3-10-2010

Part Count: Monolithic Part Effects on Manufacturing Labor Cost, an Aircraft Applied Model

Aaron M. Lemke

PART COUNT: MONOLITHIC PART EFFECTS ON MANUFACTURING LABOR COST, AN AIRCRAFT APPLIED MODEL

THESIS

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AFIT/GFA/ENV/10-M02

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AFIT/GFA/ENV/10-M02

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THESIS

Presented to the Faculty

Department of Systems and Engineering Management

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Financial Analysis

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March 2010

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

AFIT/GFA/ENV/10-M02

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AFIT/GFA/ENV/10-M02

Abstract

There are significantly different manufacturing processes and part counts associated with composites that are not currently addressed within the aircraft procurement and life cycle management processes in the Department of Defense (DoD). 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. An Air Force Research Laboratory program, Advanced Composite Cargo Aircraft (ACCA), provides substantial support for the impact of part size on life cycle cost for payload aircraft. This research evaluates select methods used and seeks to introduce modifications to the projected manufacturing hours cost. The discussion addresses the far-reaching implications of trading several parts for one. This research finds that a significant relationship between relative part count and major cost categories does exist. Specifically, a percentage reduction in part count drives a corresponding percentage reduction in the manufacturing hours. Furthermore, the findings suggest the impact of monolithic parts appears to permeate most of the major cost categories in development and production. The series of findings pertaining to part count and cost merit consideration for updates to the current cost estimating relationships and interim modifications to capture some portion of the impact in current life cycle cost models.

I dedicate these pages to my wife and our two beautiful boys. Their daily sacrifice of husband and father frame this academic effort as meager by comparison. Praise the Lord, oh my soul, for it is well.

Acknowledgements

Not one breath would I take without the grace given me by my Father. Not one day moment of hope could I desire without the mercy bestowed by sacrifice of my Lord.

Without the loving support and understanding of my wife, who munificently watched me fight not only the work to be done, but myself as well, this work would not have been completed.

Without the tireless fawning of my boys, who forlornly saw me depart those many days to write, I could not have maintained proper perspective of this project.

Without the investment of my committee members in their own professionalism, there would not have been a solid foundation for me to develop and grow academically, and ultimately deliver a product reflective of their character.

Without the exhaustive care of my sponsor and other supporting individuals and organizations, I would not have known a composite fiber from a box of bran flakes, and could only dream of life in the world of composites.

Without the daily reflection of my classmates, who endured the same struggles and challenges indicative of a rigorous program, I could not have hoped to have an appreciation for the gauntlet we have endured and overcome together.

Without the God-fearing support and counsel of my class leader, who was my vibrant ally through all facets of career and life, I would be much less prepared for this degree and what military service truly beholds.

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I: Introduction

Background

A composite is a combination of dissimilar materials in which each constituent remains identifiable, but in which the mechanical properties of the composite are different from the properties of any one constituent alone. The characteristics exhibited by the resulting composite are unlike that of either/any contained material without physically changing the state of the contained materials themselves. Among the most primitive composites are straw and mud bricks. Many common materials are composites, such as plywood, paper Mache, fiberglass, and rebar-enforced concrete or pavement.

Absent in aircraft procurement and life cycle management processes are significantly different manufacturing processes and part counts associated with composites. Industry and consumers perceive more implied risk with composite structures over metallic structures, despite the associated cost advantages. This is due in large part to insufficient characterization of the life cycle benefits from optimal composite use. Their use has therefore been historically limited to components versus major structural assemblies.

Composites display a myriad of differences from isotropic metallic materials. For example, composite strength and stiffness can be tailored to meet loads and they display greater resistance to fatigue damage. The differences between composites and metallic materials result in certain benefits for composites. Key among those differences in context of this research is that ability to lower manufacturing costs by reduced machining and produce tapered sections and compound contours easily. To date, metallic materials retain some advantages over composites; briefly, metallics offer lower material cost and the isotropic nature has some advantages in its design (Beer et al, 1981).

It has been long anticipated that realized benefits of composite materials can and will likely overcome the known disadvantages of its manufacture and operation. Benefits translated into applications means increases in airframe longevity, fuel and payload capacity, and potential performance as well as decreases in part and fastener count, manufacturing infrastructure and personnel, maintenance infrastructure, thermal stresses in space and high-altitude applications, and much more. Furthermore, it is expected that maturing composite disciplines will overcome or mitigate many of the current advantages of metallic materials as they become more readily available.

Current assumptions and methods of estimating total life cycle cost put composite materials at a decisive disadvantage in decision-making. Generally, any raw increase to composite material as a percent of a whole structure increases the total life cycle cost estimate by a cost procurement factor. This is without consideration for potential or real savings in other areas such as operations and sustainment (O&S) or procurement. It is notable that none of the savings or benefits of composites are accounted for elsewhere in the life cycle model thus creating an inflated total life cycle cost estimate where composites are to be used. Additionally, the result is a higher probability that cost per flying hour (CPFH) is universally inflated for structures of greater composite makeup.

This tends to skew one of the single largest planning and budgeting elements in the Air Force.

Purpose of This Study

The purpose of this research is to improve the means for evaluating predominately composite material aircraft in comparison to historic metallic aircraft from the perspective of life cycle cost. The culmination of this effort is the basis for modification to the currently accepted life cycle cost model, which will better characterize the benefits / tradeoffs associated with composite aircraft development and production.

Research Questions

1. Is there a cost relationship between part count, relative to the traditional whole, and the resulting manufacturing labor?
2. If said relationship exists, how do we define or quantify that relationship?
3. If said relationship exists, how can the nature of that relationship be incorporated into current life cycle cost models?

II: Literature Review

Cost Estimating Methodology: RAND premise

The authors of RAND study R-4016 deviated from traditional data collection and statistical analyses in favor of survey approach. The rationale for said change in 1991 surrounded data and technology. The current data (for which production experience is available) are limited in terms of the number of observations. There are only a half dozen historical data points (military aircraft programs) encompassing all composite material types. The data are also limited in the range of material types. Some 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. Additionally, the data are limited in the level of usage. Projected levels of usage are far beyond what has been attained by existing production aircraft. It cannot be ignored that the manufacturing technology is rapidly evolving. (Resetar, 15)

The RAND report reported wide response variability obtained from the companies that participated in the study. There is a high level of uncertainty in the collected dataset, formed over two time periods: the late 1980s and mid 1990s. Since the time of collection (1987), more than 20 years of change have been applied to the technology and application of composites, thus rendering the anticipated data of the mid 1990s primarily irrelevant at best. However, since that time, very little of the rationale for the survey has changed.

Section IV of the report addresses the cost data responses. Each table consists of an average, minimum, and maximum response value for seven different material types for each of the two time periods. Aluminum serves as the baseline, value 1.0, with each of the remaining six materials given a relative cost factor, as shown in Table 1. Predominantly each of the three evaluated composite materials (graphite/epoxy, graphite/bismaleimide, and graphite/thermoplastic) averages above aluminum but with a significant decrease between the late 1980s and mid 1990s.

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	0.8/1.0
Al-lithium	1.1	1.0/1.3	1.0	0.9/1.3
Titanium	1.1	1.0/1.3	1.0	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

Serving as an exception to the excessive cost of composite materials is one particular measure of interest: buy-to-fly ratios. Buy-to-fly is the number of pounds of material purchased to produce a single pound of that same material in the product that flies away. This factor, combined with the need for fewer total pounds of composite material to achieve the desired strength and performance as metallic materials presents a much more staggering potential as research discovers ways to make fewer and lighter composite structure pieces. This is shown in Table 2.

Table 2: Material Cost Factors (Resetar et al, 1991)

Time Period/ Material Type	Buy-to-Fly Ratio	Raw Material $/lb (FY90$)	Material[a] $/lb (FY90$)
Late 1980s			
Aluminum	2.5	11	27
Al-lithium	4.2	17	72
Titanium	3.0	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	3.0	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

[a]No burden added. The average industry burden is 15 percent.

