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A DESIGN-CENTRIC EVALUATION OF MULTI-FIDELITY COST MODELING APPROACHES

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Abstract
A new set of cost-estimating relationships is presented in an application-based assessment activity. The assessment conducts a multi-fidelity analysis of aircraft procurement costs on a selection of vehicles using both legacy models and the newly-development methodology. The study compares the overall accuracy of the different approaches as well as the difference in insight yielded by the respective levels of fidelity. The results of the comparison are examined qualitatively in the context of future aircraft development to infer affordability implications pertinent to contemporary design trends and performance requirements.

1. INTRODUCTION

Conceptual design has frequently employed parametric cost estimation methods as an additional means of describing an aircraft. Due to a variety of challenges related to data availability and transparency, parametric estimation of procurement costs has traditionally been limited to a low level of fidelity relative to most contemporary conceptual design methods. Recent developments in documentation along with a proliferation of newly proposed advanced rotorcraft configurations have prompted a reevaluation of this approach.

Fig. 1 plots the unit flyaway price trends of a selection of military and civil aircraft which are either recently or currently in production and service as of 2018. Although each type of aircraft exhibits a general trend correlating vehicle size with unit cost, considerable variation also appears around each trendline. To date, system-level cost models have successfully predicted the general trends apparent in Fig. 1, but have relied on engineering judgment to assess effects such as detailed design changes or new technology. This study hypothesizes that a statistically-discernable amount of the observed cost variation is due to differences in design and performance at the component level, and thus can be assessed objectively by increasing the fidelity of the cost model.

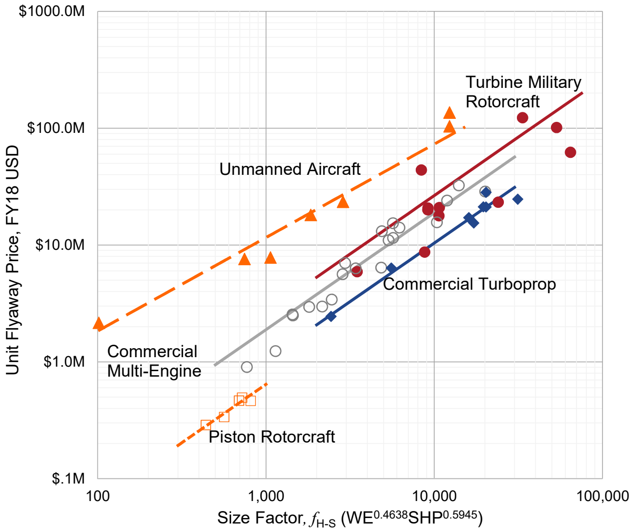

Figure 1: Unit flyaway price trends of civil and military aircraft current to 2018

To test this hypothesis, a comparative evaluation of multi-fidelity cost modeling approaches for rotorcraft and advanced aircraft is presented which measures the relative accuracy and insight of the respective approaches. Although a higher fidelity cost model yields more information in the sense that vehicle components can be sorted according to cost-driving priority and their advanced features directly assessed for cost impact, the utility of the modeling capability must still be evaluated based on the tradeoff of information and insight versus overall accuracy and workload. The results of the

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study will be examined in the context of the future design trends motivating the original research.

2. APPROACH

High fidelity cost modeling represents a relatively new perspective in rotorcraft production and procurement. Although internal studies have likely been conducted for many years by aircraft manufacturers, non-industry analysts have been challenged by a scarcity of available cost information. Prior to the widespread adoption of the MIL-STD-881C[1] work breakdown structure (WBS) for airplanes and helicopters, most aircraft delivered to a branch of the United States military reported only the total cost of the base air vehicle and the separate cost of the engines. Rotorcraft programs which predated 881C infrequently would also report rotor and drive system cost separately in this system. The blending of component costs into a single vehicle quantity in the old standard limited analysis conducted at the conceptual design stage to the cost effects of overall vehicle weight. For shaft-driven aircraft, Harris and Scully[2] moved one analytical step beyond weight-based cost analogies in developing the size factor f_{H-S} based on empty weight and installed power (used in Fig. 1) which remains a useful scaling parameter for comparison of cost trends.

Collaboration between government and industry produced one of the first widely-available conceptual cost models in the Bell PC-Based Concept Cost Model[3] which conforms to a component-level work breakdown structure. The Bell PC model was subsequently hosted in a commercial cost analysis software package known as the TrueRotorcraft model[4], and applied to sizing trades for multiple types of advanced rotorcraft[5].

