption with these calculations is that if the DO-328J had been a whole-structure modification, the part count reduction would hold constant at 10% of original parts and the weight to touch labor hours would remain constant.

Another aspect in dealing with aircraft production is learning curves (LC). The LC theory is based on the principle that the time required to perform a task decreases as the task is repeated, the amount of improvement decreases as more units are produced, and the rate of improvement has sufficient consistency to allow its use as a prediction tool (http://fast.faa.gov/pricing/98-30c18.htm). This theory is well documented in aviation manufacturing and is included in the majority of LCC models. For this research we had to decide whether to treat ACCA as a first unit iteration or as a subsequent iteration. Since the manufacturer who performed the modification of the DO-328J was not the original manufacturer, we decided to treat this modification as a first unit production vehicle. Based on conversations with both AFRL personnel involved with the ACCA program and the prime contractor, information about the original design was limited. This resulted in the contractor receiving almost no learning and in the eyes of the prime contractor the ACCA program was a new design.

As a crosscheck for our “whole-structure” calculations, we used a scaled version of Company X’s cost model to see if the model would predict results similar to the actual values. The results for design hours and tooling hours were similar with the predicted design hours being within 30% of the actual hours and the predicted tooling hours within 10% of the actual hours. The predicted results for design support hours and testing hours were not as valid with the predicted results being 80% higher. We theorize that the discrepancy for testing actuals is due to on-going flight testing and when the final actual values are known they will be closer to the predicted amount. The inconsistency between predicted design support hours and actual design support hours is unknown at this time and needs to be researched further. Even with the discrepancies between the predicted values and actual values, we still treat these findings as valid and have included the values into the dataset.

Identify Relationship

If a relationship does not exists among the design, design support, tooling and testing hours and part count, the remaining research question will be immaterial and we will not be able to complete the objectives of this study. The first step in identifying a statistical relationship between the variables of interest is to show that a relationship does exist between the vehicle weight and traditional part count. The Ordinary Least Squares Method (LSM) will be used to perform all regression analysis for this research. The statistical software that we will use to perform our analysis is JMP and Microsoft Excel. If this relationship is shown, it will allow for the projection of average pounds per part relative to vehicle weight. This relationship, along with real part count reduction instances, will provide the opportunity to project touch labor hours for a particular part count. If there is a trend, then we can make the assumption that a relationship does exist between part count and our variables of interest

Classify the Relationship

If a statistically significant relationship does exist, the next step is to quantify this relationship in a manner that the relationship can be included in the AFRL LCC model. If a relationship does exist, the fit and appearance of the CER will determine the impact that the CER will have on the LCC model. The assumption is that a reduction in part count will lead to a reduction in design, design support, testing and tooling hours. The magnitude of this reduction is dependent on both the statistical significance of the CER and the method in which the current LCC model CERs are incorporated into the model.

The current model is a product of continuous revisions and updates by cost estimators at AFRL. The foundation for the CERs in the AFRL model for design hours (recurring engineering hours), design support hours (non-recurring engineering hours), testing hours, and tooling hours are the RAND equations developed in the 1990's. This research, as with previous research, is not attempting to substitute the current CERs but is rather a concentrated effort to update the current CER. Presently, the AFRL model has notional factors to account for reduced part count when using composite materials. These notional factors were incorporated into the model based on research from the Composite Affordability Initiative; however the factors are a static value and do not consider that with increased composite usage, the part count will decrease. The goal of this research is to replace or validate these notional factors with a statistically significant factor in order to further strengthen the current model.

In order to gain a comprehensive understanding of the current model, we will dissect portions of the model and conduct interviews with the owners and users of the model. This understanding of the methodology and mathematical dependencies within the model will enable us to determine the impact of any recommended changes. A byproduct of this analysis is a qualitative understanding and layout of the AFRL LCC model. We did not evaluate the model for accuracy; the model is the property of the sponsor organization and is their theories and methods of calculating life cycle cost. A visual representation of the model is contained in Appendix A.

Employ the Relationship

The sponsor organization for this project, the Air Force Research Lab, has provided the LCC model used by their cost estimators. Assuming a relationship exists between part count reductions and touch labor hours for design, design support, testing and tooling, it will be necessary to incorporate this relationship into the AFRL LCC model. If part count is already integrated into the model, we will need to review its utilization and any prospective changes to such process to capture the relationship in question. If part count is not included in the current CERs for the LCC model, it may be necessary to add a factor to account for cost savings due to reduced part count.

Assuming a relationship exists and that we incorporate or validate the part count reduction factors into the AFRL LCC model, we will evaluate the cost differential for a production scenario for 100 unmanned drones. This evaluation will show the potential cost savings for touch labor hours when large scale parts are integrated into the production process.

ACCA Manufacturing Process vs. DO-328J Manufacturing Process

The final question for this research involves comparing the touch labor hours for ACCA to the touch labor hours of the original DO-328J. The DO-328J was originally manufactured by Dornier Luftfahrt GmbH, a German aerospace manufacturer, in the early 1990's. The company was acquired by Fairchild Aircraft Company in 1996 and subsequently went out of business. Due to the dissolution of the original manufacturer, limited data is available on the DO-328J. This lack of actual data makes it difficult to compare the manufacturing processes for the two air vehicles.

Being unable to obtain the actual data relating to our variables of interest, we will have to estimate the number of touch labor hours that was required to produce the DO-328J. Company X has graciously assisted with this estimation. Using the cost model developed by Company X, we will attempt to estimate the number of hours required by the original equipment manufacturer (OEM). We will rely on Company X, the ACCA manufacturer, and AFRL personnel for inputs into this model. Assuming that we are able to estimate the number of touch labor hours required by the OEM, we will have to scale the hours down to account for the ACCA program being a modification and not a whole-structure process.

IV: Analysis and Results

Identify the Relationship

In order to establish that a relationship exists between part counts and touch labor hours, we must first show that a relationship exists between the Defense Contractor Planning Report (DCPR) and part count. Using data provided by Company X, we were able to show that an exponential relationship does exist. This is shown in Figure 9; the adjusted R^2 for this relationship is 0.95.

Numerous empirical studies have shown that vehicle weight is a leading contributor to air vehicle cost, however, the statistically significant correlation between part count and weight confirms that part count also has an important influence on cost.

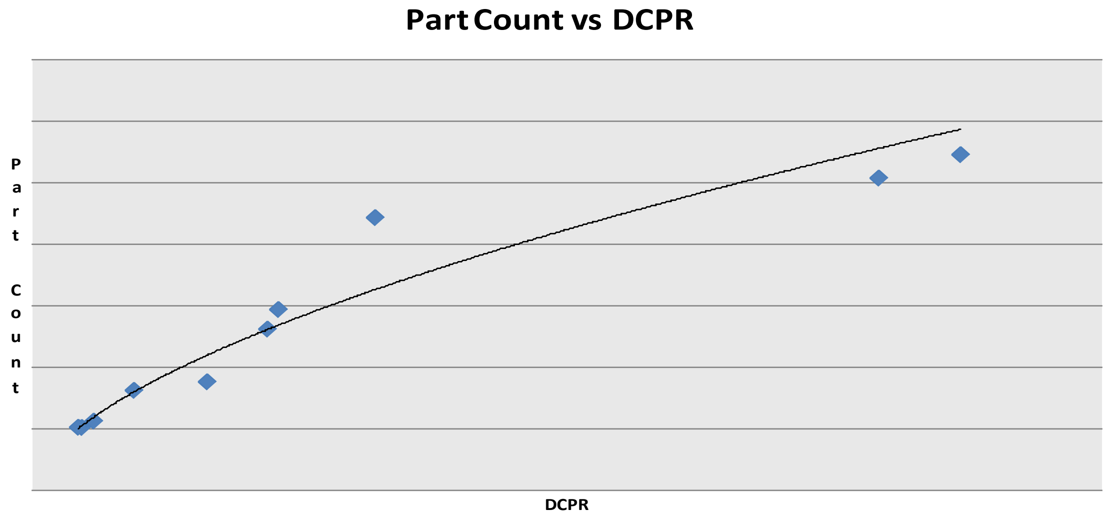


Figure 8: Part Count vs. Defense Contractor Planning Report/Vehicle Weight (Company X)

As with other figures shown in this document, we have excluded scale values to protect the proprietary information of Company X and have only retained the fit of the line itself.

Using our dataset we are able to separate the cost in terms of hours per pound by functional discipline with hours per pound by cost element on the vertical access and average part size on the horizontal access. All the cost elements demonstrated fewer hours per pound with larger part sizes and we were able to show some uniformly downward sloping cost trends as shown in Figure 10.

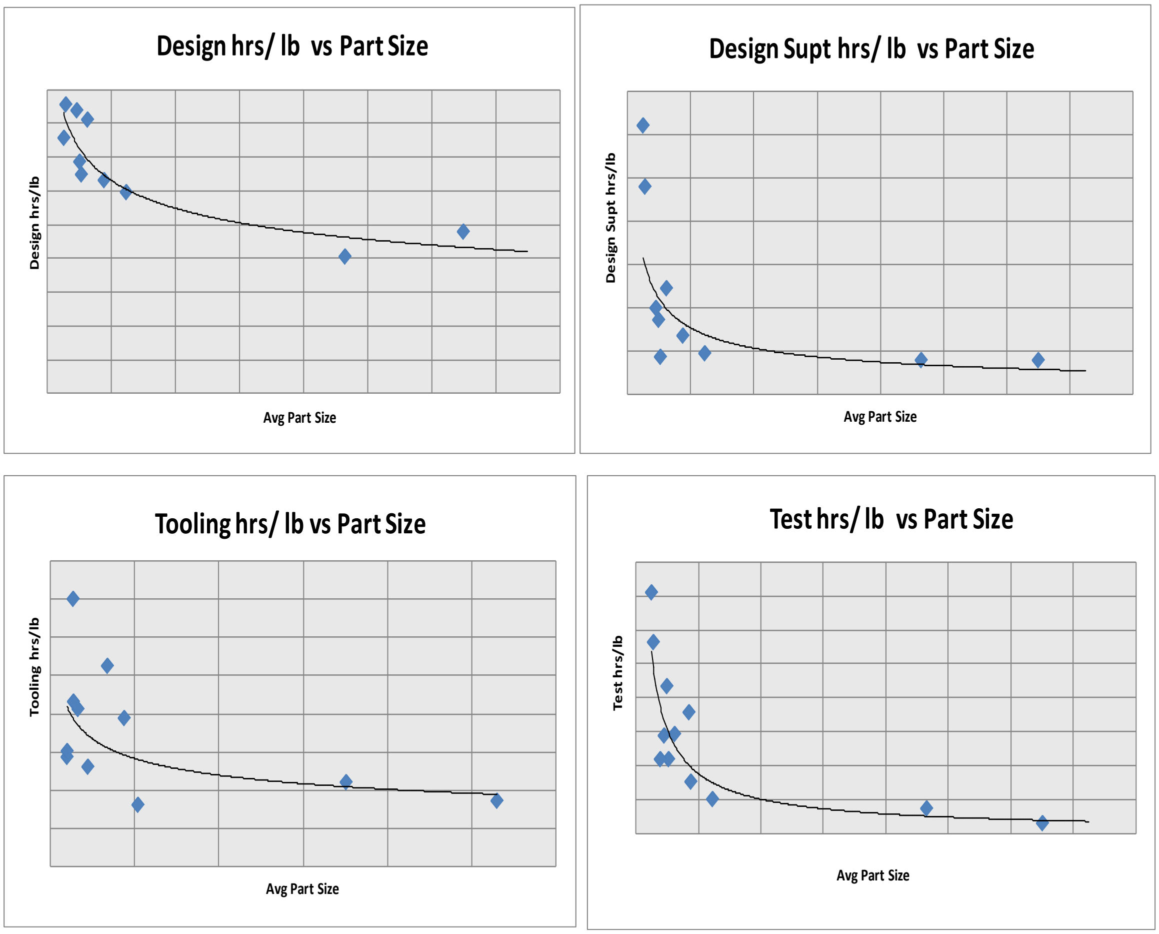


Figure 9: Discipline Hours vs. Average Part Size

A limitation with this data set is the lack of data relating to large scale composite parts. This is visually shown in Figure 10 with the two data points on the right side of the four graphs. The data points could be overly influential in the data set and driving the regression results. There are two methods for determining whether data points are influential: removing the two data points and observing the change in the overall regression results and a statistical test called Cook's D. We first removed the data points and observed the change in the regression parameters. While the removal of the data points did change the regression parameters, the change was not significant. The next process that we undertook was to perform the Cook's D test in the JMP statistical software. The test determined that the data points were not influential data points. The regression results of this process illustrated that while the two data points strengthen the regression results, they are not influential because the overall regression results remained statistically significant. The addition of the two data points strengthens the relationships shown but does not drive the results and thus we can assume that the relationships derived from this analysis meets the statistical requirement of independence.

The adjusted R^2 for design hours and testing hours were relatively high and the relationships were statistically significant as can be seen in Table 8. Design support hours had a low adjusted R^2, however, the relationship is still significant with a p-value less than 0.05. The one element that was not statistically significant was tooling hours. Although tooling hours did have a downward sloping trend, the adjusted R^2 and p-value were not statistically significant. Due to tooling hours' adjusted R^2 and p-value, we conclude that while tooling hours and part count have a relationship, it is not statistically significant and was excluded from further analysis.