The article cites a handful of considerations that may affect and therefore reduce the cost of composites. Of interest within those reasons composites endure such consistency in the paper is that design utilization will reduce part count and simplify the overall design process (Resetar, 59-63). Additionally, two common themes emerge from the considerations: the impact of autoclave curing and immature/lack of experience.

Additionally, the study asserts that aircraft empty weight and maximum speed/velocity are necessary for the cost estimating relationship (CER) methodology to work.

Finally, RAND cost implication conclusions were applied to two hypothetical aircraft, both fighters, that are more structurally demanding in many ways than a military transport or cargo aircraft. Nevertheless, RAND study R-4016 is the best product that addresses CERs with some validity for composites. However, more recent work gives strong indications that those CERs are not sufficiently valid.

Modern Programs and Methods

One article concludes that the minimum weight factor is a dated and less effective approach to airframe structural design than is the measure of direct operating cost (Castagne, 161). This challenges the validity of the method of CER construction in favor of more relevant measures given the much more broad collection of material mixes used in modern aircraft. Amidst literary rework that challenges a fundamental tenant of the current CERs for metals, there are also modern research programs that are quickly advancing the deployable technologies of advanced composites. (Castagne et al, 2008)

One company and one aircraft stand alone atop the world of commercial aviation in composite use. The Boeing 787, originally denoted the 7E7 for “Efficient,” is reportedly 50% composites by weight (Boeing, 2010). Given the favorable weight-replacement ratio of composites, more than half of the aircraft structure is comprised of some form of composite material. Conceptual evidence is in the skin of the aircraft vehicle, shown in Figure 1. While the details of the construction of the vehicle are of mild interest, more important is the production example of such a large composite investment. Boeing has assembled a complete production capability for this immense vehicle and has done so with profit as a primary driver. Critical to the efficiency of the production process is the use of fiber placement machines. These machines automate the layup of the composite materials prior to curing, providing very consistent costs for per unit production. Although the methods and application of composites used are unique to Boeing, clearly the company did not commit without properly vetting and returning feasible profit rates.

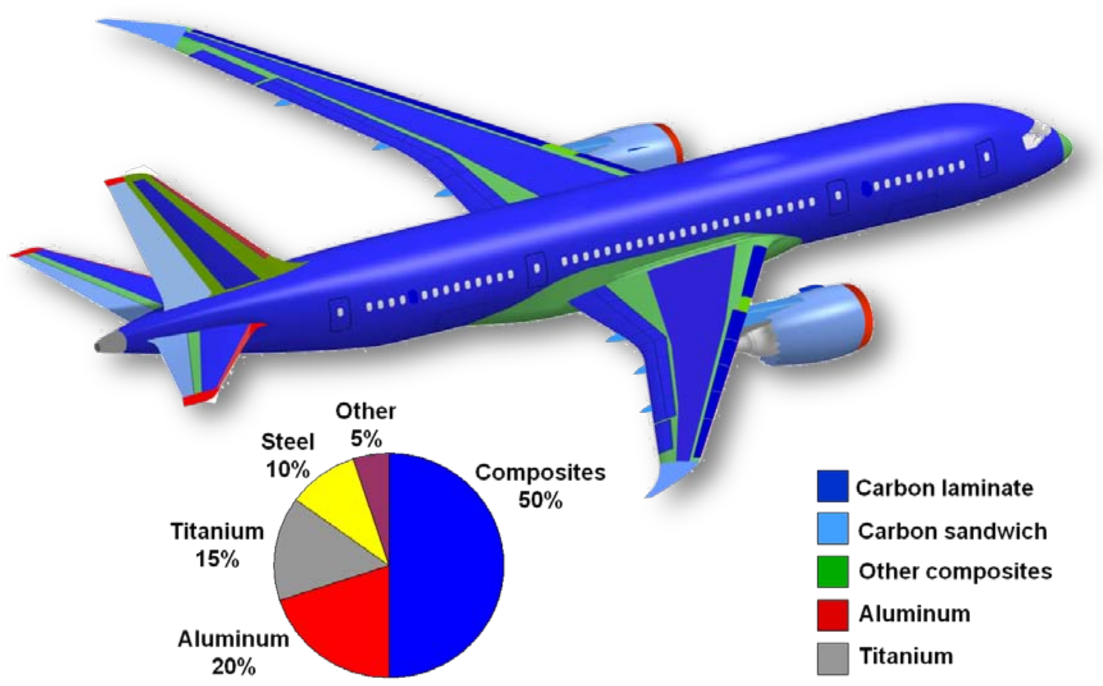

Figure 1: Boeing 787 External Skin Materials (Boeing, 2010)

The Composites Affordability Initiative (CAI) was established to significantly reduce cost, development cycle time, and weight of military aircraft. The specific goal is to develop an "all composite" airframe utilizing innovative design and manufacturing concepts to enable breakthrough reductions in cost, schedule and weight. The Phase I "Concept Design Maturation" activity was established to characterize the structural efficiency and cost benefits of some innovative structural design and manufacturing approaches that could be explored further during the follow-on phases of CAI. The Phase II "Pervasive Technology" vision was to reduce acquisition cost of composite structures by 50%.

Trade studies were conducted in late 1999 to develop a new structural concept based on the developments and lessons learned during the first two years of CAI Phase II. The CAI Concept C structural configuration was evaluated and compared with the baseline aircraft structure. The table below shows the comparison of the Baseline and Concept C metrics data. As was expected, the Concept C structural configuration shows a substantial increase in the percentage of composites used and an equally substantial reduction in the number of structural parts and fasteners. The projected 47% cost savings is very close to the CAI Phase II program goal.

Table 3: 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%

When this data is conveyed by source, the Figure 2 is the result. This dramatic reduction in cost will occur due to a paradigm shift, which combines affordable designs with affordable processes at the system level. Reducing the cost of producing a composite structure with processes mature enough to achieve an acceptable level of risk will lead to increased applications of composites (Butler, 2002).

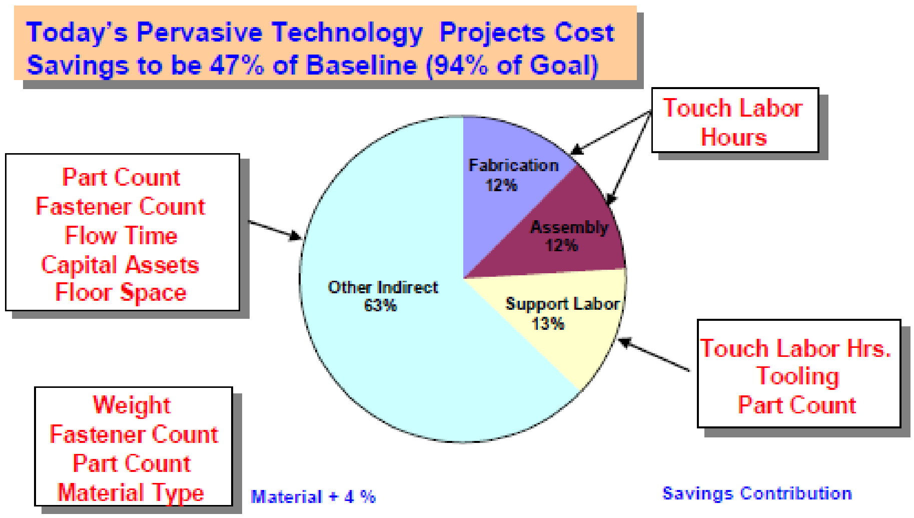

Figure 2: Projected Cost Savings for Concept C by Category (Butler et al, 2002)

The Advanced Composite Cargo Aircraft (ACCA) program is the culminating effort of CAI. The ACCA Production Study document details how a conceptual future military transport vehicle could apply the lessons from ACCA in low rate production, as well as the technologies with the most significant impact on the weight and cost of that concept vehicle. While these technologies still need to mature, current development progress places acceptable probability to achieve a Technology Readiness Level / Manufacturing Readiness Level of 5 by 2013. The program flow is here as Figure 3. The latter part of Task 2 will serve as the focal point for this research.