In order to directly address the pertinent cost effects of requirements, advanced configurations, and advanced technology inherent to present and future user needs, new cost estimating relationships (CER's) were developed as part of the present study using the same statistical methods employed by Harris and Scully within the higher fidelity framework of the 881C standard. The present study is devoted largely to an applications-based evaluation of the performance of the new CER's against pertinent test cases. A more statistically-oriented assessment of the models employing regression metrics and tradeoffs of modeling techniques will follow this study in future work. Additional model development will also attempt to replicate the same analytical principles in assessment of operating and support costs and other as well as other areas of the complete aircraft life-cycle.

2.1. Data

Government procurement of aircraft in major programs satisfying the conditions which mandate the use of the 881C standard is documented in Cost and Software Data Reporting (CSDR) forms, which cover the cost of a given number of production units over a specified period of time. Cost data from CSDR forms spanning various models of aircraft and engines was queried from the Defense Acquisition Cost Information System[6] and analyzed in the R statistical programming language. The rotor and drive system populations were additionally supplemented with 12 data points representing civil rotorcraft using two commercial databases[7,8] to expand the breadth of designs and the size range of aircraft represented in the surveyed population. Table 1 summarizes the datasets used to develop each of the parametric CER's. Design characteristics for each aircraft component were compiled directly from aircraft weight statements as well as other sources[9] and screened against the corresponding cost data to develop the CER's.

Table 1: Component data population demographics

Component	Airc./Eng. Models	Cost Reports	Proc. Timeframe
Wing	19	120	1990-2015
Fuselage	24	185	1988-2016
Rotor	22	121	1969-2016
Drive	22	108	1970-2016
Avionics	17	17	1978-2012
Engines	30	155	1958-2013

2.2. Analysis

In keeping with the original study objective of a comparison of high and low fidelity cost assessments, a set of equations adapted from the original Harris-Scully model were used as system-level alternatives to the new component-level model. The modified Harris-Scully unit flyaway equations are given in Appendix B.

Within the high fidelity prediction approach, the fully-parametric equations developed from statistical regression of the reference data described in Table 1 were developed for the components which

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represented the greatest joint interest among design and cost concerns. Components such as the landing gear, fuel system, electrical group, and furnishings which typically do not contribute major cost-driving effects to the overall cost of most aircraft received lower analytical priority. These components were assessed using a combination of semi-parametric methods based on either the parametric estimates of related components or analogies based on percentages or dollar per pound trends. Table 2 describes both the work breakdown structure adapted from 881C[1] for the study and the methods used to predict the cost of each element.

Appendix A presents equations for the unit production cost of a component in a delivery lot of N_q units with N_p units already produced prior to the current lot. The unit production cost represents the recurring price the customer pays for the materials and labor required by the component. The integration and assembly of the components along with the systems engineering and the profit and fees charged by the manufacturer on a recurring basis with each lot are applied to the entire set of components by separate CER's. The only exception to this rule in the high-fidelity model are Eqns. 9 and 10, which estimate the total procurement cost of engines. In keeping with the practice observed more frequently in aircraft procurement, engines are modeled as items which are procured separately and integrated into the vehicle as government-furnished equipment (GFE).

Both the high and low fidelity methods predict the unit flyaway price c_{FA}. The lower fidelity Harris-Scully model predicts this quantity directly. The higher fidelity component-based model predicts unit flyaway price by summing the costs of the prime equipment production; integration, assembly, and systems engineering; and profit.

(1) $$c_{FA} = c_{pq} + c_{int+SE} + c_{profit}$$

For the component level model, the predicted prime equipment cost is the sum of the parametric and semi-parametric analysis components.

(2) $$\hat{c}_{pq} = \hat{c}_{param} + \hat{c}_{semiparam}$$

(3) $$\hat{c}_{param} = \hat{c}_{wing} + \hat{c}_{fuse} + \hat{c}_{eng} + \hat{c}_{prop} + \hat{c}_{xmsn} + \hat{c}_{av}$$

The analysis procedure computes the parametric cost elements first, since several of the semi-parametric equations depend on the parametric estimates.