Table 8: Discipline Statistic Values

Cost Element	Adjusted R^2	P-Value
Design Hours	0.804	0.000
Design Support Hours	0.558	0.008
Tooling	0.275	0.056
Testing	0.830	0.000

With the relationship shown between part count and the three cost disciplines, we were able to generate the curves shown in Figure 11. The horizontal access for these charts is the percentage reduction in part count and the vertical access is the corresponding percentage reduction in touch labor hours for each discipline. As with other figures throughout this document, we excluded scale values to protect Company X competitive advantage. Excluding tooling hours, the trends indicate that a relationship does exist between part count and design, design support, and testing hours. We tested for normality by plotting the standardized residuals of design hours, design support hours and testing hours and performing the Shapiro-Wilkes test. There were no outliers identified by these graphs and the graphs are contained in Appendix C.

While the data curves in Figure 11 appear to be exponential, it is more realistic that the curves are polynomial or linear in nature. It is unrealistic to make the assumption that the most efficient outcome for touch labor hours is one single aircraft part. Realistically, there will be a low point on the bottom left hand corner of the graph (Lemke, 23). This is a point of interest among numerous researchers in the aircraft composite field on the optimum level of large scale composite parts. Researchers realize the benefits of using large parts but also recognize that there is an optimum point on that curve, where large parts would become more of a hindrance than beneficial. While this facet of using large scale components is intriguing, this research will not investigate the optimum usage at this time.

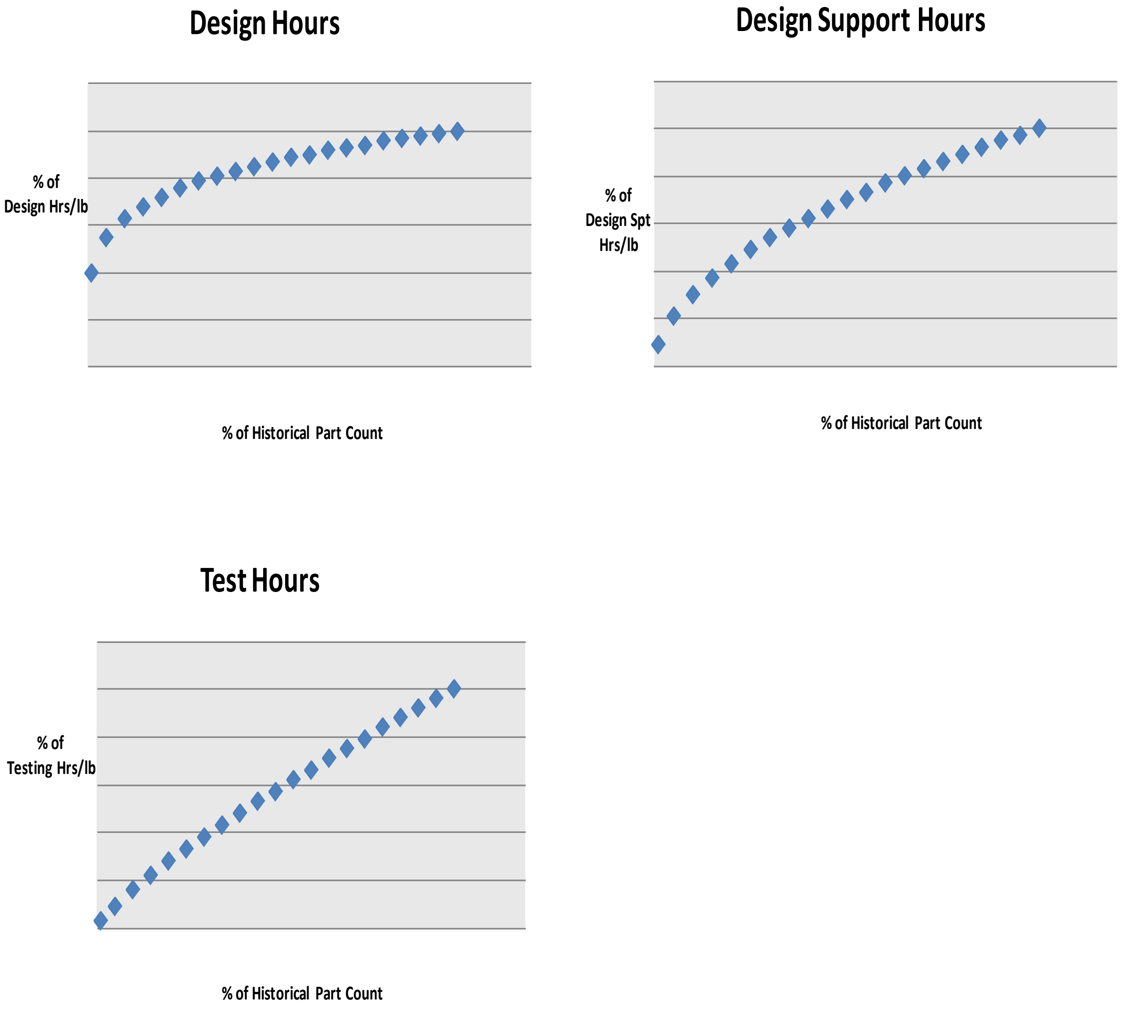


Figure 10: Touch Labor Hours vs. Part Count

The shapes of the curves differ by cost discipline with testing hours having the steepest slope and displaying almost a linear relationship. Conceptually, testing hours will reduce as the part count reduces, since fewer parts need to be tested. We still contend that testing hours is a polynomial relationship due to conversations with experts in this field and that there will be an optimum point in part count reductions below which testing hours will start to increase with reduced part counts. Design support hours or non-recurring engineering also follows a polynomial curve. Design hours or recurring engineering hours is a time intensive operation and is contingent on numerous factors with the number of parts being one of many inputs into the total design of a system. However, as can be seen in Figures 10 and 11, the design hours will fall as the number of parts decrease, but the reduction is not as dramatic as that of testing and design support.

The adjusted R^2 for these curves were 0.95 for design hours and 0.99 for design support and testing hours, where n =10 for design and design support and n=12 for testing hours. A significant limitation of this research is the regression of the curves in Figure 11. If a power fit had been used in lieu of the polynomial fit, the adjusted R^2 would have been 1, a perfect fit.   The unusually high adjusted R^2s are due to the curves being generated by an estimate. Generating data points using estimates will remove all variation and error from the subsequent relationship. This poses significant statistical problems and the estimate is only viable for estimating the mean values.

Classify the Relationship

Each cost discipline portrays a generally positive slope, as depicted in Figure 11. The upper right hand corners of the graphs equates to a traditional 100% normal part count in air vehicles. Consequently, the greatest reduction in hours per pound would occur at the bottom left corner of the graph. Thus the relationships can be quantified with a reduction in part count leading to a reduction in touch labor hours.

We quantify this relationship by the fit of the line; we exclude the actual values of the relationships to protect the proprietary information of Company X. The masked fit of the lines are as follows:

- *Part Count Percentage Reduction for Design hours* (H_{RE} *%) =*
- *Part Count Percentage Reduction for Design Support Hours(*H_{NRE}*%)=*

- *Part Count Percentage Reduction for Testing Costs (*C_T *%) =*

The variables *a-i* represents the masked coefficients of the line and PCP is the variable created to represent the percentage of part count reduction.

Employ the Relationship

Now that the research has determined that a relationship does exist between part count and design, design support, and testing hours and quantified the relationships, the next task is to incorporate those relationships into the AFRL LCC model. Currently the LCC model has notional static values incorporated into the model for recurring manufacturing hours, recurring engineering hours (design hours), recurring tooling hours, and contractor test. This project is attempting to replace the static values for recurring engineering and contractor test, as well as incorporate the non-recurring engineering (design support) hours into the model and remove the value for recurring tooling hours.

Incorporating the CERs into the model is not difficult for recurring engineering due to the static factor being currently built into the model and, therefore, we only have to replace the static value with the new CER. Non-recurring engineering is not currently incorporated into the model and will have to be incorporated into the model later to reflect the recommended changes resulting from this research. The static factor for testing cost is currently built into the model, but the current CER for testing cost is a percentage of non-recurring developmental costs. Due to the testing cost being a percentage of non-recurring developmental cost, there will be a compound effect when the percentage reduction is incorporated into the model for non-recurring engineering hours. With this compound or multiplicative effect in mind, we will examine alternative CER's for testing costs for the AFRL model.

With these new CER's for recurring and non-recurring engineering hours incorporated into the model, we can evaluate the effect that part count reduction has on the LCC model. We will examine the contractor testing cost later in this report. We will accomplish this by building a LCC estimate with the new CER values and comparing this value to a LCC estimate not incorporating part count.

To evaluate the LCC model with the new CERs in place we will examine a hypothetical scenario of 100 drones with a 25 year life cycle. We are not stating that this is reality but rather we intend to provide a quantitative value for comparison. The values themselves will be irrelevant and that only the deltas or percentage increases/decreases between the models will be of interest to the reader. We will not examine every input into the model but we will highlight several of the significant inputs to illustrate the scenario.

A main driver of reduced part counts is greater use of composite materials in the materials composition of the aircraft. For our scenario, we concluded that 80% of the drone materials would be made of composites. This large percentage of composites in the material composition of the drones will give validity to our assumptions of reduced part count. In addition, the inclusion of composites as the greatest percentage of materials in the composition of the aircraft will highlight the bias in the RAND CERs towards composite materials. Other inputs of interest include the assumption that the development stage of the program would last five years and the drones would be in produced over a nine year time period beginning in 2010, all dollars are in base year 2010.

As a first step into our analysis of the AFRL LCC model, we will examine the total life cycle cost for our scenario and inspect the cost drivers for the life cycle cost. Figure 12 is the relative percentages of the elements within the total life cycle cost. Procurement and Development, which represent over 60% of the LCC, are the two points of interest for this research and we will examine how the incorporated CERs affect these two cost elements.

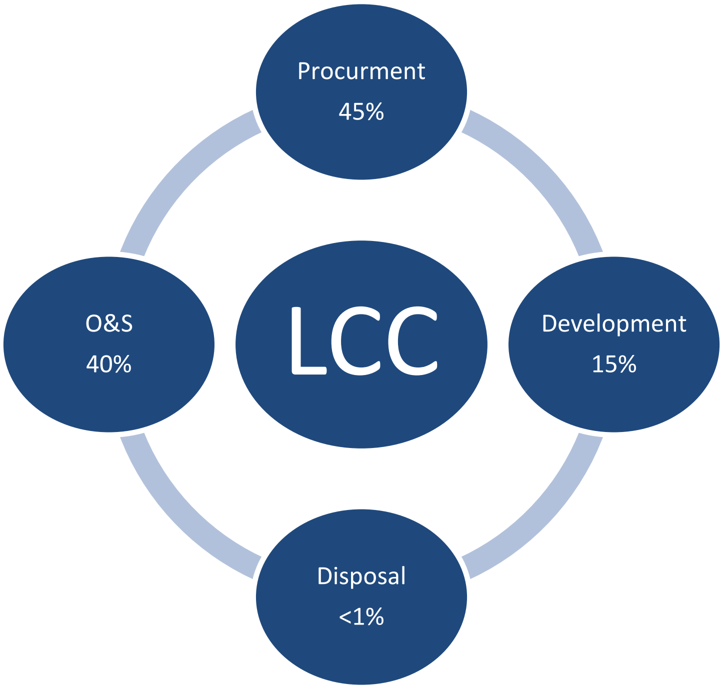


Figure 11: Cost Elements of Life Cycle Cost

The cost elements examined in this research filter through both the development and production aspects of our scenario. Design hours or recurring engineering hours occur during the production stage of the weapon system life cycle, while design support or non-recurring engineering and testing transpires during the development stage of the program. These variables constitute approximately 11% of the program total life cycle cost. Specifically, recurring engineering comprises 4% of the total life cycle cost and non-recurring engineering and testing represent 6% and 1% of the total life cycle cost respectively.   Figure 13 illustrates the progression of the elements through the different aspects of the program life cycle costs. The variables of interest are highlighted within the figure. While manufacturing costs were not a focal point of this research, we included the values to give a comparison of the different cost disciplines and how each discipline relates to the total life cycle cost.

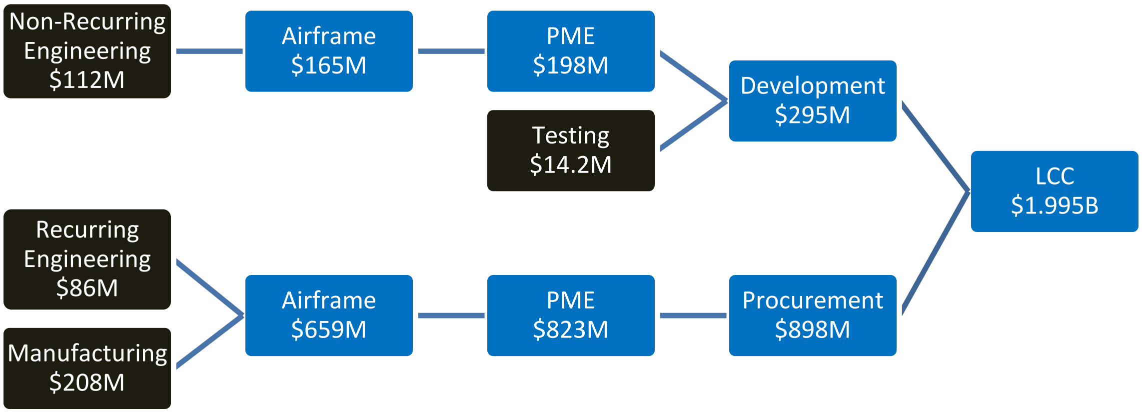


Figure 12: Cost Elements Life Cycle Cost Progression

Only the variables of interest were included in Figure 13; the progression starts with the variable of interest (highlighted cells) and follows this variable through the program to the total life cycle cost. If all cost elements were included in a single diagram, manufacturing, tooling, quality control, and material would all sum to the $659M value listed for airframe in the diagram. Subsequently, airframe, engines, and avionics would sum to the $823M for prime mission equipment.