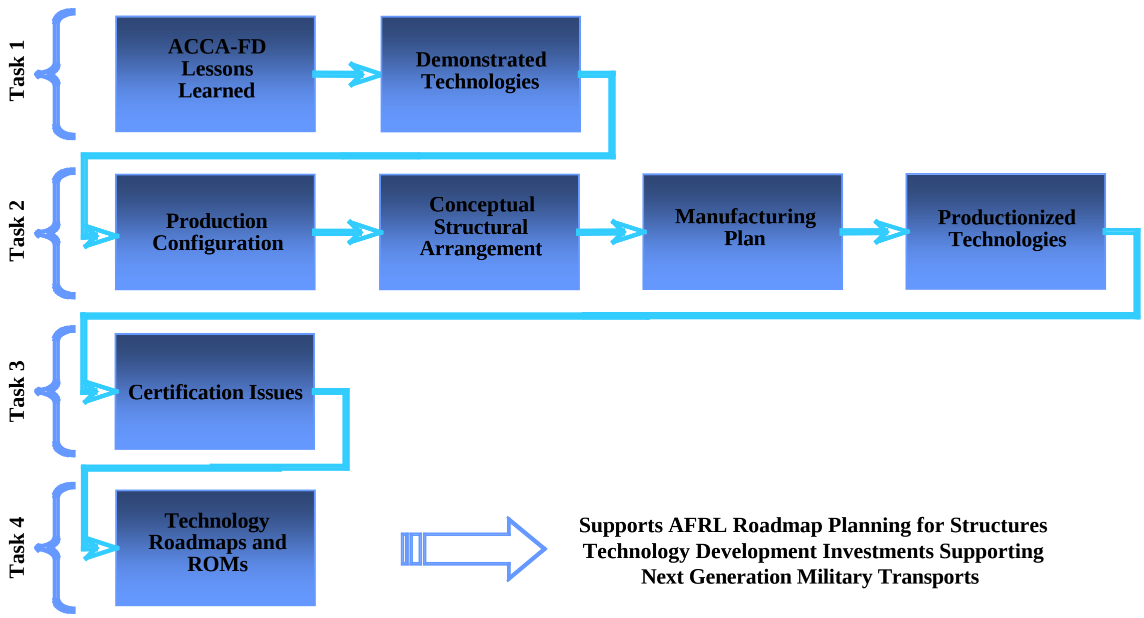

Figure 2: ACCA Task Sequence (Neumeier et al, 2009)

In terms of cost, the ACCA production study addresses many valuable trends. For example, reductions in part count and/or increases in individual part size indicate that costs will decrease to a measurable, but not narrowly predictable extent. Fewer, larger parts should experience decreases in both recurring and nonrecurring costs (Neumeier 37-38). Past programs have shown that there are several benefits to reducing the part count of a structure. Some of these impacts are reductions in up-front tooling cost, drawing count, planning complexity, and build span time (Neumeier, 7) One broadly specific area that needs to be addressed is the nature of cost and how exactly these findings may affect the current CERs and show potential for more favorable LCC estimates when composites are to be used.

III: Data Collection and Methodology

Data Sources and Variables

The open and available data for this effort came almost exclusively from the Advanced Composite Cargo Aircraft (ACCA) program itself. The ACCA program was funded entirely by Air Force Research Laboratory, thereby defining the respective data as wholly accessible to the Department of Defense (DoD). The ACCA reports are utilized at length to generate values for this analysis.

Additional datasets are partially and temporarily available from a member of defense industry, subsequently referred to as "Company X," for the purpose of ambiguity in this report. We give considerable care to protect any violation of proprietary information classifications and respective competitive advantages held by Company X. The datasets consisted primarily of composite manufacturing cost data from a wide variety of military-derivative aircraft. We use the datasets in part to provide a sufficient *n* for statistical analyses and fits. However, in accordance with the noted protection of Company X interests, only the fit itself is retained for this thesis. Any relationships to such data interests are not intentional and we consider it protected information.

This analysis exploits a Company X predictive cost model, which utilizes proprietary Cost Estimating Relationships (CERs), to determine if the calculated whole-structure values, are appropriately representative of expected values. The counter-contribution to the contractor thereby adds ACCA to its available dataset for the model in continued development and refinement. We do not intend any inference to model design or products beyond context only and, again, we consider it protected information.

The predictive cost model is intentionally simplistic, designed in part for first unit predictions for prototype programs. While the model itself addresses all costs deemed applicable to the projected unit, the variables here are limited to those that pertain directly to manufacturing labor costs. The vehicle weight from the Defense Contractor Planning Report (DCPR) is fundamentally important to, among others, the manufacturing labor hours RAND CER. Along with DCPR, the contractor utilizes a benchmarked state-of-the-art (SOA) value scale and draws numerical distinction between military and civilian aircraft structure. Although unused due to preference for more conservative results, one of the alternate manufacturing hours equations does include consideration of maximum velocity as well.

In total, 18 different input values are used in the predictive cost model. Among those values (not yet mentioned but not necessarily part of the manufacturing labor cost calculations) are aspect ratio to capture the broadest cross-section, stealth presence, quantity, max velocity, and status as a military or civilian aircraft. Although this was a civilian aircraft, the contractor performed modifications for military functionality; most notably, the included the addition of a cargo load ramp justified classification of the modified Do-328J as a military aircraft.

This is consistent with the RAND CER for manufacturing labor hours employed in the studied DoD LCC predictive model. That CER, optimized for unit 100, makes use of empty weight, rather than DCPR, and maximum velocity. It is that CER which is up for consideration of modification for the first unit based on the results of this study.

The variable of interest is ultimately a respective percentage to be applied as an additional or final factor to the Rand CER for manufacturing labor hours. In order to obtain that product, two data collections are required. First, a sufficiently large and distributed set of actual first unit manufacturing labor hour values is necessary; this is followed by the respective part counts as a percent of standard configuration. These two collections comprise the necessary dataset to return an applicable percentage for a predictive model.

Find the relationship.

This first question is perhaps both the most intensive and exclusive. Should we be unable to validate the existence of a cost relationship, the remaining research questions are essentially irrelevant and rendered obsolete by the lack of initial results. The intensity comes from the level of understanding that is required to pursue the relationship. Although the reviewed literature begins to answer this, Company X provides much of the necessary information in an unpublished form. The definition of that work, included for context, not numerical content, is included in Chapter IV.

To begin, it is necessary to show that vehicle weight and traditional part count relate. This relationship allows for the projection of average pounds per part relative to vehicle weight. Combine these results with real part reduction scenarios and we have the opportunity to project manufacturing hours relative to part count. If there is a definable trend, then a relationship is said to exist.

The necessary remaining step to validate the existence of the relationship in question is to bring ACCA into the fold and re-compute. The addition of ACCA data brings a much larger vehicle part-count initiative to the dataset of collected vehicles. The effect on the resulting fit line and the related statistical values are of interest for comparison, both for consistency and quality of fit. If the resulting fit line is statistically valid, the definable trend is present and the relationship exists.

Define that relationship.

Assuming a relationship, the function of the fit line serves as a quantification of the relationship. The function and physical appearance of the fit will determine the definition, which should project some downward trend in relative total manufacturing costs with the decline of relative part count. In preparation for this research, we are investing in the dissection of the current life cycle cost (LCC) model. The goal is to gain a firm and comprehensive understanding of the mathematical dependencies within the model itself. A natural byproduct is the qualitative analysis of the layout of the model. Additionally, we will reveal, at least partially, obsolete and irrelevant fields and calculations. Excluded from the analysis is any mathematical assessment itself. We do not intend to evaluate the model for accuracy, as the model is the product of the owning organization's theories and methods of calculating a projected life cycle cost. Details of that dissection are included in Appendix B.

With an understanding of the model in place, we are able to determine possible values of impact. We can assess any potential inputs that are understated and perhaps others that are missing completely. This is not an implied or direct substitution for the study necessary to generate updated CERs. Rather, this assessment serves only to provide partial numerical validation for one of the many notional cost implications of composites. Our look at the ability to use monolithic part sizes thereby reducing total part count falls directly as support for such notions. We will be doing so by analyzing part size specifically in terms of labor costs for manufacturing.