Table 2: Cost assessment methods organized by aircraft components

Component	Method
Structure	
Wing	Parametric, Eq. (6)
Rotor (Incl. Tail Rotor)	Parametric, Eq. (7)
Fuselage	Parametric, Eq. (8)
Empennage Landing Gear Nacelle	Semi-Parametric, Eqns. (14) & (15)
Propulsion	
Engine	Parametric, Eq. (9), (10)
Propeller	Parametric, Eq. (11)
Auxiliary Power Fuel System Other Propulsion	Semi-Parametric, Eq. (16)
Drive System	Parametric, Eq. (12)
Systems	
Flight Controls Instruments Hydraulic System	Semi-Parametric, Eq. (17)
Electrical System	Semi-Parametric, Eq. (18)
Avionics	Parametric, Eq. (13)
Arm. Provision Furnishings & Equip. Load & Handling	Analogy, Eq. (20)
Air Conditioning Anti-Ice	Analogy, Eq. (19)
Integ. & Assembly	Semi-Parametric, Eq. (21)
Profit & Fee	Semi-Parametric, Eq. (22)

(4) $$\begin{aligned}\hat{c}_{semiparam} = (\hat{c}_{emp+nac+LG}) + \hat{c}_{elec} + \hat{c}_{env} \\ +(\hat{c}_{FC+Inst+Hyd}) + \\ (\hat{c}_{aux+fuelsys+propsys}) + (\hat{c}_{arm+furn+LH})\end{aligned}$$

The predictions generated by the two methods are compared for relative accuracy based on the residual ϵ_{FA} of the estimated unit flyaway price $\hat{c}_{FA}$ normalized to the actual unit flyaway price c_{FA}.

(5) $$\epsilon_{FA} = \frac{c_{FA} - \hat{c}_{FA}}{c_{FA}}$$

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The equivalent residuals at the component level are additionally evaluated for the high fidelity model.

3. RESULTS

3.1. Summary

The study surveyed the data population in Table 1 for relevant aircraft for which cost and technical data were available, ultimately selecting 11 aircraft from government procurement references (including 9 rotorcraft, 2 fixed wing, and 1 UAV) for which a complete WBS cost buildup was available. A second group of 10 civil rotorcraft were also selected to supplement the evaluation. In both cases, the two cost approaches were tested against the most reliable data corresponding to early production or recurring material development. The accuracy of the predictions can thus be viewed as representing the models' attempts to predict a T1, or first production unit cost. In the cases where EMD or SDD aircraft recurring costs are used, the regression analysis procedure modifies the cost estimating relationship with a development factor to control for any difference in cost trend. A study of learning curve effects across aircraft components is left to future work.

Tables 3 and 4 summarize the helicopters tested using the two methods. Figures 3, 4, 5, and 6 compare the component and system-level accuracy of the results. In terms of overall performance, the high fidelity model predicts the unit flyaway price to within $\pm 9.3\%$ of actual value on average for military aircraft and $\pm 36.0\%$ on average for civil helicopters. The modified Harris-Scully model's average absolute accuracy was 39.8% for military aircraft and 21.1% for civil.

Table 3: Government procurement test cases selected for evaluation

Aircraft	Prod. Lot	Prod. Year
UH-60A	Lot 3	1979
UH-60M	LRIP 1	2005
CH-47F	Lot 6	2008
AH-64E	Lot 3 (1st New Build)	2012
MV-22B	LRIP 1	2001
UH-1Y	Lot 8	2010
AH-1Z	Lot 8	2010
CH-53K	SDD (Recurring costs only)	2006
RAH-66	EMD (Recurring costs only)	2000
C-130J	FY07 MYP - 1st deliv.	2009
MQ-1C	LRIP 1	2010

Table 4: Civil rotorcraft test cases selected for evaluation

Aircraft	List Price Year
Hughes/Schweizer 269A	1961
Bell 206L-3	1992
Bell 407	2014
Agusta A109A	1990
MD Explorer	2013
Bell 427	2009
Aérospatiale (Airbus) AS365N-1	1990
Bell 412	1983
Sikorsky S-76B	1997
Sikorsky S-92A	2015

3.2. Model Evaluation

Considering that the component-level model was developed principally from military rotorcraft, while the database used in the Harris-Scully study was biased to civil helicopters, these results clearly provide a qualitative confirmation of the validity of both approaches, which each model performing best over the data set on which it is more closely based. In the context of the large offsets in trends between different types of aircraft shown in Fig. 1, as well as the large variation of flyaway prices even within the same type of aircraft, weight-based analogies would clearly require substantial adjustment on a case-by-case basis for each estimate to reproduce comparable accuracy to either of the parametric models.