The points of interest in this scenario are the 11% of the total life cycle cost, recurring engineering 4%, nonrecurring engineering 6%, and testing 1%, that are affected by the part count reduction relationship. We will examine the current methodology for determining the cost of recurring engineering, non-recurring engineering, and testing, and incorporate our recommended changes into the current CERs.

For the subsequent figures, C_{RE} represents cost of recurring engineering, C_{NRE} represents the cost for non-recurring engineering, and C_T represents the costs of testing. C_{RE} and C_{NRE} are calculated by taking the number of hours for that particular variable multiplied by the respective labor rate (LR). Currently, C_T is a percentage of total non-recurring development cost. H_{RE} corresponds to recurring engineering hours and H_{NRE} is the variable representing non-recurring engineering hours. Figures 14 and 15 demonstrate the inputs relative to the cost of recurring engineering and non-recurring engineering.

Figure 13: Recurring Engineering CER

RENG is a Recurring Engineering Factor and NRENGR is a Non-Recurring Engineering Factor. These factors are associated with vehicles using large scale composite materials. Weight and speed are the two main cost drivers for hours in these CERs and part count is not taken into account in either CER.

Figure 14: Non-Recurring Engineering CER

Currently, C_T is a percentage of non-recurring development costs. Testing refers to the cost associated with flight test incurred by the contractor and occurs during the developmental stage of the program. In the current form, testing costs are a function of non-recurring developmental costs, of which non-recurring engineering cost is an input. Any change to the CER for non-recurring engineering will have a multiplicative effect in determining testing costs due to this relationship. Now that we have identified this compound effect related to testing costs and non-recurring engineering, we can explore alternative CERs for testing costs. One of the most widely used CERs for calculating testing and more specifically flight test is Daniel Raymer’s CER. Raymer’s CER is widely accepted as an accurate prediction for testing costs and has been used by AFRL in several of their cost models. We contend that this CER should be included in the LCC model in lieu of the current CER to offset any potential compounding effects of part count reductions. Figure 16 shows the inputs for calculating the cost of flight testing (Raymer, 2006: 587).

Figure 15: Testing Costs CER

With the inputs outlined for the three cost disciplines, we can now make our recommended changes. As mentioned previously, part count is not currently taken into account in the LCC model. Any concentrated effort to reduce part count is not reflected as an input into the cost elements. Based on the relationship between part count and the three cost elements of interest, we expect that as part count decreases, a decrease will be seen in recurring and non-recurring engineering hours and the testing costs. We will now apply the relationship as a new calculation for each cost element with H_{RE}% reflecting the part count percentage reduction for recurring engineering hours, H_{NRE}% representing the part count percentage reduction for non-recurring engineering hours, and C_T% representing the part count percentage reduction for testing costs. These new percentage reductions will be additional factors for the existing CERs. The recommended CERs for these elements are:

- Non-Recurring Engineering Hours = $16.88 * W_E^{0.747} * V^{0.800} * NRENGR * H_{NRE}\%$
- Recurring Engineering Hours= $0.000306 * W_E^{0.880} * V^{.485} * RENGR * H_{RE}\%$
- Testing Cost =$1807.1 W_E^{0.325} * V^{0.822} * FTA^{1.21} * C_T\%$

where

W_E = empty weight (lbs)
V = maximum velocity (knots)
Q = production quantity
FTA = number of flight test aircraft
NRENGR = Non-Recurring Engineering Factor
RENGR = Recurring Engineering Factor
$H_{NRE}\%$ = Percentage of Non-Recurring Engineering Hours
$H_{RE}\%$ = Percentage Recurring Engineering Hours
$C_T\%$ = Percentage Testing Cost

With the CERs updated we can now analyze the effect that this will have on the LCC of our scenario. As was mentioned previously, we assumed for this scenario that the aircraft would be made from largely composite materials to achieve a large part count decrease. We have arbitrarily chosen a 50% part count reduction for this scenario. We do not suggest that a material mix of 80% composites will lead to a 50% part count reduction but rather it is not unreasonable to expect this decline in parts considering the ACCA program achieved a 90% part count reduction. Incorporating a 50% part count reduction into the model, our PCP CERs returns an approximate value of 87% for $H_{RE}\%$, 70% for $H_{NRE}\%$, 57% for $C_T\%$, and 76% for $H_M\%$. $H_M\%$ is the part count percentage reduction for recurring manufacturing hours. While this analysis did not focus on manufacturing hours, we did update the CERs done in previous research and felt it appropriate to include the cost element in our scenario.   In the manner applied, the reduction has a direct effect on our variables of interest with recurring engineering decreasing from \$86M to \$75M, or 87% of the original value. Likewise non-recurring engineering decreased from $112M to $79M, testing cost decreased from $14M to $8M, and manufacturing decreased from $208M to $158M. The ripple effect of these decreases can be seen throughout the life cycle of the program. Figure 17 is identical to Figure 13, but now includes the original values and the applied values.

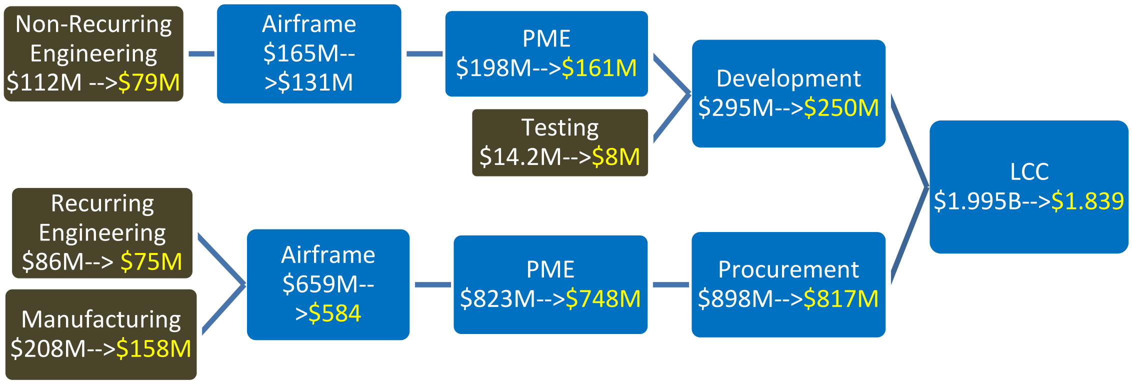


Figure 16: Applied Cost Elements Life Cycle Cost Model

By incorporating the part count percentage reductions for our four cost elements into the model, we can see the changes throughout the life cycle cost of the given scenario. The initial part count percentage reductions of 50% for the four cost elements led to an initial cost reduction of $101M. However, due to intricacies and related relationships throughout the model, we project an acquisition cost decrease of $126M or an 11% decrease and a total decrease in life cycle cost of $156M or 8% of LCC of our given scenario.

ACCA Manufacturing Process vs. DO-328J Manufacturing Process

The ACCA program was a success by most standards. The program achieved its technical goals, came in on schedule, and did not have cost overruns. In today's acquisition environment, on schedule and under cost is not the norm. However, it is difficult to compare the ACCA manufacturing process or more specifically, the amount of touch labor hours required for ACCA to the original DO-328J touch labor hours. The ACCA program consisted of 310,000 touch labor hours subdivided into several work breakdown structure elements. The primary driver of labor hours was manufacturing hours which accounted for nearly half of the total hours. As was stated in chapter three, the original manufacturer of the DO-328J is no longer operating and we were unable to gather original data for the air vehicle. Due to the original data for the DO-328J being non-existent or not at our disposal, we estimated the DO-328J original hours.

Company X's has kindly allowed us to use their cost estimating model to make these calculations. Company X's model was able to predict manufacturing hours for the ACCA program to within 1% of the actuals for manufacturing touch labor hours. Furthermore, Company X's model predicted the total touch labor hours for ACCA at 398,000 hours and the actuals were 310,000 touch labor hours, which was within 28% of the actuals. The largest discrepancies between the model and the actuals were for testing and design support. Understanding that the ACCA acquisition strategy was a rapid acquisition, the testing and design support aspects of the program were shortened to achieve the schedule set forth by the program office. Taking these issues into consideration, we contend that Company X's model is highly accurate and we proceeded with incorporating the inputs for the original aircraft into the model. Due to proprietary concerns we cannot discuss each input that goes into the model, however, several inputs into the model include minimum empty weight, aircraft speed, and takeoff thrust. These inputs were obtained from an open source and we contend that these are the correct values for the DO-328J (www.zenithaviation.com/0410/pdf/tech_spec_328jet).

Incorporating the input values for the DO-328J into the model, we calculate that the total touch labor hours for the first aircraft to be 2,692,000 total hours. The ACCA project only modified 40% of the DO-328J and accordingly we scale the labor hours down to be able to have an equivalent figure to compare to the ACCA actual touch labor hours. The adjusted number for touch labor hours is 1,077,000 hours. Comparing this figure to the ACCA actuals, 310,000 hours, we can see that the original amount of hours is approximately 3.5 times as large as the ACCA touch labor hours. Given the models accuracy in predicting manufacturing hours, we will examine this cost element in more detail. The estimated manufacturing hours were 532,000 hours, 3.6 times as large as the ACCA program (145,000). To give a comparison of the magnitude of the difference in labor hours, we will look at the dollar value associated with this difference in labor hours.

There are numerous variables that go into the total life cycle cost for any air-vehicle, however, we are only examining the labor cost and are excluding other variable costs such as material cost. We used the 2010 AFRL labor rates for this analysis. The actual labor rate is inconsequential, and the rates are only used to show the magnitude of the difference between the two manufacturing techniques. Using the AFRL labor rates and the estimated labor hours we calculate that the cost for touch labor hours for the first prototype DO-328J was $96M (BY2010) and using the same labor rates, the ACCA cost was $28M. We realize that the ACCA program cost was actually much larger than this purported figure, but this is due to labor rate differences. Using a constant labor rate, this analysis shows that the total labor hour savings for the ACCA program is $67M. This estimated savings is in line with the Composite Affordability Initiative estimate for fabrication hours and assembly hours savings of 50% and 63% respectively.

V. Conclusions

The primary objective of this research was to examine the relationship between part count and design, design support, testing and tooling, and if a relationship exists, to incorporate that relationship into the Air Force Research Laboratory (AFRL) life cycle cost (LCC) model. With the relationship confirmed between design, design support, and testing hours, we were able to integrate that relationship into the LCC model. The reduction exhibited in the drone scenario is an illustration of the implications that part count has on the life cycle cost of aircraft programs. This research focused mainly on the production and development portions of the life cycle and did not examine the operations and support phase of programs. However, with the increased use of composite materials in aircraft, additional data will become readily available in the near future to quantify the effects of composite materials on the sustainment phase of programs.

The provisional recommendations that this research has made to the LCC model are a step in the right direction in studying the current composite life cycle cost models. This analysis provides realistic cost estimating relationships (CERs) for aircraft that use large scale composite materials and will present more reliable estimates for aircraft using composite materials.

Strengths, Limitations, and Policy Implications

The addition of the Advanced Composite Cargo Aircraft data into Company X’s data set was instrumental for this research and beneficial to Company X in that it provides Company X with another data point. Additional data strengthens the current dataset and provides statistical justification to the theory that increased part size leads to fewer hours per pound in numerous cost elements. The initial findings are encouraging for this field of research and there is ample evidence to support additional research in these areas to further strengthen the CERs of interest. While this research concluded that currently the data set for tooling cost does not statistically confirm a relationship between part count and tooling hours, we believe that new techniques for designing and manufacturing tools related to composite materials will in time support the theory that part size and tooling hours are related.

This research relied heavily on the cost models provided by Company X, which were designed for prototype first units. There are considerable differences between first unit prototypes and a production first unit. Keeping this concern in mind, the life cycle cost model is for production scenarios. We realize that the relationships outlined in this document may be inaccurate in comparison to production vehicles. Additional research is needed to prove that the relationships found for prototype aircraft exists in production aircraft.