Company X has provided the fundamental dataset; other than a periodic corroboration, we accept that dataset as valid for the intended analysis. We will add ACCA to that dataset only after we make any necessary adjustments or evaluations to keep scales consistent with the aggregate information. For the sake of inclusiveness, it is appropriate to seek measure and fit for more cost categories of development and production. Beyond recurring manufacturing, we will also seek fits for design, design support, testing/QA, and tooling. These other categories will not be part of the utilization discussion, but should be generally part of the projected impact. Should similar relationships appear to exist, it is reasonable to anticipate that there will not be any offsetting cost losses because of part count reductions across development and production.

Utilize that relationship

The sponsor organization for this effort has graciously provided the LCC model in use by their supporting staff. We are interested in that model, both in current and potential or applied form. Assuming a relationship, whether as anticipated or not, such a relationship should be able to be captured and added to the model for a more complete picture of cost sources. If part count is captured in the model, it will be necessary to assess its utilization and any potential changes to such process to capture the relationship in question. If part count is not a factor in the LCC model, it may be necessary to add an appropriate input value to capture relative part count percentage and develop a new process to capture the effect of the relationship on manufacturing cost.

In an effort to protect both the data and competitive methods of Company X, we will speak broadly about the steps taken to bring the ACCA data points into the primary dataset. Using previous aircraft vehicles, we project systems and structures weights from the partial modification of the Do-328J as if the entire aircraft is new production. This assumes that such proportions are consistent between similar vehicles; we do not have sufficient data points to validate this statistically. We rely purely on Company X for the derivation and accuracy of vehicle complexity and state-of-the-art, as well as other proprietary measures that we utilize in the initial predictive model. This assumes that the historical work of Company X is valid and they have properly applied that work to the predictive model. These values are not part of the life cycle cost model evaluated in this thesis.

We can apply a rate of learning to any repeatable task. With purpose to improve performance, any subsequent iteration of a task should achieve completion more efficiently. We can use this rate of learning to project future performance. It is important that the modification of the Do-328J, an existing vehicle, as performed as part of the ACCA initiative, is not valued as a second unit or iteration. In this case, the manufacturer is no longer in business and was not the contractor awarded the ACCA contract. Additionally, relatively little information about the original design was provided to the contractor, thereby passing almost no learning to the new design team. Essentially, only the vehicle itself changed hands. We assume that the modified portion is therefore qualified as a 100% new design, and we will only evaluate that portion within the models of Company X. There is also a rate of learning for the new aircraft itself. ACCA is a single model prototype vehicle; therefore, we cannot apply any direct learning to the manufacturer itself. We are forced to assume that any reduction in manufacturing labor requirements at the onset will not bear the burden of atypical inefficiency as a result.

In order to render the ACCA data usable, a few steps are necessary to whole-size the vehicle from a partial part count mod to a complete structure. By comparing known part and weight values of various aircraft parts and component structures, we can extrapolate final weights from the portions of the Do-328J that underwent modification for ACCA. This final weight, or whole vehicle weight, is available to the existing dataset for updating the model. As a crosscheck, we scale the model result to see if the model prediction produces a similar value to the actual modified weight. With a valid crosscheck, ACCA results and CAI Concept C findings are comparable. Additional information, as required, is available on a by-case basis from the author.

IV: Analysis and Results

Find the relationship.

Using DCPR rather than MEW, an exponential relationship is shown to exist, given n=10, between vehicle weight and part count. This is shown in Figure 4 with an R^2 of 0.96.

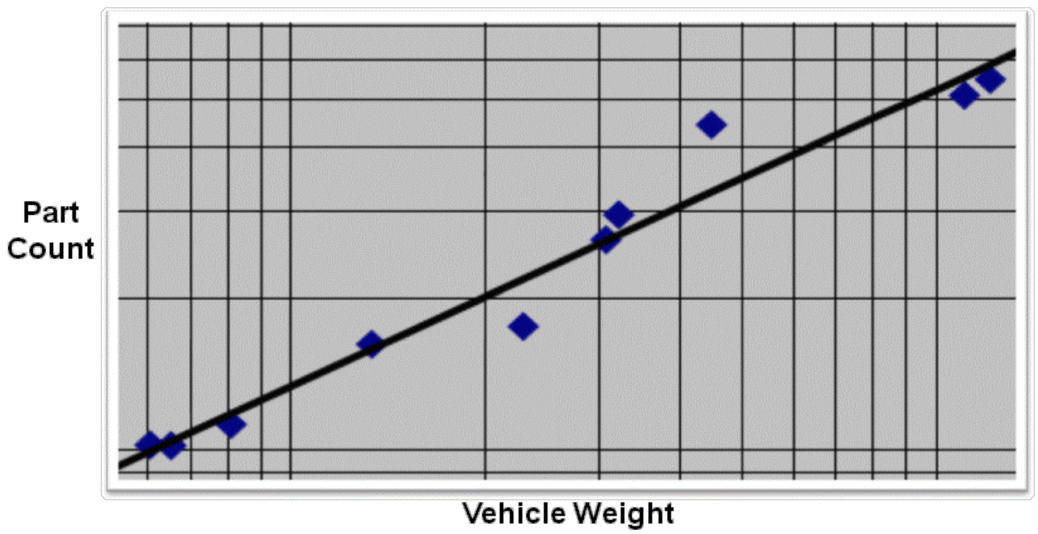

Figure 3: Part Count v. Vehicle Weight

Subsequently, we calculated total pounds per part relative to vehicle weight.. This is shown in Figure 5 with an R^2 of 0.91.

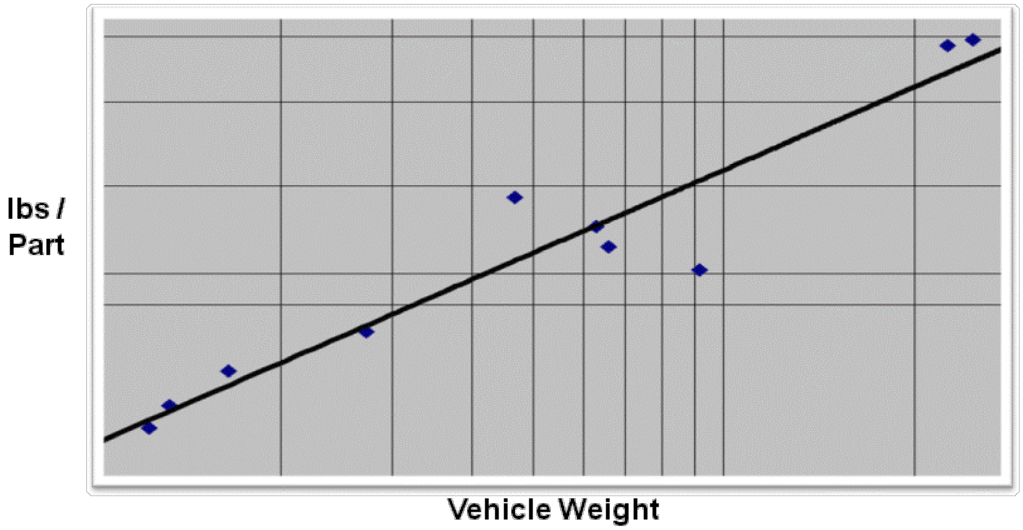

Figure 4: Pounds per Part v. Vehicle Weight

Company X has performed a number of real part replacement scenarios, either prototypical or on production vehicles. A small dataset, including only prototype vehicles, offers the fit shown in Figure 6 with an R^2 of 0.56. The depicted scenario, excluded from the original fit, adds two more points to the dataset and, by nature of the values, increases the R^2 to 0.86. The corresponding summary information displays key factoids of a direct 90% part reduction for a given subset of 10 parts. The most valuable resulting data point is the hours per pound. In the original 10 part situation, the manufacturing hours per pound required was 71 hours. After the reduction, that same value dropped to only 20 hours. That is a 72% reduction in manufacturing hours in response to the 90% part reduction.