One source of uncertainty related to a component-level assessment of civil and commercial helicopters relates to market effects. Since the Harris-Scully model contains an implicit model of commercial profits by virtue of its direct assessment of the total listed flyaway price, its improvement in accuracy for commercial helicopters may be partially attributable to the lack of visibility at the component-level into the profit and pricing strategies of commercial helicopter manufacturers. As Fig. 5(b) shows for military aircraft, the high fidelity model's ability to predict integration & assembly, systems engineering, and profit expenses displays similar accuracy to the performance of any of the detailed parameteric CER's in Appendix A. As Fig. 2 shows, the net change in accuracy of the high fidelity model increases the total

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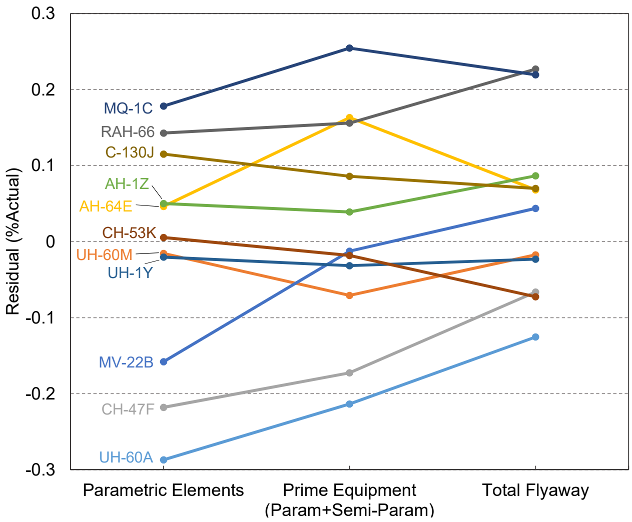

Figure 2: Progression in modeling accuracy of component-based cost model

residual of some examples and decreases that of others in the progression from the net residual of only the parametric items to the net of the total prime equipment (with the addition of the less-sophisticated semi-parametric items) to finally the net residual of the total unit flyaway cost (the addition of the error from the predicted integration and assembly, systems engineering, and profit). The even distribution of positive positive and negative changes in overall accuracy illustrates the variance in the non-parametric items as well as the components such as assembly and profit which are speculated to include influence from non-design factors. Future work could be devoted in the higher-fidelity approach to the development of a modification which acts as a commercial pricing factor.

In terms of design effects, the difference in flyaway accuracy between the two approaches is most pronounced for very light helicopters as shown in Figures 6(b) and 6(d). The difference in overall prediction accuracy for commercial aircraft flyaway is particularly driven by the smallest examples in the database, the Hughes/Schweizer 269A and the Bell 206L-3., suggesting that future modeling work could also be devoted to examining the unique cost effects of very light rotorcraft.

Conversely, some of the biggest improvements in accuracy seen in moving to the high fidelity approach are highlighted by the examples of highly advanced aircraft such as the V-22 tiltrotor, RAH-66 Comanche, and the unmanned MQ-1C. Each of these aircraft represent development and acquisition efforts for which procurement activities occurred after the original Harris-Scully study. In this sense, some of the immediate value of the new CER's developed for this study resides in their currency as compared to legacy cost models. In addition to the evolving trends in the prices of conventional aircraft components, many of the CER's in Appendix A showcase their greatest value in assessing design features which are paradigm-shifting, such as the provision for direct assessment of the cost of the base avionics loadout according to its size and function, or the configuration effects in wings and drive systems present in advanced rotorcraft configurations.

Fig. 2 illustrates another benefit of moving to a high-fidelity, component-based cost model which is arguably more mundane in nature, but no less relevant to the effectiveness of the model in estimating flyaway cost. Thanks to the even distribution of over and under-prediction in the component model results illustrated in Figures 3 through 5, shortcomings in the assessment of one component are occasionally canceled by errors of opposite sign in other components simply by virtue of spreading the uncertainty over several equations. This effect is observable in Fig. 2, with some helicopters showing substantial improvement in accuracy as more pieces of the total flyaway price are considered. The average absolute value of error slightly improves for the 11 aircraft shown, from 11.2% on average over the parametric items, to 11.1% over the prime equipment, to 9.3% over the flyaway cost.