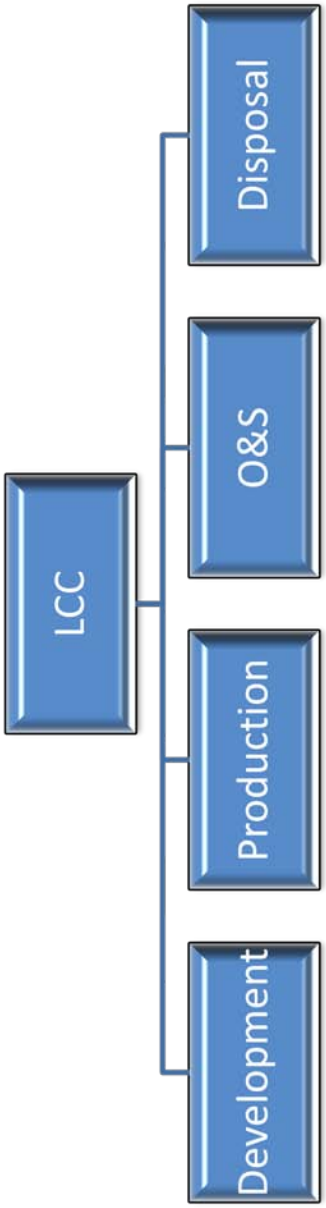
Furthermore, ACCA was not a complete aircraft design or production but rather a modification of an existing aircraft. The methods used to scale the design and production costs to whole values may be incorrect. Also, the data set used for this analysis consisted of data only from one company plus the ACCA data. While it was encouraging that the ACCA data followed the same trend as the relationships Company X had identified, the generalization and precision of these findings may be inaccurate. A comprehensive industry wide data set is required to confirm these relationships.

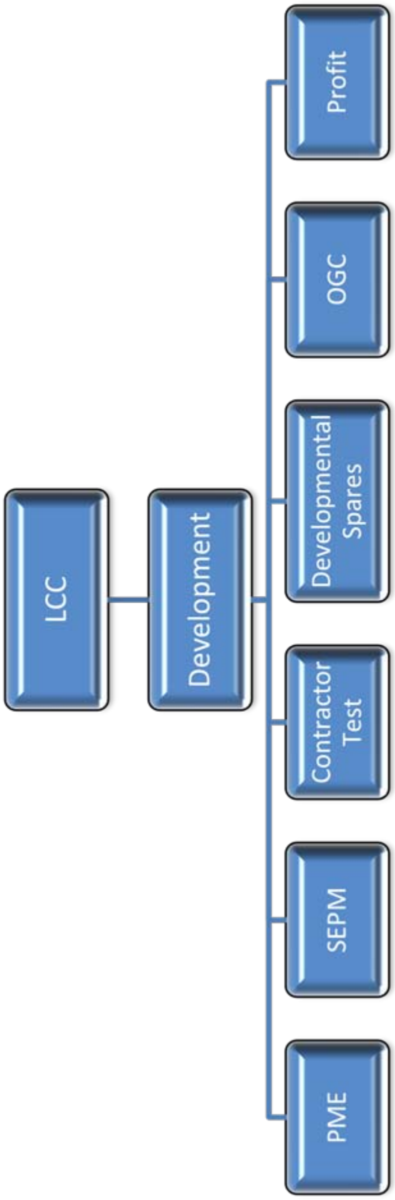
Another issue of great concern is that ACCA is a cargo aircraft and provides internal access for repairs and maintenance, thus, large scale part sizes do not create problems relating to gaining access to the inner structures and systems to perform routine repairs and maintenance. However, not all aircraft provide the same degree of access to inner structures and systems. While this research does recognize that these are legitimate concerns, we did not seek to address these issues at this time. This research focused exclusively on production and development stages of the LCC model, however, the current model examines all three phases of a program. We realize that introducing variables into the production and development phase of the model will have a mathematical effect on the sustainment phase of the program, however, we did not investigate if these reductions in the sustainment portion of the program are justifiable or correct.

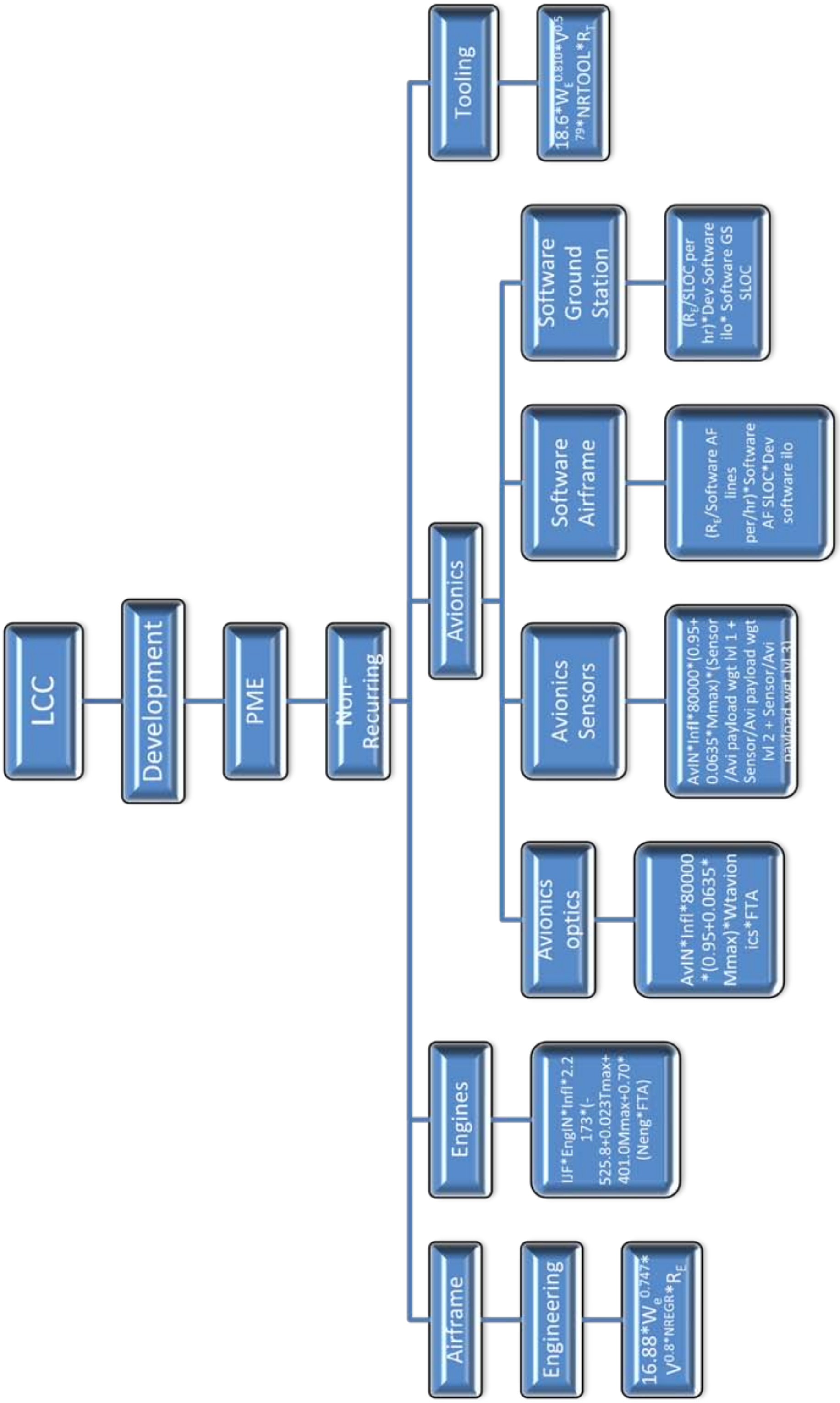
Future Research

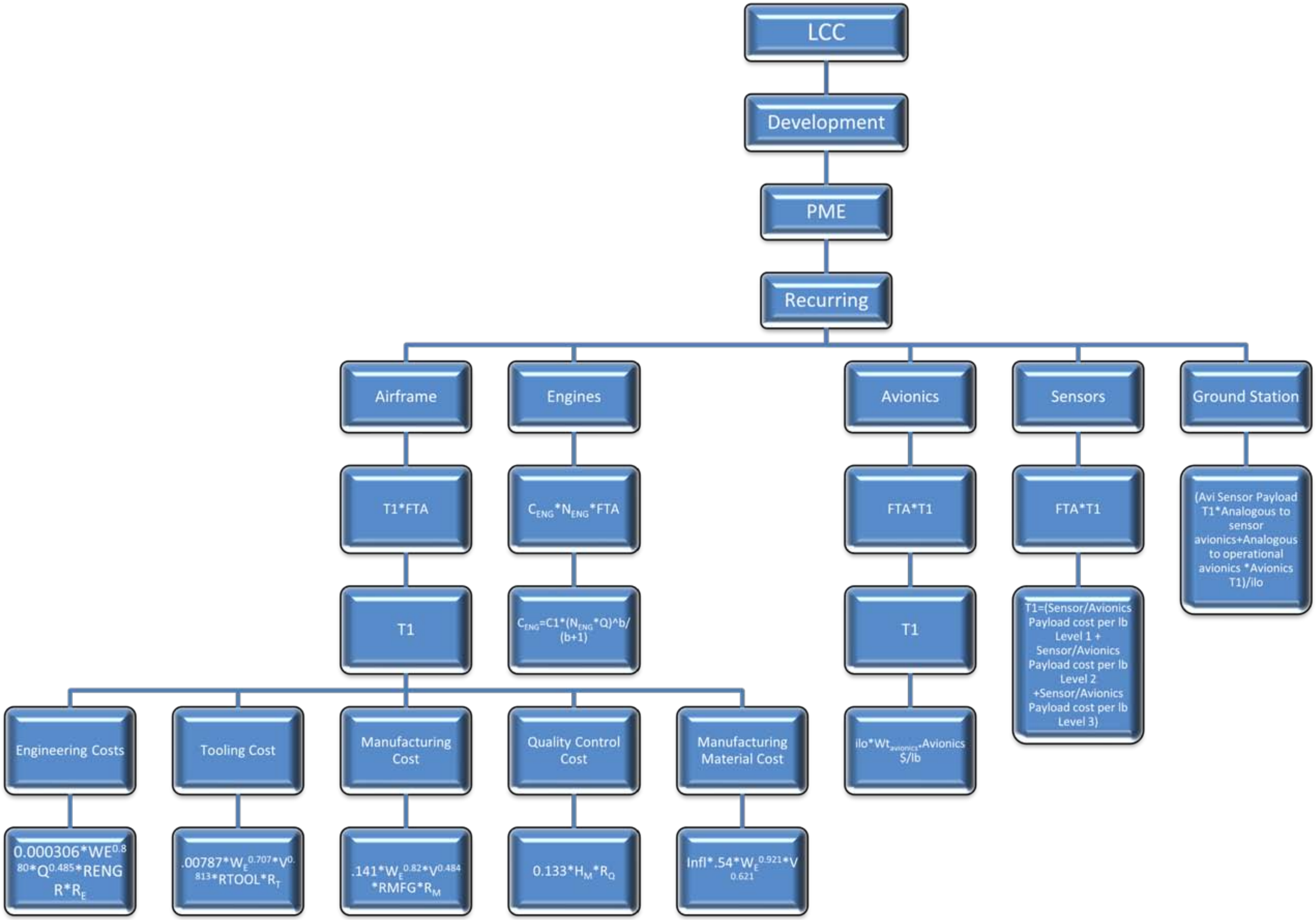
While composite materials have been used in aircraft manufacturing for numerous years, interest in estimating costs for aircraft using large composite structures is still in its infancy and there are no commonly accepted cost models for composite aircrafts. This lack of a universally agreed upon LCC model provides ample opportunities for further research into this area. As research continues in the area of composite aircraft, an area that requires additional research is the effects of automation on cost. Fiber placement machines are frequently being integrated into the manufacturing process to improve the efficiency of composite manufacturing in production scenarios. Further research is required to determine if a learning curve is present with the incorporation of fiber placement machines. Other research that is needed concerns the material cost factors currently used in cost models concerning composites. These material cost factors, which were outlined in chapter 2, were developed by RAND in the early 1990's and have not been updated since that time. These efforts will lead to a more vigorous and accurate cost model that can aid the decision maker in determining the trade-offs in acquiring aircraft systems.