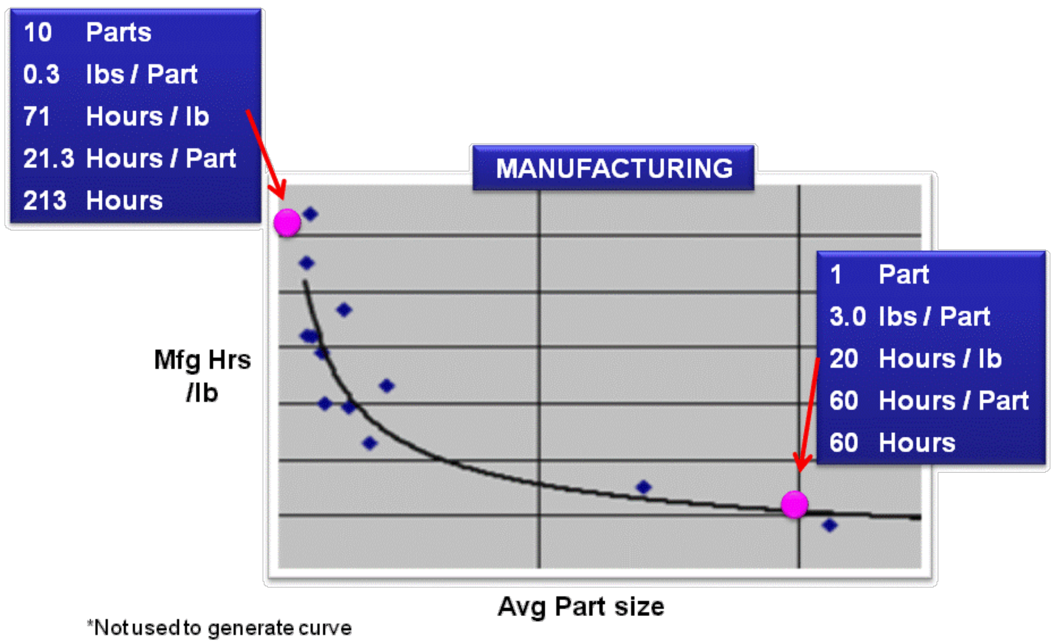

Figure 5: Manufacturing Hours v. Average Part Size

Scenarios like these, along with other proprietary data collected by Company X, form a dataset that permits the generation of Figure 7. This figure shows what appears to be an exponential curve depicting the relationship between percentage reductions in part count and the resulting percentage reductions in total manufacturing hours for a given vehicle. It is more likely that the curve is actual polynomial in nature and will have a global low at some point near the bottom left of the figure; it is not realistic to consider that a vehicle made of one single part would necessarily inherit the greatest manufacturing labor hour reduction. As with the other figures, we have excluded scale values to maintain information that could be competitively beneficial to industry members external to Company X. This series leads us to conclude that there is indeed a relationship between part count and manufacturing hours.

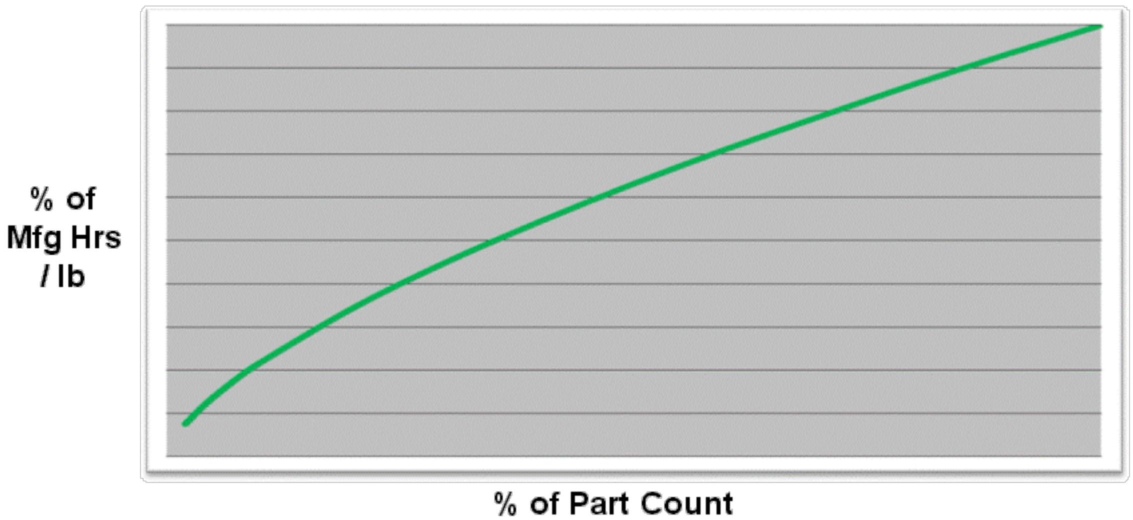

Figure 6: Manufacturing Hours v. Part Count

Define that relationship.

The relationship, as depicted by the fit line in the previous figure has a general positive slope. In the case of percentage reductions, with 100% of traditional value falling at the extent of each axis (upper right of the figure), thereby the greatest reductions occur at the opposite corner (bottom left of the figure). Therefore, the relationship has the appearance of some quantifiable percentage reduction in manufacturing hours because of the respective reduction in total part count.

We quantify this relationship by the fit of the line. We have excluded the actual value of that fit, however, so it is referenced only as $\boldsymbol{w \cdot PCP^3 + x \cdot PCP^2 + y \cdot PCP + z}$ where variables w, x, y, and z represent the masked coefficients of the fit. PCP is a variable created to represent the percentage of part count reduction, rephrased as part count percentage, or PCP. The associated R^2 for this curve is approximately 0.9, where n=10. Note that this is a polynomial fit, and is included here in lieu of a power fit that returned a perfect R^2 of 1 given the dataset available.

Utilize that relationship.

If said relationship exists, how can the nature of that relationship be utilized in context of current life cycle cost models?

To address this question more completely, it was necessary to consider other cost categories of development and production. Five major categories headline the data made available by Company X. One of those categories, manufacturing hours, is the focal point of this project, and is what we calculated to the furthest extent. However, preliminary results, including those provided in the interim ACCA phase reports, provide a glimpse into four others: design, design support, tooling, and testing/QA. Before delving into the numbers, we will look at these categories conceptually.

For the sake of consideration, we presume that a similar relationship exists for each of these other four categories. At a very macro level, testing likely has the most linear relationship, since fewer parts creates a lesser requirement for the number and types of parts that need to be tested (this does not include flight-testing of the entire vehicle). Similarly, design support (described very blandly as drawing sets and engineering evaluations) is a very piece-based process, and will likely project a relationship more linear than not. At the opposite end of the spectrum lie design and tooling. Design for a vehicle in whole is necessary regardless of the number of parts used; there is likely a part count effect but not nearly as great as manufacturing or testing. Similarly, the number of parts may lessen tooling requirements, but complexity increases with part size, thereby mitigating some of the likely labor hour reductions that come with fewer parts. As we reviewed the preliminary results, this appeared to hold true. Figure 8 shows a snapshot of the same scenario effect described above for manufacturing hours per pound. The R^2s vary rather widely, from 0.83 on Design, down to 0.19 on tooling.