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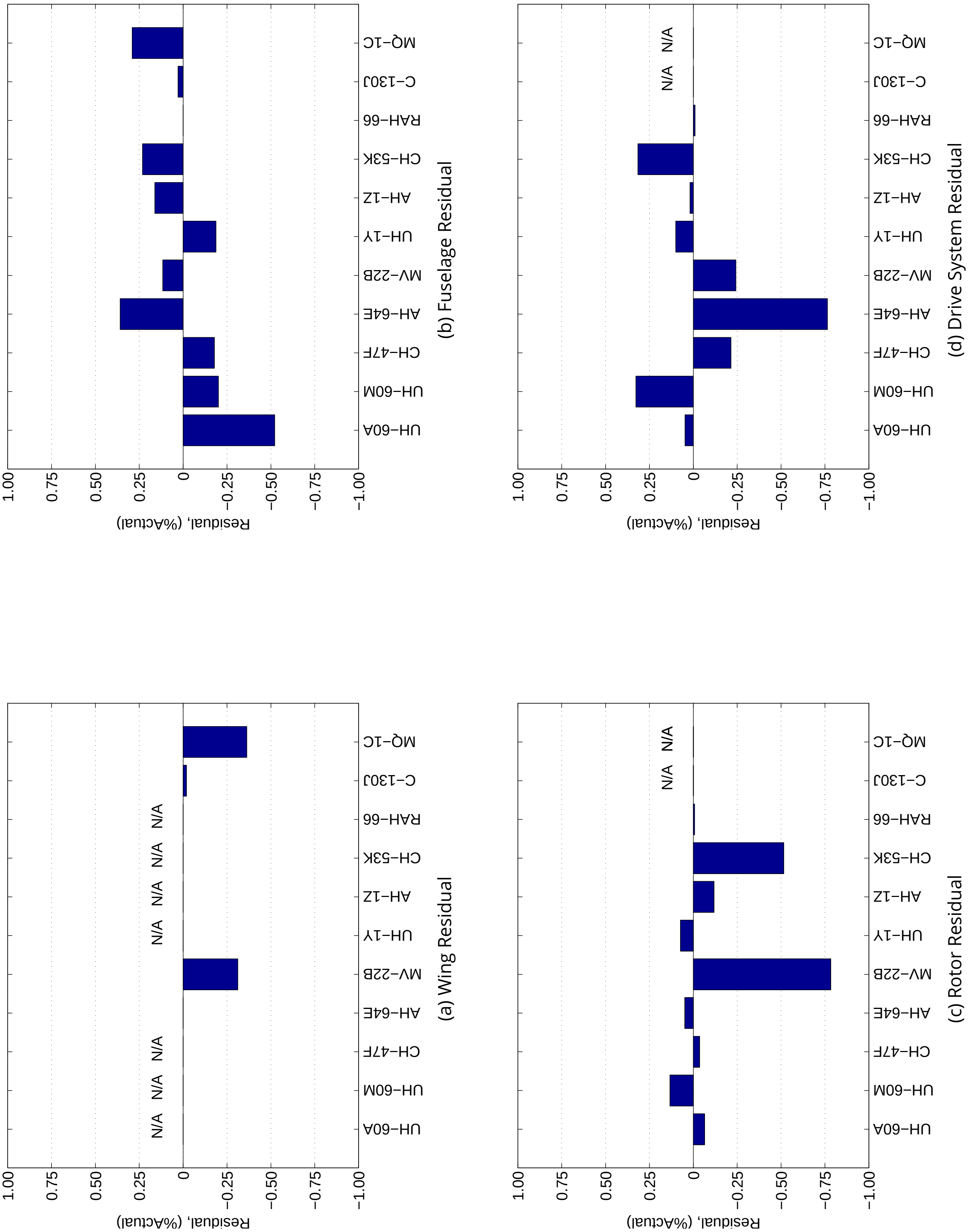

Figure 3: Prediction accuracy of wing, fuselage, rotor, and drive system cost models on military aircraft set