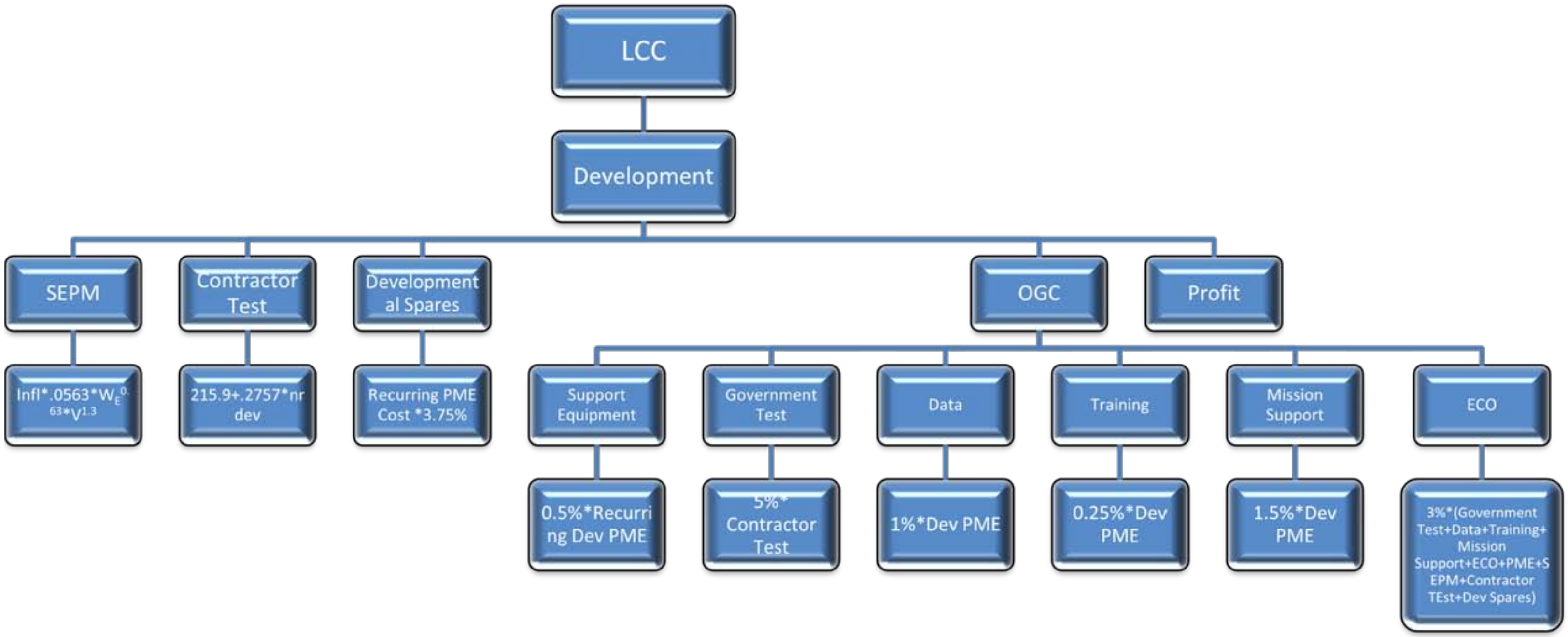
Appendix A: AFRL LCC Model Flowchart

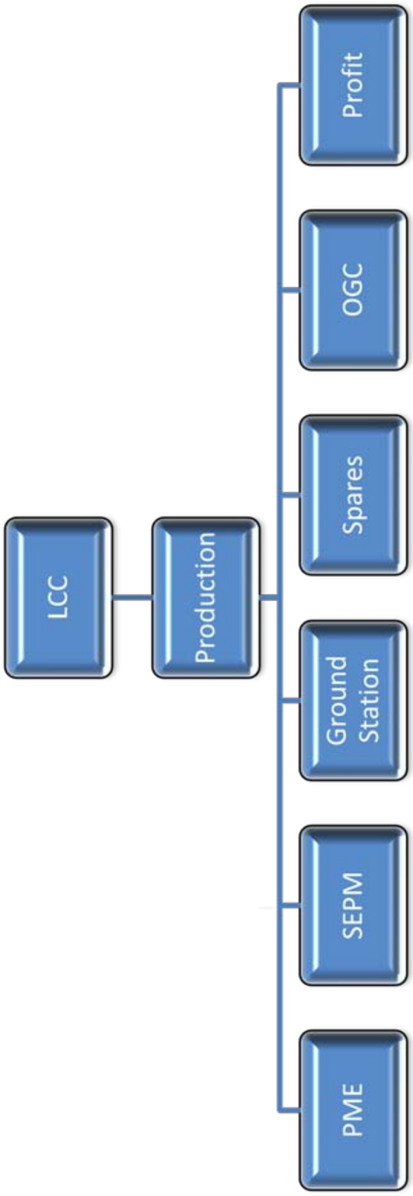


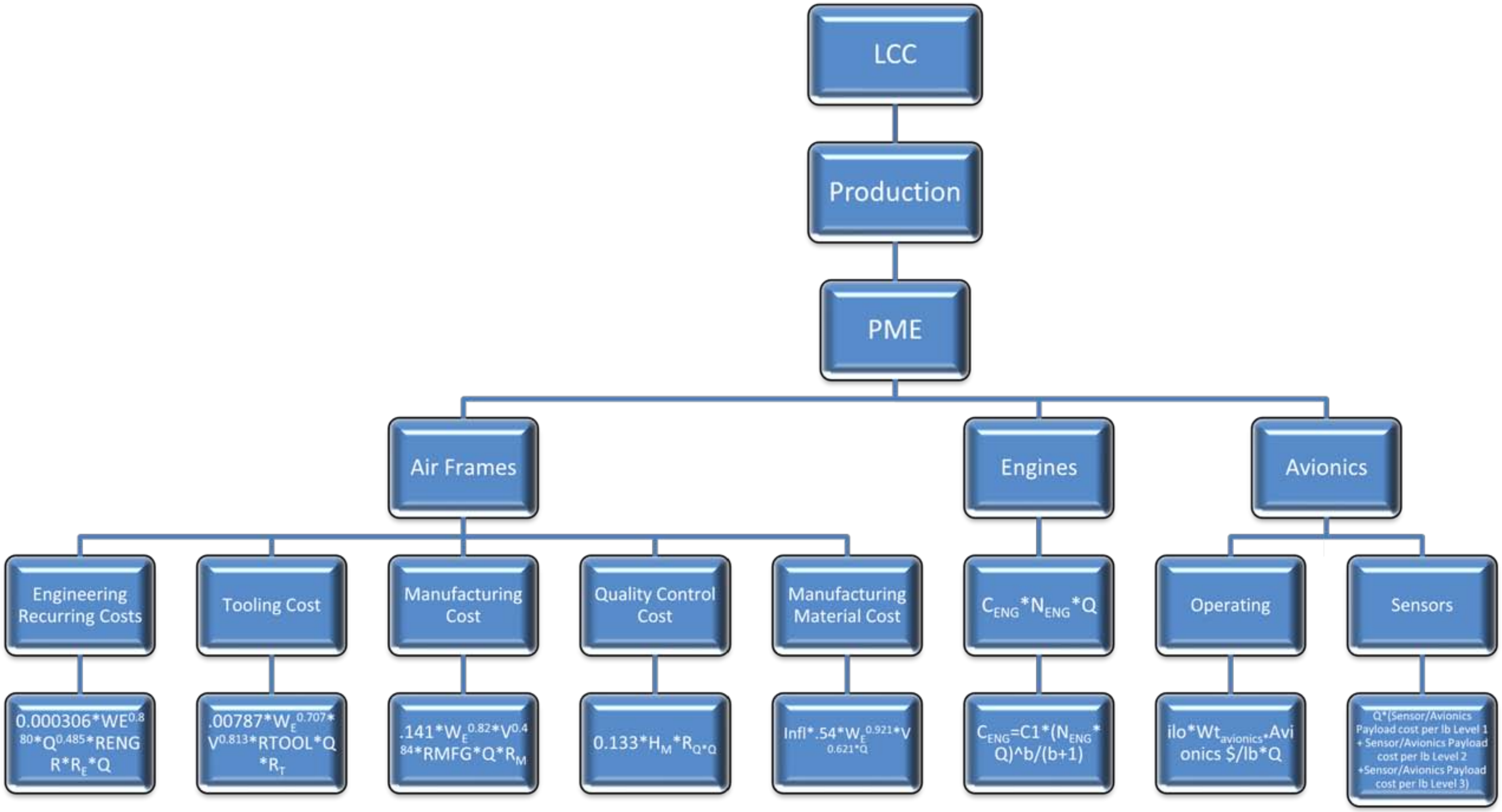

LCC
Development
PME
SEPM
Contractor Test
Developmental Spares
OGC
Profit

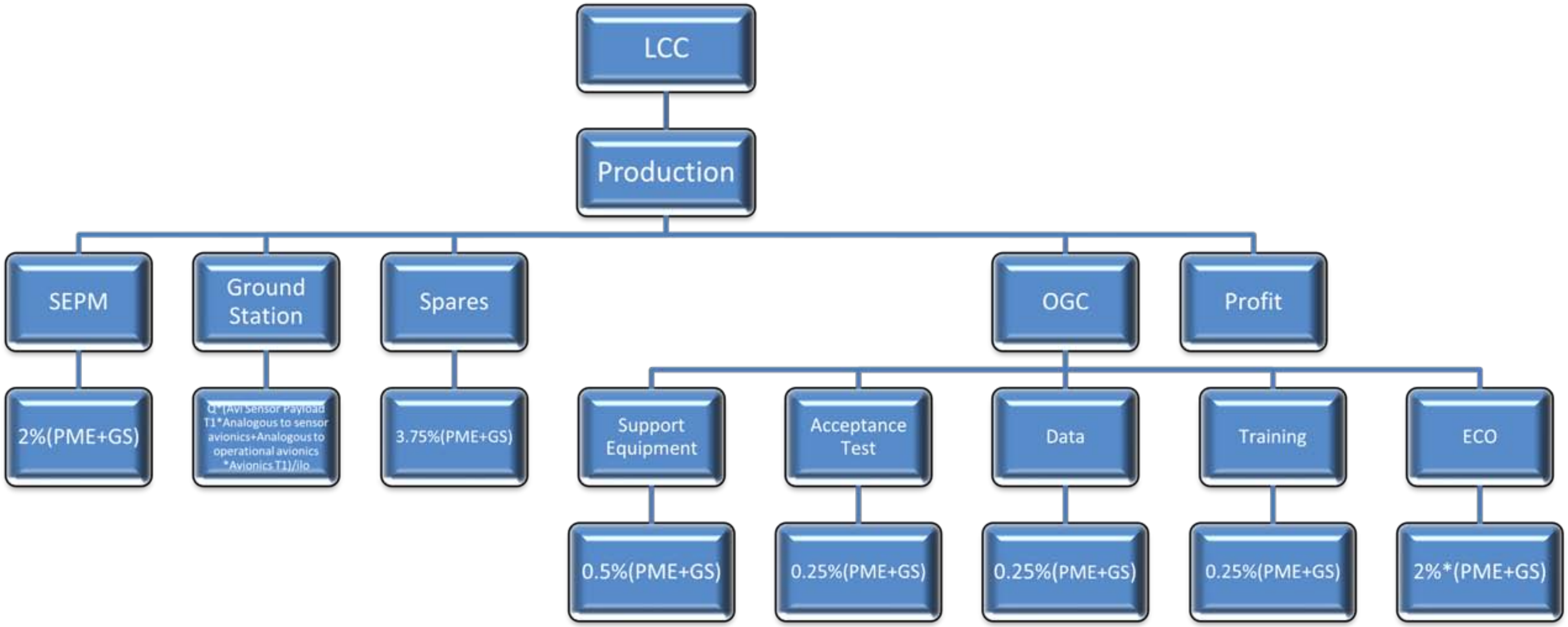

LCC
Development
PME
Non-Recurring
Airframe
Engineering
16.88*We^0.747*V^0.8*NREGR*RE
Engines
IJF*EngIN*Infl*2.2173*(-525.8+0.023Tmax+401.0Mmax+0.70*(Neng*FTA)
Avionics
Avionics optics
AvIN*Infl*80000*(0.95+0.0635*Mmax)*Wtavionics*FTA
Avionics Sensors
AvIN*Infl*80000*(0.95+0.0635*Mmax)*(Sensor/Avi payload wgt lvl 1 + Sensor/Avi payload wgt lvl 2 + Sensor/Avi payload wgt lvl 3)
Software Airframe
(RE/Software AF lines per/hr)*Software AF SLOC*Dev software ilo
Software Ground Station
(RE/SLOC per hr)*Dev Software ilo* Software GS SLOC
Tooling
18.6*WE^0.810*V^0.579*NRTOOL*RT

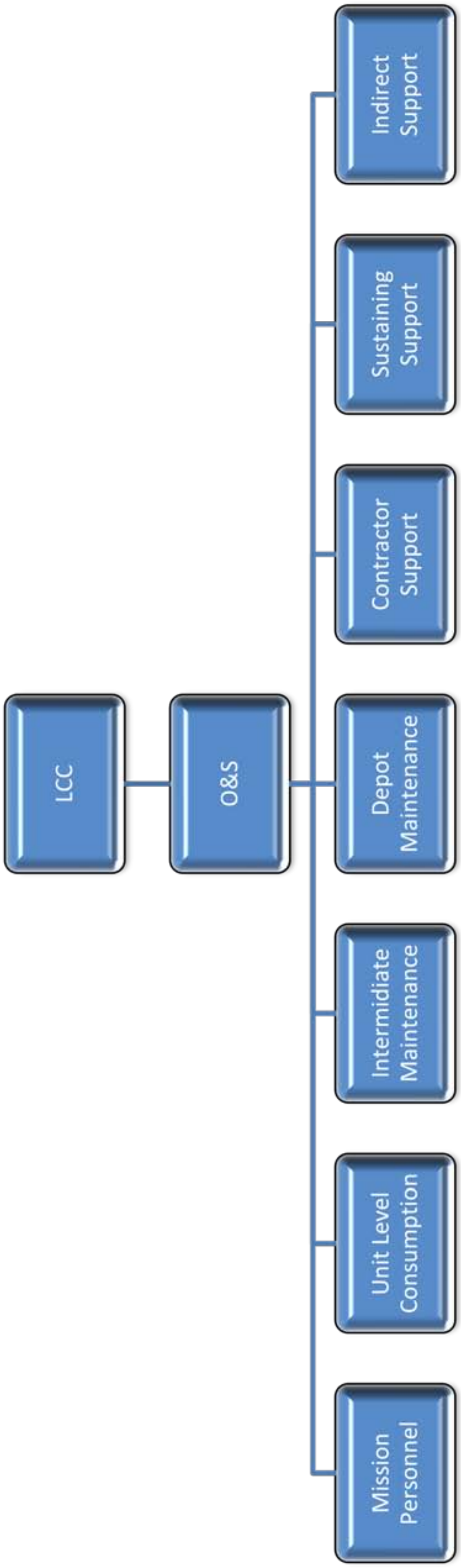

LCC
Development
PME
Recurring
Airframe
Engines
Avionics
Sensors
Ground Station
T1*FTA
C_{ENG}*N_{ENG}*FTA
FTA*T1
FTA*T1
(Avi Sensor Payload T1*Analogous to sensor avionics+Analogous to operational avionics *Avionics T1)/ilo
T1
C_{ENG}=C1*(N_{ENG}*Q)^b/(b+1)
T1
T1=(Sensor/Avionics Payload cost per lb Level 1 + Sensor/Avionics Payload cost per lb Level 2 +Sensor/Avionics Payload cost per lb Level 3)
Engineering Costs
Tooling Cost
Manufacturing Cost
Quality Control Cost
Manufacturing Material Cost
ilo*$Wt_{avionics}$*Avionics $/lb
0.000306*$WE^{0.880}$*$Q^{0.485}$*RENG R*R_E
.00787*$W_E^{0.707}$*$V^{0.813}$*RTOOL*R_T
.141*$W_E^{0.82}$*$V^{0.484}$*RMFG*R_M
0.133*H_M*R_Q
Infl*.54*$W_E^{0.921}$*$V^{0.621}$