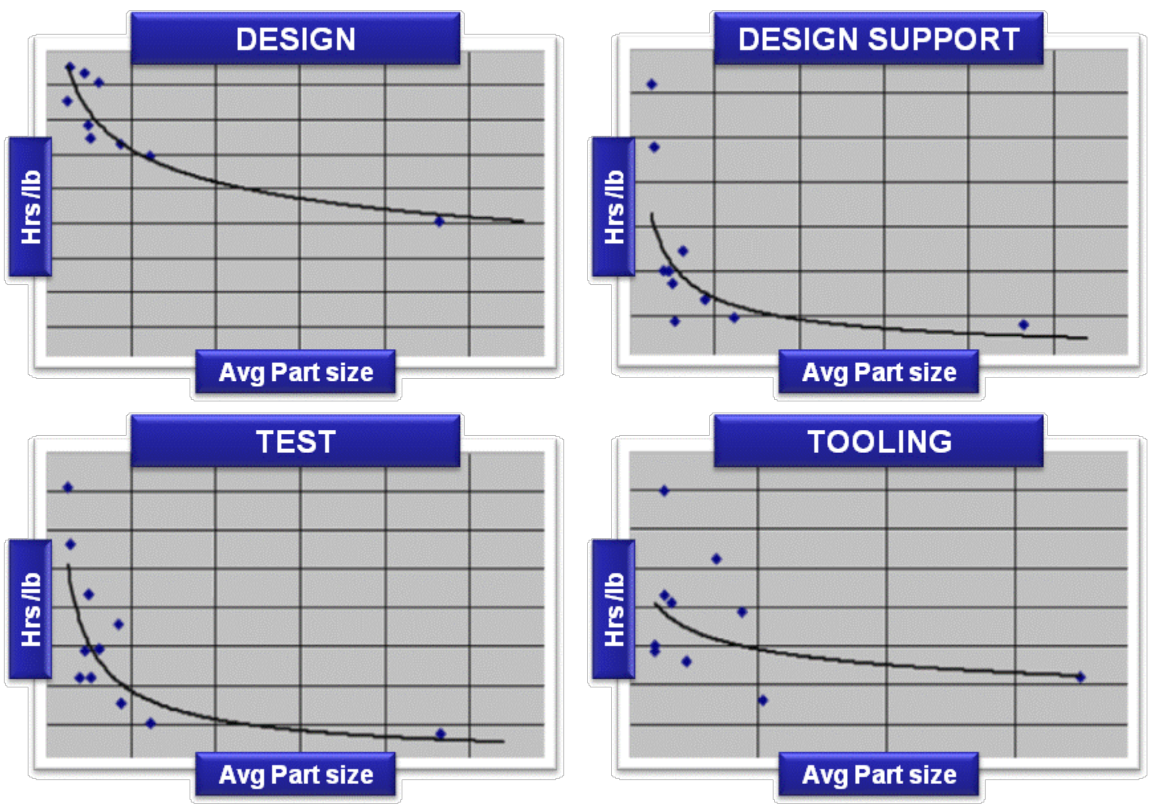

Figure 7: A Snapshot: Other Disciplines

In each case, there is a similar appearance to that witnessed in manufacturing hours, and can converted to a percentage reduction for comparison alongside manufacturing hours. Indeed, it would appear that the very simplistic relationship characteristics expected are supported by these preliminary results. Testing exhibits the flattest, most linear relationship, and tooling takes the deepest bend along its curve, showing much more diminished effects on manufacturing hours (as a percent of cost) until the vehicle is relatively very simple.

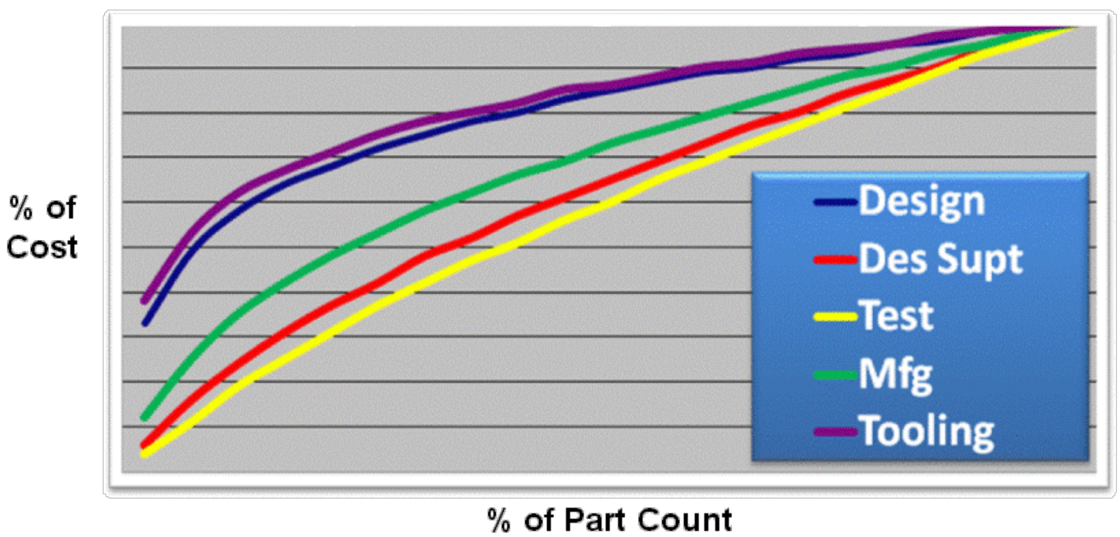

Figure 8: A Snapshot: Cost v. Part Count

The implication of this snapshot is that the effect of part count reduction permeates the development and production stages of vehicle life cycle. Any effects captured through manufacturing hours will likely yield a similar opportunity in the other cost categories, as delineated by Company X. It is the manufacturing hours effect that is shown in the model modification text and images following.

To begin, consider a brief, generalized snapshot of the LCC model through the points of interest, to gather perspective on the cost accumulation of the total life cycle. For the figures and example following, we used a simple scenario based off on an existing estimate. The scenario is for a 100-unit drone life cycle with an expected usable life of 25 years. We do not necessarily mean to reflect reality with the scenario; rather we intend to provide a numerical base for comparison. Note that the values themselves are relevant only in their relative magnitude. Figure 9 represents, for the utilized example, the relative percentage cost drivers of total life cycle cost. Procurement, one of the two primary cost drivers, is the point of interest we will follow as we drive deeper into this model.

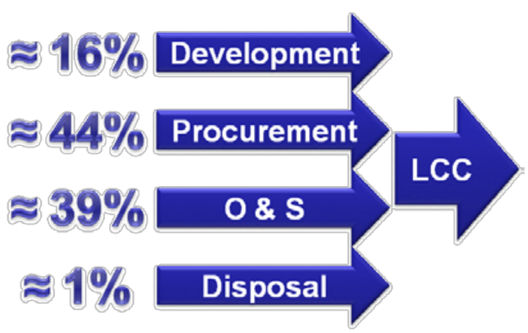

Figure 9: Cost Elements of Life Cycle Cost

Manufacturing is the true point of interest. Here we show the model through five tiers of dependent calculations and subsequent rollups. In this example, the value of interest represents approximately 10% of the total life cycle cost. Figure 11 is a conceptual view of the flow of calculation, with each vertical column summing to the large cell in the next column. For simplicity, only the values that depend on the proposed changes (introduced later) are included in the figure. If full numerical detail was provided, engineering, tooling, manufacturing, quality control, and material would all sum to the $630M value listed under airframe. Subsequently, airframe, engine, and avionics would sum to the $790M value for prime mission equipment (PME)

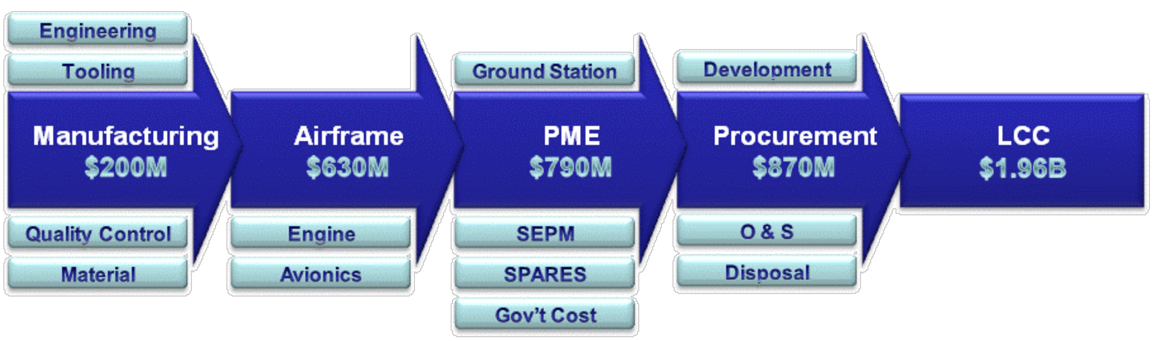

Figure 10: Cost Elements from Manufacturing Hours to Life Cycle Cost

It is that ten percent, approximately $200 M, that is affected by the results of the relationship. Here "Airframe" is the summation of manufacturing expense categories, each a product of materials, if applicable, and labor hours assessed at the appropriate labor rate. These figures do little other than explain the rollup of cast categories. To explain the changes to the model itself, it is necessary to drive deeper in the actual flow of the calculations.