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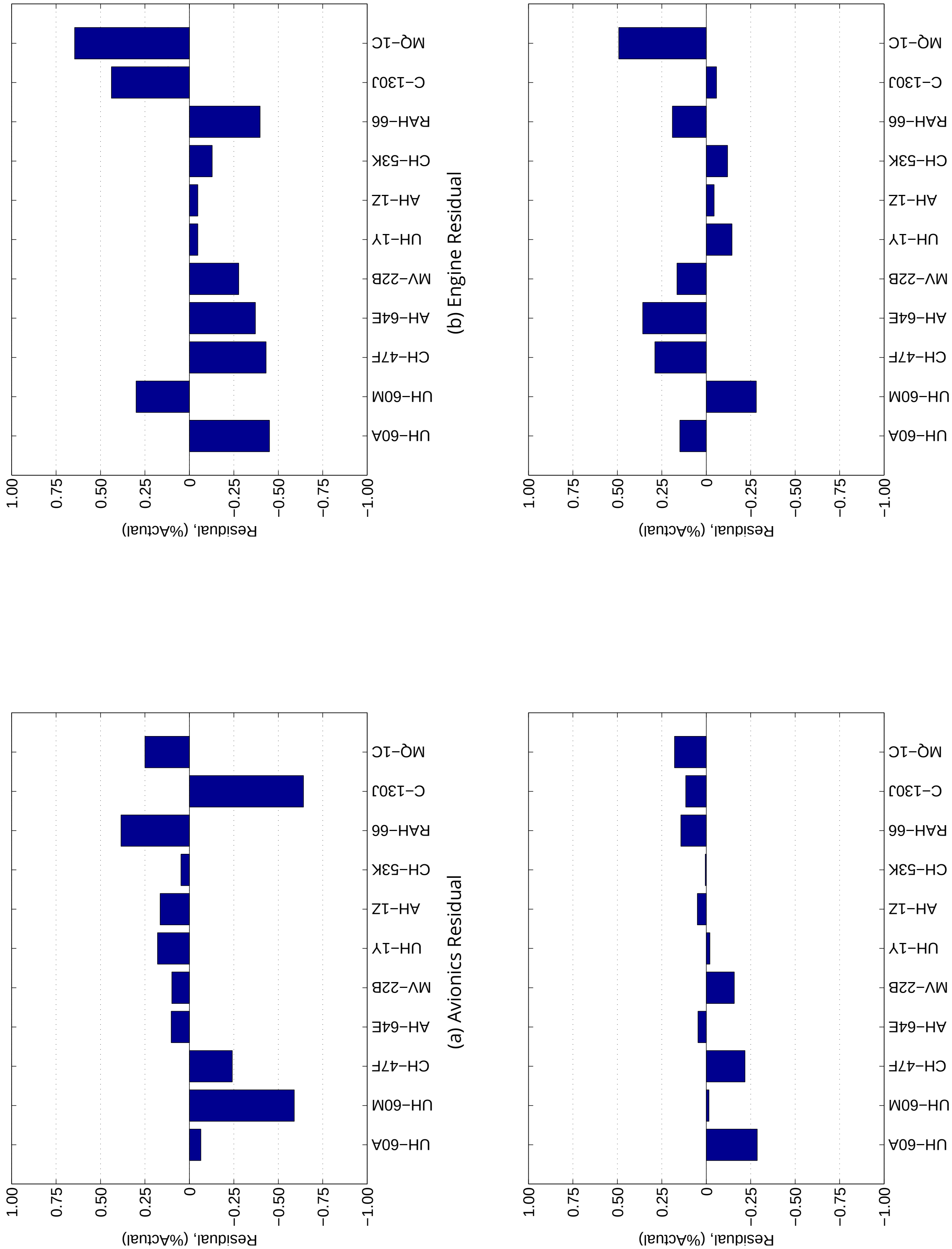

(a) Avionics Residual

(b) Engine Residual

(c) Overall residual of parametrically predicted items (Wing+Fuselage+Rotor+Drive+Avionics+Engine)

(d) Overall residual of semi-parametrically predicted items (Emp,Nac,LG+Prop.Sys+Flt.Cntrl,Inst,Hyd+Env)

Figure 4: Prediction accuracy of avionics and engine systems; and overall parametric and semiparametric accuracy

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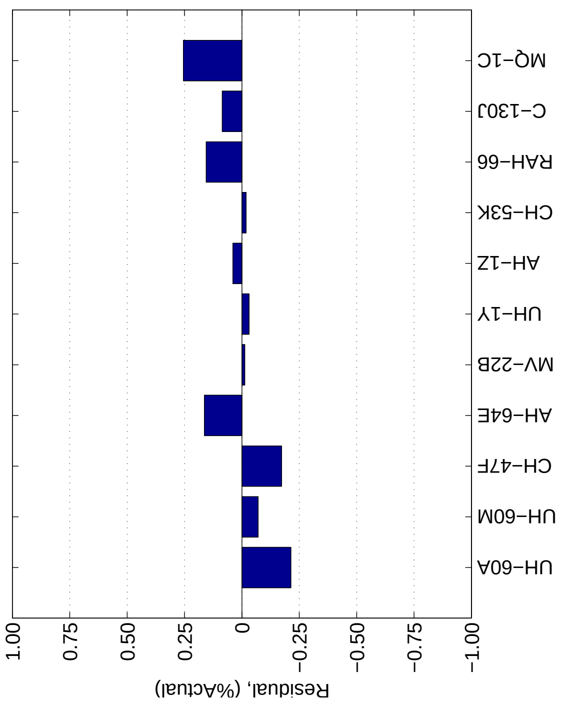
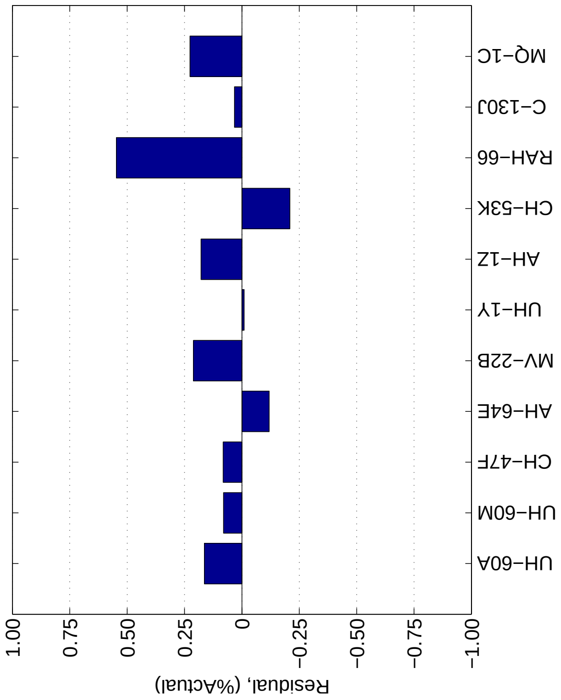