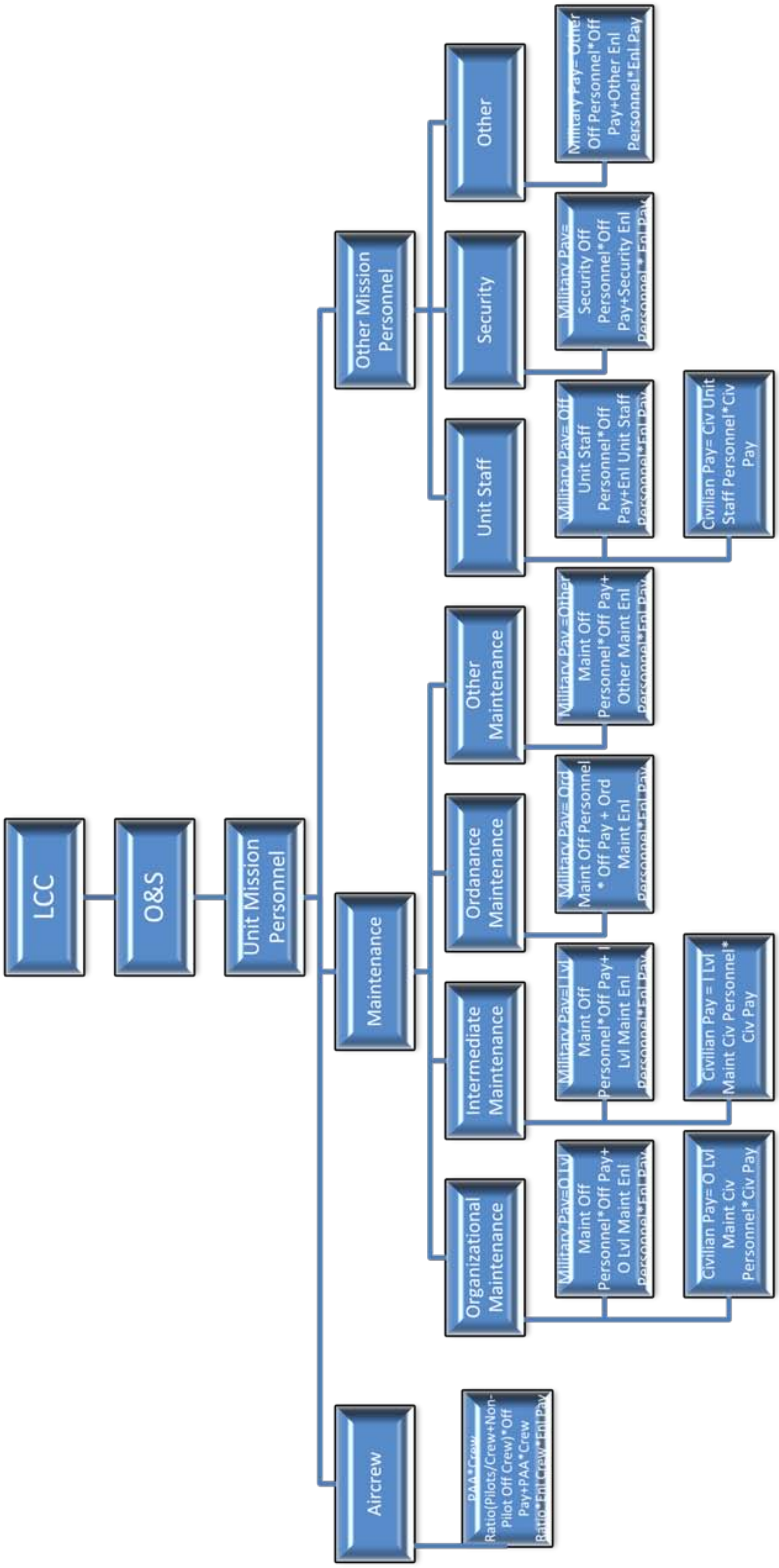

LCC
Development
SEPM
Contractor Test
Developmental Spares
OGC
Profit
Infl*.0563*W_E^0.63*V^1.3
215.9+.2757*nr dev
Recurring PME Cost *3.75%
Support Equipment
Government Test
Data
Training
Mission Support
ECO
0.5%*Recurring Dev PME
5%* Contractor Test
1%*Dev PME
0.25%*Dev PME
1.5%*Dev PME
3%*(Government Test+Data+Training+Mission Support+ECO+PME+SEPM+Contractor TEst+Dev Spares)

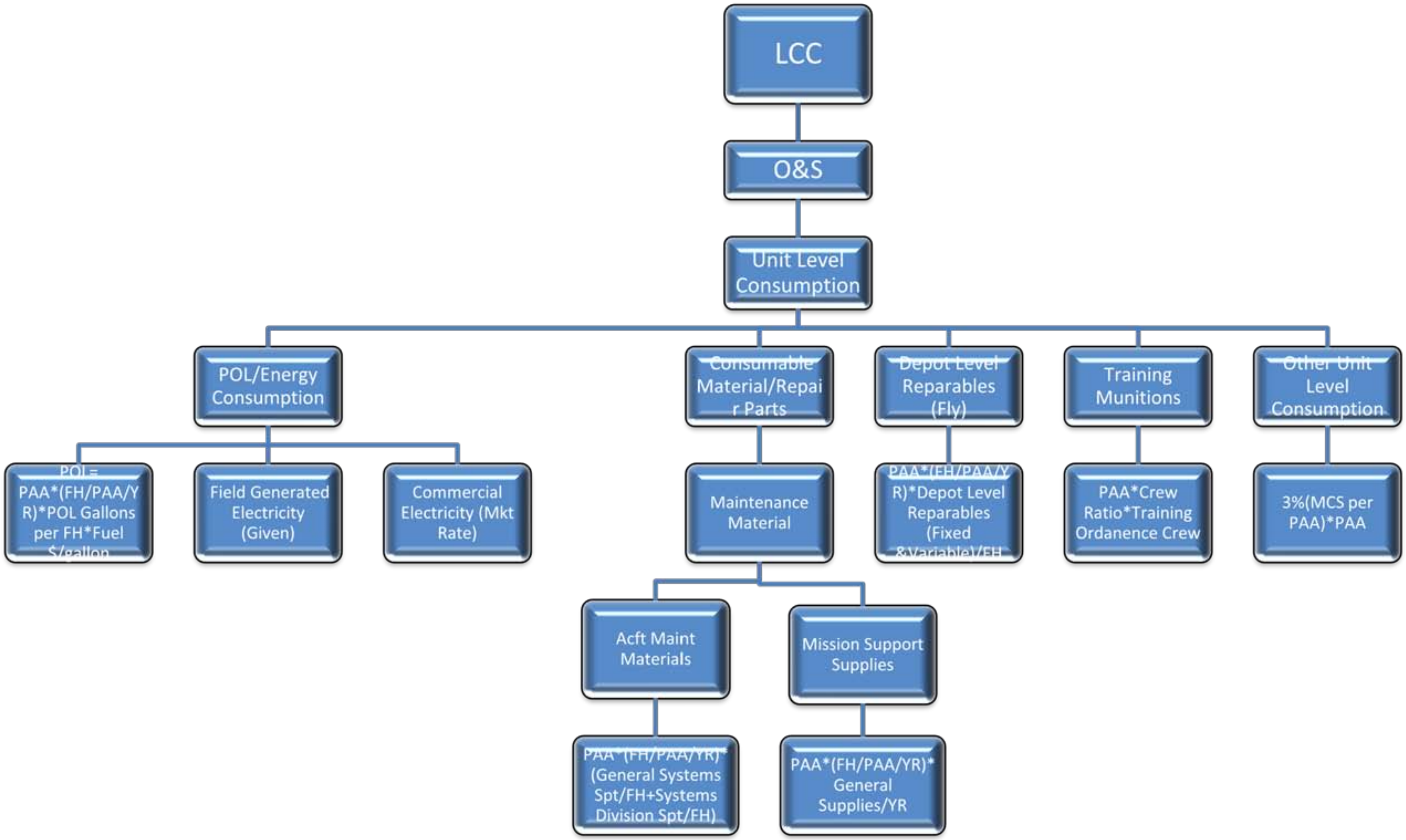

LCC
Production
PME
SEPM
Ground Station
Spares
OGC
Profit

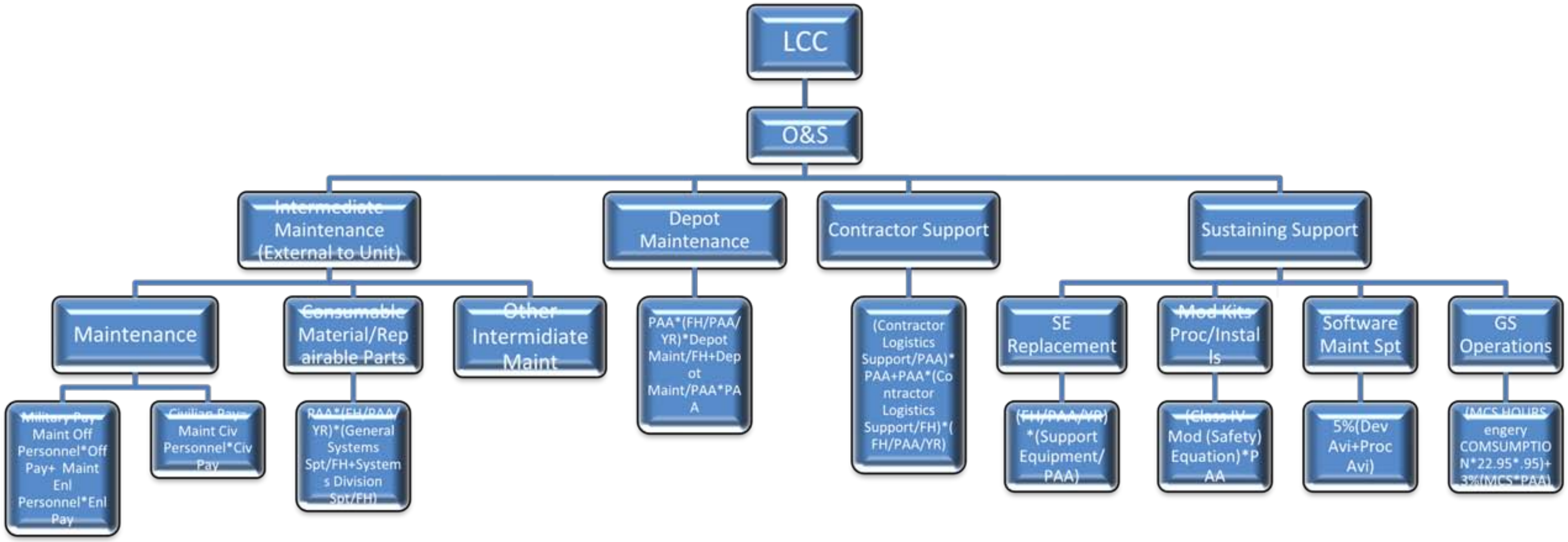

LCC
Production
PME
Air Frames
Engines
Avionics
Engineering Recurring Costs
Tooling Cost
Manufacturing Cost
Quality Control Cost
Manufacturing Material Cost
C_{ENG}*N_{ENG}*Q
Operating
Sensors
0.000306*$WE^{0.8}$ ^{80}*$Q^{0.485}$*RENG R*R_E*Q
.00787*$W_E^{0.707*}$ $V^{0.813}$*RTOOL*Q *R_T
.141*$W_E^{0.82}$*$V^{0.4}$ ^{84}*RMFG*Q*R_M
0.133*H_M*R_{Q*Q}
Infl*.54*$W_E^{0.921}$*$V^{0.621*Q}$
C_{ENG}=C1*(N_{ENG}* Q)^b/(b+1)
ilo*$Wt_{avionics}$*Avionics $/lb*Q
Q*(Sensor/Avionics Payload cost per lb Level 1 + Sensor/Avionics Payload cost per lb Level 2 +Sensor/Avionics Payload cost per lb Level 3)