In the current form of the model, we zoom in immediately to the manufacturing hours portion of the model. We represent "Manufacturing" with the variables $C_{M,}$ manufacturing cost; on subsequent figures. This particular value is the number of manufacturing labor hours (H_M) multiplied by the respective labor rate. According the definition of the relationship, a change in relative part count should return a change in manufacturing hours. Figure 12 depicts the current relative position of manufacturing hours (H_M), post inputs and pre results (RMFG is a Recurring Manufacturing factor, as prescribed by the current CERs).

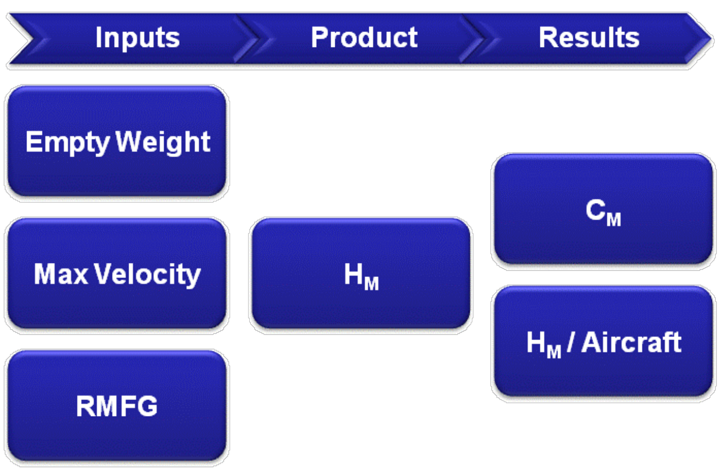

Figure 11: Life Cycle Cost Model, Current, Excerpt

From here, we can now make recommended changes. Currently, part count reduction or relative part count is not a factor in the LCC model and therefore any deliberate change to part count remains ignored as an input or by effect on total cost. Based on the nature of the relationship, we expect a change in the value of manufacturing hours because of a reduction in relative part count. Taken simply, by reducing part count, we expect a reduction in manufacturing hours, each as a percentage of a whole or traditional expected value. In Figure 13, we apply the fit as a new calculation, $H_M\%$, percent of manufacturing hours. The value PCP is again present, representing the part count percentage of the whole or traditional expected value.

$H_M\%$

$$H_M\% = u * PCP^v$$

$$H_M\% = w * PCP^3 + x * PCP^2 + y * PCP + z$$

$$R^2 \approx 0.9$$

Figure 12: Life Cycle Cost Model, Applied, $H_M\%$

This new calculation, $H_M\%$, can be applied as an additional, interim layer prior to the processing of H_M itself. To do so, PCP needs to be added as an input from which $H_M\%$ can be derived. Therefore, the H_M calculation necessitates modification. Currently a product of the utilized CERs, H_M inherits the additional factor, $H_M\%$. The resulting function for manufacturing hours is:

$$H_M = .141*(WE^{0.82})*(V^{0.484})*RMFG*HM\%.$$

where

$$WE = \textit{Empty Weight} \text{ (lbs)}$$

$$V = \textit{Max Velocity} \text{ (knots)}$$

$$RMFG = \textit{Recurring Manufacturing Factor}$$

$$HM\% = \textit{Percentage of Manufacturing Hours}$$

Figure 14 shows H_M% in context of the inputs and the H_M product.

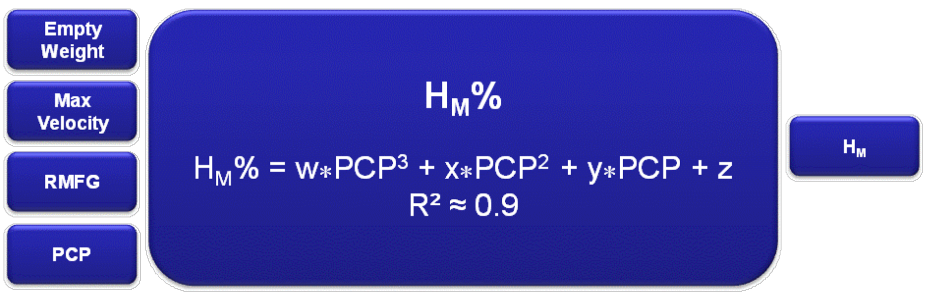

Figure 13: Life Cycle Cost Model, Applied, H_M% Context

To get a feel for where this fits in to the LCC model, Figure 15 shows a macro, zoom-out view. It includes more detail from the airframe production portion of the prime mission equipment cost lane of the total life cycle model. The values on the left are inputs. The values on the right are products used in cost summaries or supporting context. We have included both the original and modified (shown as "applied") manufacturing hours in the proposed model change to capture a point of comparison.

Any modifications to CER and model calculations due to part count should include, by our recommendation, this same type of comparison point.

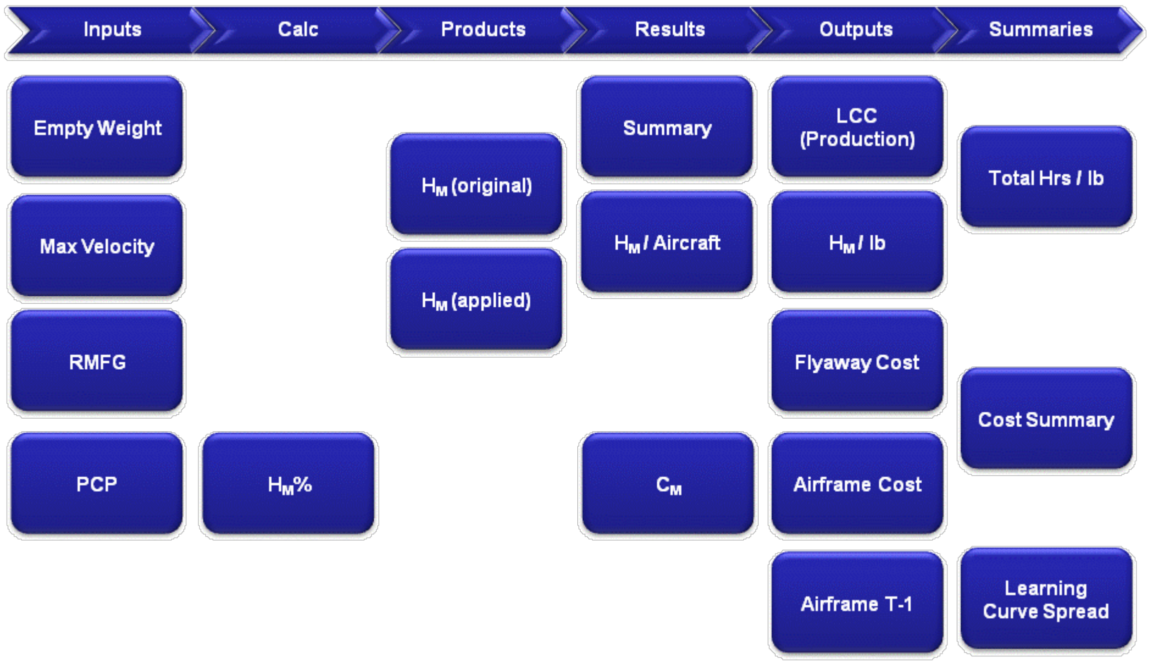

Figure 14: Life Cycle Cost Model, Applied, Excerpt

We added back in the values from the utilized scenario to measure what the compound effect of this factor is on the model. By assessing an arbitrary 50% part count reduction, the fit returns an approximated value of 65% for H_M% (this value is deliberately inexact to maintain protection for Company X). In the manner applied, this has a direct effect on H_M, decreasing from the original $200M to $130M, or 65% of the whole value. This can be followed through the entire model, where the compound effect is truly visible, doubling in magnitude throughout the whole life cycle of the scenario. Figure 16 is identical to an earlier figure, but now includes the original value and the applied value. Thus, we are able to apply the fit from the relationship to the model and produce a corresponding change in the results because of the findings in the previous research questions. The drone example used here generates a 7% total LCC reduction of $146M with the addition of a 50% part count reduction input.