(a) Total Prime Equipment Production Residual
(Parametric + Semi-Parametric Aircraft Components)



(b) Total assembly and engineering overhead residual
(Integration&Assembly+Sys.Engineering)

Figure 5: Prediction accuracy of prime equipment production and overhead production and business items

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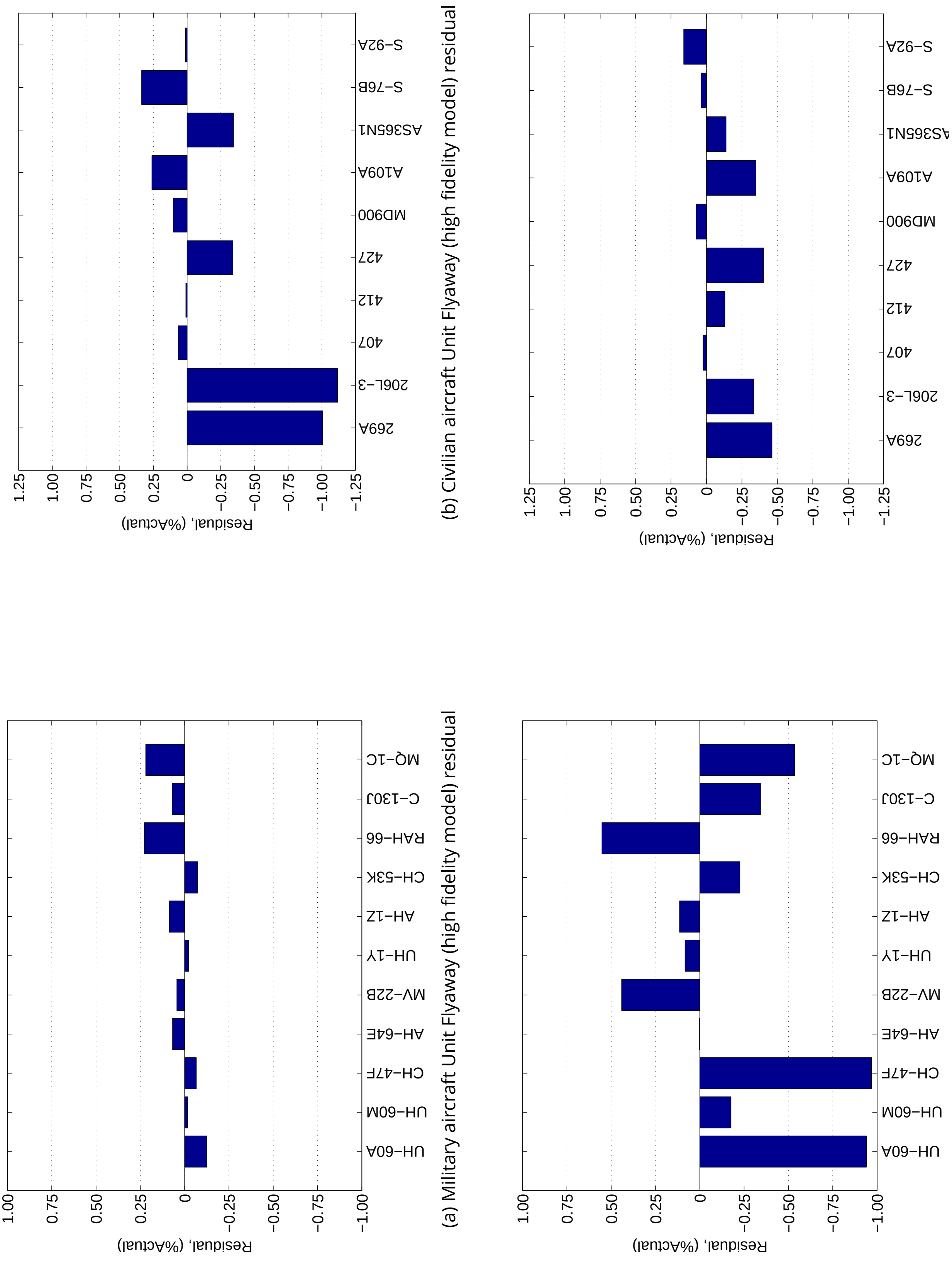