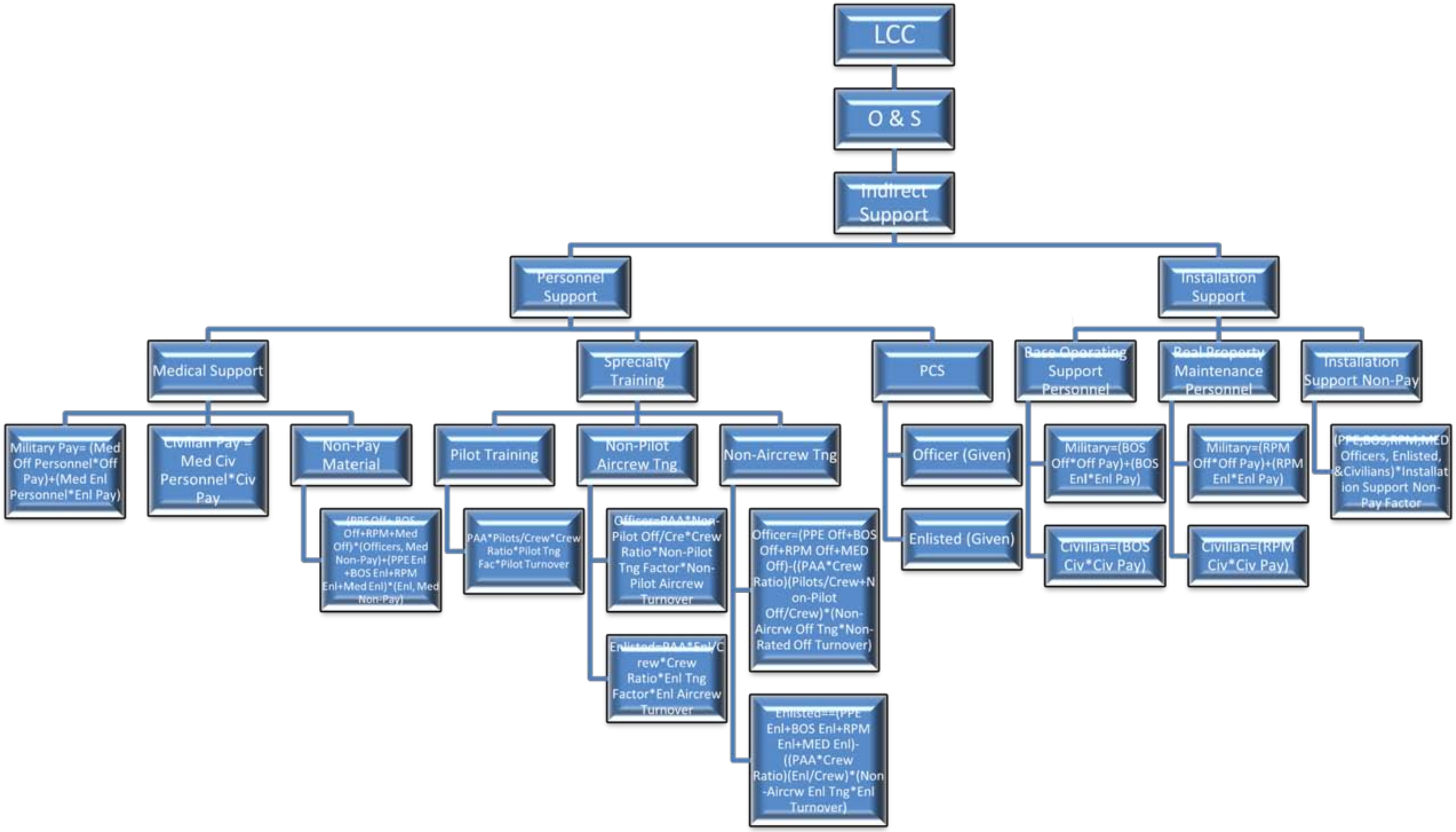

LCC
Production
SEPM
Ground Station
Spares
OGC
Profit
2%(PME+GS)
Q*(Avi Sensor Payload T1*Analogous to sensor avionics+Analogous to operational avionics *Avionics T1)/ilo
3.75%(PME+GS)
Support Equipment
Acceptance Test
Data
Training
ECO
0.5%(PME+GS)
0.25%(PME+GS)
0.25%(PME+GS)
0.25%(PME+GS)
2%*(PME+GS)

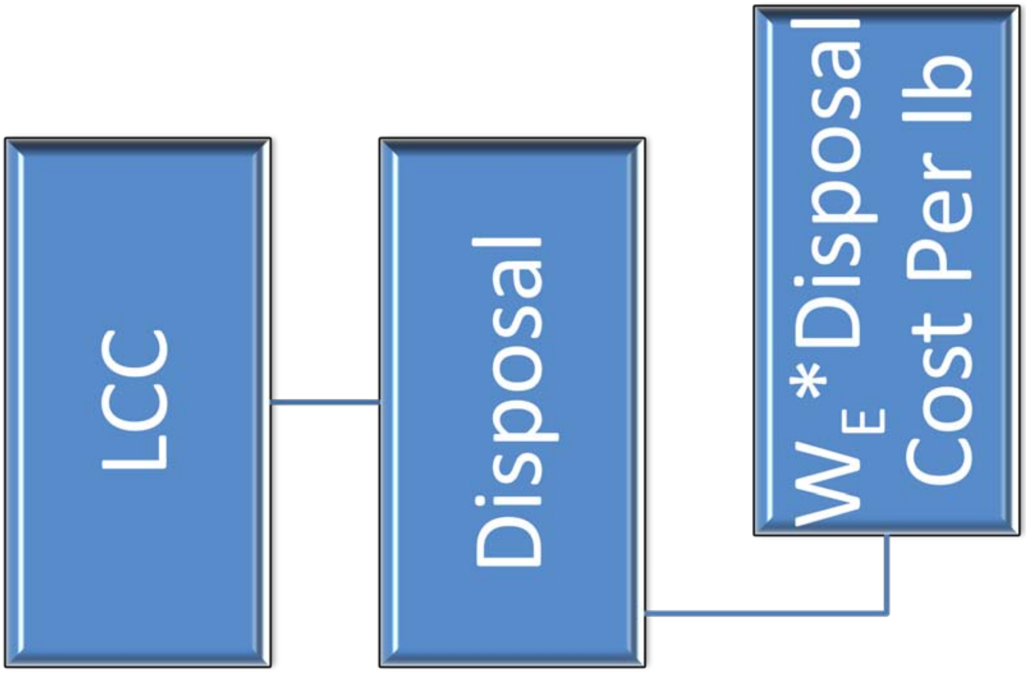

LCC
O&S
Mission Personnel
Unit Level Consumption
Intermidiate Maintenance
Depot Maintenance
Contractor Support
Sustaining Support
Indirect Support


LCC
O&S
Unit Mission Personnel
Aircrew
PAA*Crew Ratio(Pilots/Crew+Non-Pilot Off Crew)*Off Pay+PAA*Crew Ratio*Enl Crew*Enl Pay
Maintenance
Organizational Maintenance
Military Pay=O Lvl Maint Off Personnel*Off Pay+ O Lvl Maint Enl Personnel*Enl Pay
Civilian Pay= O Lvl Maint Civ Personnel*Civ Pay
Intermediate Maintenance
Military Pay=I Lvl Maint Off Personnel*Off Pay+ I Lvl Maint Enl Personnel*Enl Pay
Civilian Pay = I Lvl Maint Civ Personnel* Civ Pay
Ordanance Maintenance
Military Pay= Ord Maint Off Personnel * Off Pay + Ord Maint Enl Personnel*Enl Pay
Other Maintenance
Military Pay =Other Maint Off Personnel*Off Pay+ Other Maint Enl Personnel*Enl Pay
Other Mission Personnel
Unit Staff
Military Pay= Off Unit Staff Personnel*Off Pay+Enl Unit Staff Personnel*Enl Pay
Civilian Pay= Civ Unit Staff Personnel*Civ Pay
Security
Military Pay= Security Off Personnel*Off Pay+Security Enl Personnel * Enl Pay
Other
Military Pay= Other Off Personnel*Off Pay+Other Enl Personnel*Enl Pay


LCC
O&S
Unit Level Consumption
POL/Energy Consumption
Consumable Material/Repair Parts
Depot Level Reparables (Fly)
Training Munitions
Other Unit Level Consumption
POL= PAA*(FH/PAA/YR)*POL Gallons per FH*Fuel $/gallon
Field Generated Electricity (Given)
Commercial Electricity (Mkt Rate)
Maintenance Material
PAA*(FH/PAA/YR)*Depot Level Reparables (Fixed &Variable)/FH
PAA*Crew Ratio*Training Ordanence Crew
3%(MCS per PAA)*PAA
Acft Maint Materials
Mission Support Supplies
PAA*(FH/PAA/YR)*(General Systems Spt/FH+Systems Division Spt/FH)
PAA*(FH/PAA/YR)* General Supplies/YR


LCC
O&S
Intermediate Maintenance (External to Unit)
Depot Maintenance
Contractor Support
Sustaining Support
Maintenance
Consumable Material/Repairable Parts
Other Intermidiate Maint
PAA*(FH/PAA/YR)*Depot Maint/FH+Depot Maint/PAA*PAA
(Contractor Logistics Support/PAA)*PAA+PAA*(Contractor Logistics Support/FH)*(FH/PAA/YR)
SE Replacement
Mod Kits Proc/Installs
Software Maint Spt
GS Operations
Military Pay Maint Off Personnel*Off Pay+ Maint Enl Personnel*Enl Pay
Civilian Pay= Maint Civ Personnel*Civ Pay
PAA*(FH/PAA/YR)*(General Systems Spt/FH+Systems Division Spt/FH)
(FH/PAA/YR)*(Support Equipment/PAA)
(Class IV Mod (Safety) Equation)*PAA
5%(Dev Avi+Proc Avi)
(MCS HOURS engery COMSUMPTION*22.95*.95)+3%(MCS*PAA)


LCC
O & S
Indirect Support
Personnel Support
Installation Support
Medical Support
Specialty Training
PCS
Base Operating Support Personnel
Real Property Maintenance Personnel
Installation Support Non-Pay
Military Pay= (Med Off Personnel*Off Pay)+(Med Enl Personnel*Enl Pay)
Civilian Pay = Med Civ Personnel*Civ Pay
Non-Pay Material
(PPE Off+ BOS Off+RPM+Med Off)*(Officers, Med Non-Pay)+(PPE Enl +BOS Enl+RPM Enl+Med Enl)*(Enl, Med Non-Pay)
Pilot Training
PAA*Pilots/Crew*Crew Ratio*Pilot Tng Fac*Pilot Turnover
Non-Pilot Aircrew Tng
Officer=PAA*Non-Pilot Off/Cre*Crew Ratio*Non-Pilot Tng Factor*Non-Pilot Aircrew Turnover
Enlisted=PAA*Enl/Crew*Crew Ratio*Enl Tng Factor*Enl Aircrew Turnover
Non-Aircrew Tng
Officer=(PPE Off+BOS Off+RPM Off+MED Off)-((PAA*Crew Ratio)(Pilots/Crew+Non-Pilot Off/Crew)*(Non-Aircrw Off Tng*Non-Rated Off Turnover)
Enlisted==(PPE Enl+BOS Enl+RPM Enl+MED Enl)-((PAA*Crew Ratio)(Enl/Crew)*(Non-Aircrw Enl Tng*Enl Turnover)
Officer (Given)
Enlisted (Given)
Military=(BOS Off*Off Pay)+(BOS Enl*Enl Pay)
Civilian=(BOS Civ*Civ Pay)
Military=(RPM Off*Off Pay)+(RPM Enl*Enl Pay)
Civilian=(RPM Civ*Civ Pay)
(PPE,BOS,RPM,MED Officers, Enlisted, &Civilians)*Installation Support Non-Pay Factor