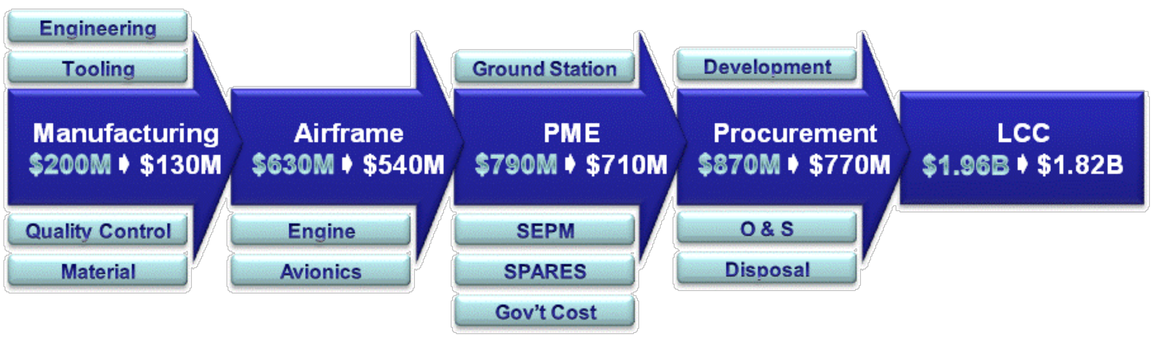

Figure 15: Life Cycle Cost Model, Applied, Compound Effect

V: Conclusions

Conclusions

The reduction noted in the drone example is a sample of the scale of cost implications that part count has on life cycle cost (LCC). There is potential for application of the expected effects of design, design support, testing, and tooling, which offer their own potential effect on total airframe cost. Furthermore, with likely initiatives and future research trending toward understanding the true implications on operations and sustainment costs, it is reasonable to expect the long anticipated cost reductions to come to quantifiable reality.

The interim recommendations of change to the LCC model is a stepping stone to study the current model and how the calculations flow. This provides a legitimate basis for analyzing the cost estimating relationships (CERs) and how LCC cost estimates have been done historically in context of composite materials that do not act like metallic materials.

Strengths, Limitations, and Policy Implications

A byproduct of this research was improvement to the predictive model owned by Company X with the addition of Advanced Composite Cargo Aircraft (ACCA) data points. The derived fit and relationship effectively influence cost, as indicated by the findings. There is sufficient material here to support additional research in this area in a further attempt to justify adjustments to the manufacturing hours CER. Given part related findings, reducing part count merits consideration in cargo vehicles.

A significant time investment went into dissecting the model itself. This does not qualify us as experienced users or developers of the model. Therefore, we did not correct, account for, or retain known or unknown mathematical errors or inaccuracies of the model for the purpose of these findings. Mathematical effects that either under or overstate the significance of the impact of the findings are inherited fully into this work.

There is a substantial difference between a prototype first unit and a production first unit. The construct of the life cycle model is for production scenarios, not prototypes. There is a very real possibility that the fit of the relationship, dependent on prototypes, is inaccurate in comparison to production vehicles. The burden falls on Company X, for the validity of the method we used to generate the fit, and future research. We need to prove these findings in production.

Additionally, ACCA was not a complete aircraft design or production. Thus, the scaling methods used may be inaccurate. Company X was remarkably helpful, but is still just a single entity. Without more comprehensive and transparent industry data, the generalizability and accuracy of these findings is at question. Fiber placement machines, such as those used by Boeing on the 787, and the cost effects of that automation are another unknown in this research.

By definition, a fiber placement machine reflects virtually no learning rate. Such use would likely substantially reduce the cost reduction impact of these findings. However, given the production quantities necessary to justify the investment in fiber placement machines, evaluation of the actual impact will fall to future research in production scenarios. On a related matter, there exist the issue of increased part size. For example, ACCA is a cargo vehicle, providing reasonable internal accessibility to both structure and systems. However, not all portions of the vehicle and certainly not all aircraft types allow the same degree of accessibility. This research does not seek to address of resolve any of the issues that come with increased part size. The compound effect of the part count reduction surpasses the product of inflation across the production spread. Therefore, the model is introducing a numerical effect that, while traceable, is not mathematically justified. The operations and sustainment implications are therefore notional only, and are not part of this research.

The sponsor is also interested in capturing the uncertainty of metallic vehicle estimates at the time of award as compared to actual procurement costs. This related but substantial effort exceeded the possible scope of this research. It is, however, critical to evaluate both the model and the accuracy of current inventory vehicles that do contain composite structural elements. This research provides a springboard for policies related to aircraft design to incorporate the impact of monolithic parts. Expectations of aircraft performance and manufacturing costs should reflect that impact. Additionally, there is likely a drastic corollary between optimization (a necessary stage/cycle in production) and viability of these findings. Furthermore, theories surrounding composite utilization may be affected. With greater longevity potential and some areas of increased performance (general notional products), we will see the savings as a result of part count reductions in cost per flying hour and total life cycle cost.

Future Research

A research continues, progress will be able to go through several stages of focus. Initially, the knowledge peer to this research is needed, such a determining an autoclave scale factor and the effects of these changes on learning curves. Additionally, the other disciplines of design, design support, tooling, and testing can be vetted and applied to the LCC model similarly. Once part count is in isolation, then more work can be done on the effects of total vehicle weight and production methods, such as fiber placement machines. Also affecting the LCC model are the life cycle duration, operations and sustainment, and specific maintenance effects, not all of which will be cost reducers. Finally, to better evaluate the legitimacy of the LCC model, research must be done on the historical uncertainty of metallic material aircraft estimates at source selection in comparison to the actual cost at production. These efforts will culminate in a more robust and accurate LCC model that can aid in the discussion of initial trade-offs in support of the decision makers.

Appendix A: LCC Model Calculation Dependencies

This graphic series is available upon request.

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 074-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From – To)*
25-03-2010	Master's Thesis	Aug 2008 – Mar 2010

4. TITLE AND SUBTITLE Part Count: Monolithic Part Effects On Manufacturing Labor Cost, An Aircraft Applied Model	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Lemke, Aaron M, Capt, USAF	**5d. PROJECT NUMBER** JON 508
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 Hobson Way WPAFB OH 45433-7765	**8. PERFORMING ORGANIZATION REPORT NUMBER** AFIT/GFA/ENV/10-M02
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Mr. Shenk, Barth W., Civ, USAF Air Force Research Laboratory, Air Vehicles Directorate 2130 8th Street, Building 20045 WPAFB, OH 45433 DSN: 785-8343	**10. SPONSOR/MONITOR'S ACRONYM(S)** AFMC AFRL/RBOT **11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

12. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

13. SUPPLEMENTARY NOTES

14. ABSTRACT
There are significantly different manufacturing processes and part counts associated with composites that are not currently addressed within the procurement and life cycle management processes in the Department of Defense (DoD). A series of initiatives have culminated in significant evidence over the last decade to combat the implied risk of composite aircraft. An Air Force Research Labs program, Advanced Composite Cargo Aircraft (ACCA), provides substantial support for the impact of part size on life cycle cost on payload aircraft. This paper evaluates select current methods used and seeks to introduce modifications to the projected manufacturing hours cost. The findings suggest the impact of monolithic parts appears to permeate most of the major cost categories in development and production. The discussion addresses the far-reaching implications of trading several parts for one. This research finds that a significant relationship between relative part count and major cost categories does exist. Specifically, a percentage reduction in part count drives a corresponding percentage reduction in the manufacturing hours. The series of findings pertaining to part count and cost merit consideration for updates to the CERs and interim modifications to capture some portion of the impact in current life cycle cost models.

15. SUBJECT TERMS
Advanced Composite material, Composite aircraft, Monolithic parts, Part count, Manufacturing hours, Life cycle cost model, Advanced Composite Cargo Aircraft

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Dr. Som R. Soni (AFIT/ENV)
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(Include area code)*
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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

	Form Approved *OMB No. 074-0188*