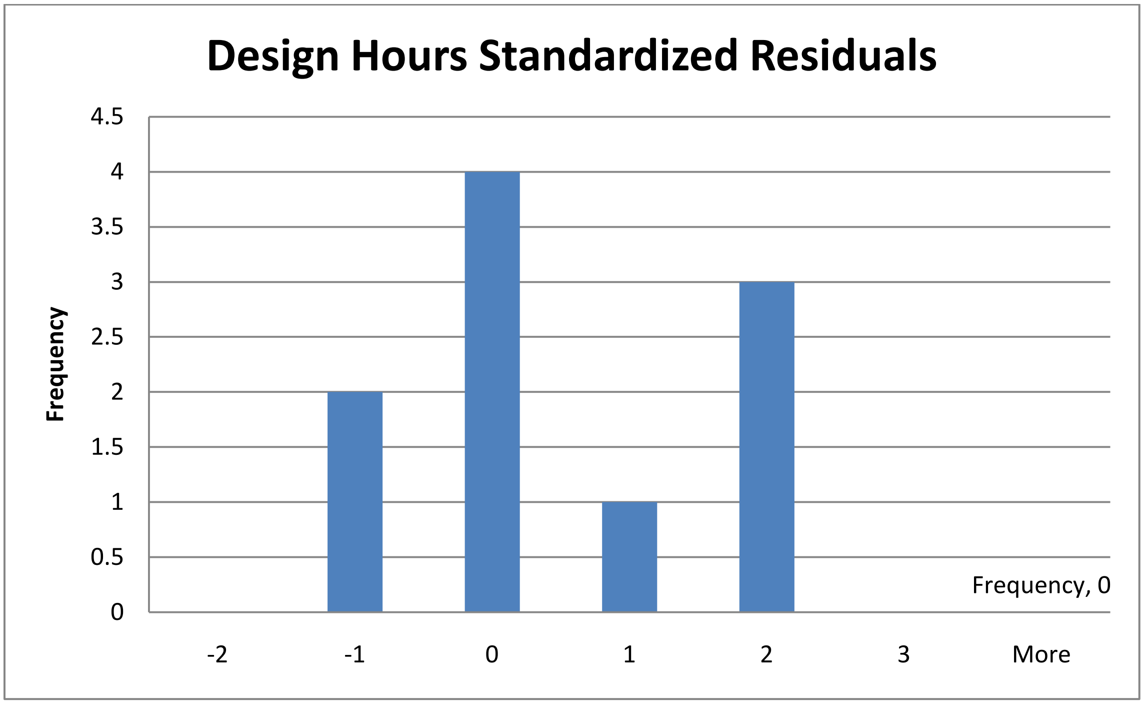

LCC
Disposal
W_E*Disposal Cost Per lb

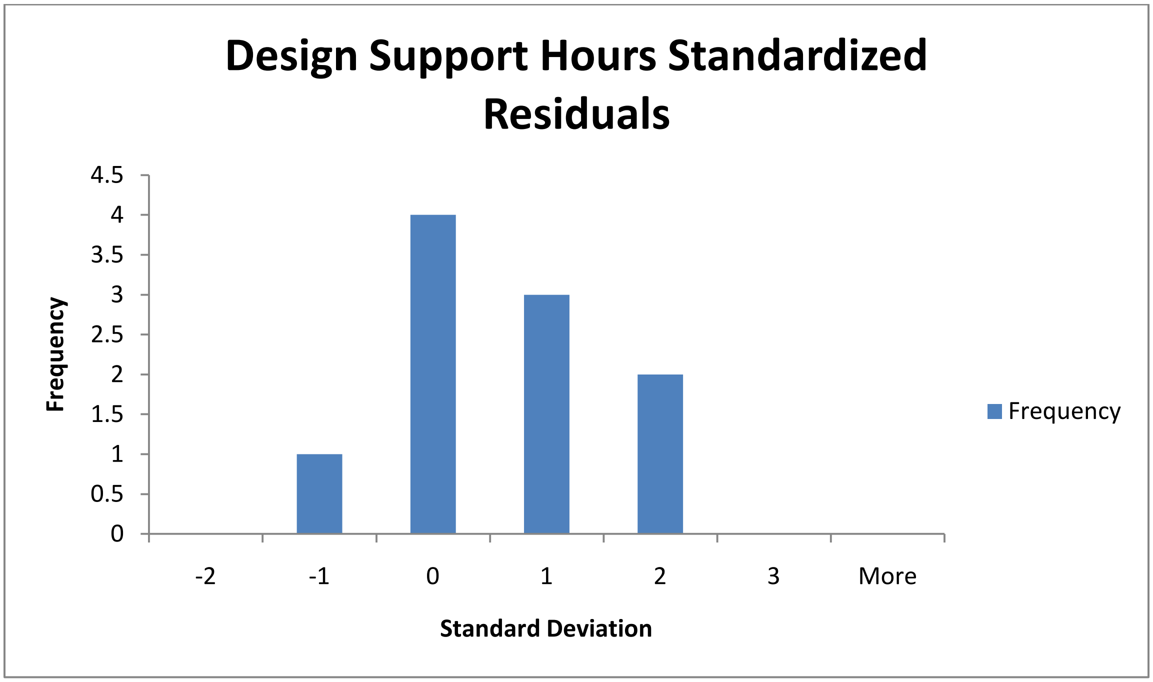
Appendix B: AFRL LCC Model Flowchart Acronyms

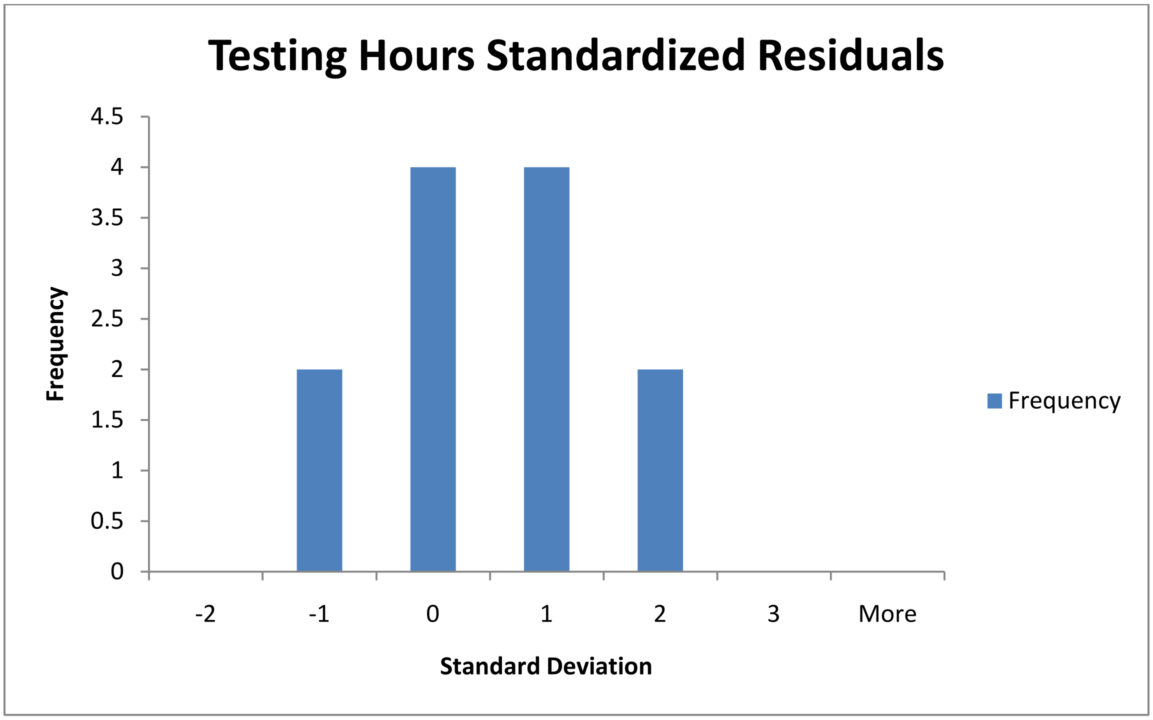
- AvIN: Index for Avionics Calculations
- b: Learning Curve
- BOS: Base Operating Support
- C_{ENG} = Cost Per Engine ($)
- Dev: Development
- ECO: Engineering Change Order
- EngIN: Index for Engine Calculation
- Enl: U.S. Military Enlisted
- FH: Flight Hour
- FTA: Number of Flight Test Articles
- GS: Ground Station
- H_M: Manufacturing Hours
- I_{JF}: and 1980 Engine Regression Mostly Turbojets: For Turbojet=1 for Turbofan=1.15 to 1.20
- Ilo: Low observable
- LCC: Life Cycle Cost
- MCS: Mission Control Station
- MED: Medical
- Mmax: Engine Maximum Mach Number
- N_{ENG}: Number of Engines per Aircraft
- NENGR: Recurring Engineering Factor
- Nrdev: Total Non-Recurring Development Cost
- NREGR: Non-Recurring Engineering Factor
- NRTOOL: Non-Recurring Tooling Factor
- O&S: Operation and Support
- Off: U.S. Military Officer
- OGC: Other Government Cost
- PAA
- PCS: Permanent Change of Station
- PME: Prime Mission Equipment
- POL: Petroleum, Oil, and Lubricants
- PPE: Primary Program Element Officer (consist of Aircraft Crew +Squadron Staff + Weapon System Security Personnel
- Q: Quantity

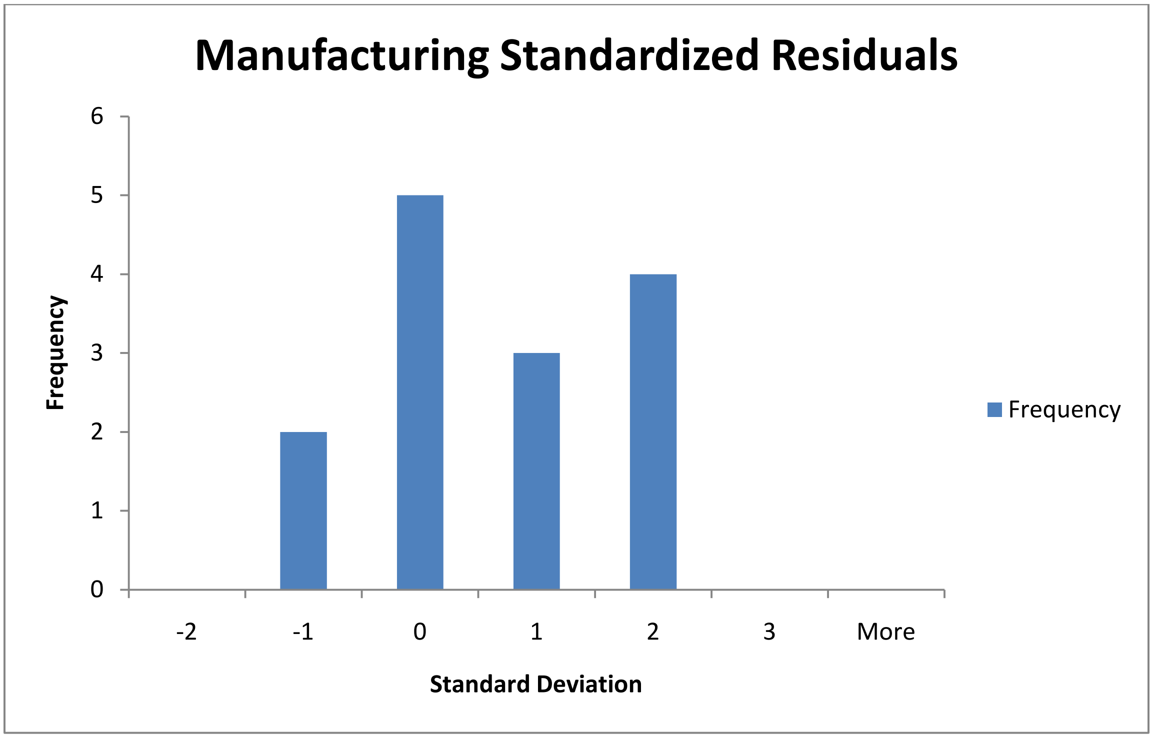
- $R_{E:}$ Engineering Hourly Rate
- R_M: Manufacturing Hourly Rate
- RMFG: Recurring Manufacturing Factor
- RPM: Real Property Maintenance
- R_Q: Quality Control Hourly Rate
- R_T: Tooling Hourly Rate
- RTOOL: Recurring Tooling Factor
- SE: Support Equipment
- SEPM: Systems Engineering Program Management
- SLOC: Source Lines of Code
- T1: First Unit of Production
- Tmax: Engine Maximum thrust at SL (lbs)
- V: Aircraft Maximum Velocity (knots)
- W_E: Aircraft Empty Weight (pounds)
- $Wt_{avionics}$: Weight of Flight System Avionics (lbs)

Appendix C: Histograms of Standardized Residuals






Testing Hours Standardized Residuals
Frequency
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-2
-1
0
1
2
3
More
Standard Deviation
Frequency


Manufacturing Standardized Residuals
Frequency
6
5
4
3
2
1
0
-2
-1
0
1
2
3
More
Standard Deviation
Frequency

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14. ABSTRACT

Composite materials are beginning to comprise a greater percentage of structural materials used throughout aircraft production. The increased usage of composites has led individuals within the Air Force community to revisit aircraft life cycle cost, LCC, models. A series of affordability initiatives has culminated in significant evidence over the last decade to better quantify the impact of primarily composite structures in aircraft. The Advanced Composite Cargo Aircraft, ACCA, a research effort sponsored by the Air Force Research Lab, attempted to determine the impact of part size and large scale composite components on LCC for cargo aircraft. This research evaluates the data provided by the ACCA program and data from aerospace industry partners to modify the existing LCC models. This research finds that a relationship exists between relative part count and touch labor hours for certain cost categories, notably, design, design support, and testing. In particular, a percentage reduction in part count drives a corresponding percentage reduction in these select cost categories. These findings suggest that reduction in part count filter through most of the major cost categories during development and production. The research findings suggest that the current LCC models require modifications in the current cost estimating relationships to capture these impacts.

15. SUBJECT TERMS
Advanced Composite material, Composite aircraft, Part count, Touch labor hours, Life cycle cost model, Advanced Composite Cargo Aircraft

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