(a) Military aircraft Unit Flyaway (high fidelity model) residual

(b) Civilian aircraft Unit Flyaway (high fidelity model) residual

(c) Military aircraft Unit Flyaway (Harris-Scully model) residual

(d) Civilian aircraft Unit Flyaway (Harris-Scully model) residual

Figure 6: Comparison of multi-fidelity Unit Flyaway prediction accuracy on military and civilian aircraft sets

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4. CONCLUSIONS

Besides the motivation for improved overall flyway price prediction accuracy, a secondary benefit of predicting cost based on a buildup of aircraft components is the additional insight it provides into the specific cost-drivers of a particular vehicle. Accepting the level of accuracy described in the results over the aircraft populations used in this study, and recognizing the substantial variance in the predicted costs shown in Figures 7 and 8, the time-sensitive statistical features of the new model nevertheless allow for a historical assessment of cost trends from a unique design perspective. Extrapolating these trends to the future enables the user to make prognostications on the future aircraft procurement costs.

Fig. 7 plots the predicted percent of total flyaway contributed by each major group of components as organized by the WBS in Table 2. The prime equipment costs such as Integration, Assembly, Systems Engineering, and Profit are labeled "Institutional" costs to signify the nature of these items in the procurement process. Strikingly, the largest growth as a percentage of total flyaway is predicted to be the non-material costs of procurring the aircraft, which have grown in recent years as a percentage largely at the expense of propulsion systems, while the fractions of total price from structures and systems have remained nearly constant.

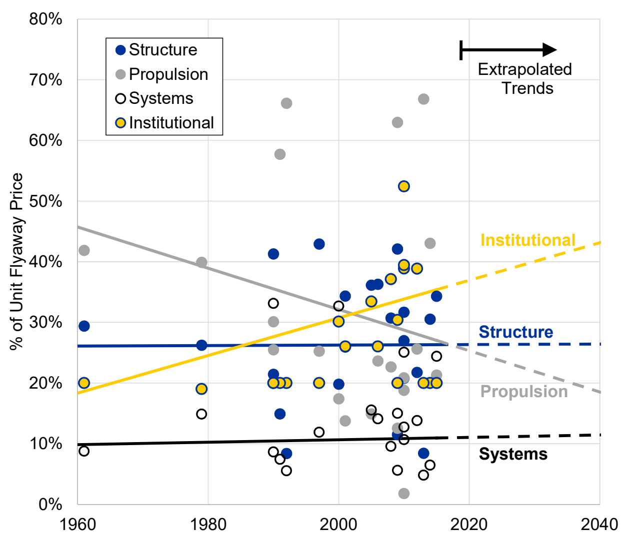

Figure 7: Predicted historical trends in component cost drivers in unit flyaway price

Although the trend shown in Fig. 7 indicates a smaller percentage of procurement cost attributable to propulsion, the overall cost of all systems, (including the engines) trends upward over time. Plotted in Fig. 8 in terms of dollars per pound, the declining percentage of propulsion cost in Fig. 7 becomes not a matter of a reduction in the actual dollar cost of propulsion, but rather an increase over time in the cost of all of the components, with the business costs of production growing at a much faster rate than the prime equipment costs. The institutional costs of production clearly represent a less visible, but increasingly critical source of program risk to contend with. As 8 shows, the overall trend in flyaway dollars per pound with institutional costs applied easily outpaces the growth of any of the individual material costs.

Looking ahead, the trends observed and modeled in the surveyed legacy aircraft procurement programs obviously suggest a net effect of rising procurement costs in the future. As plotted in 8, total flyaway price of early-production aircraft prior to consideration of learning curve effects has increased by \$33/pound of empty weight per year on average, and is projected to reach nearly \$3,500 per pound in total by the year 2040.

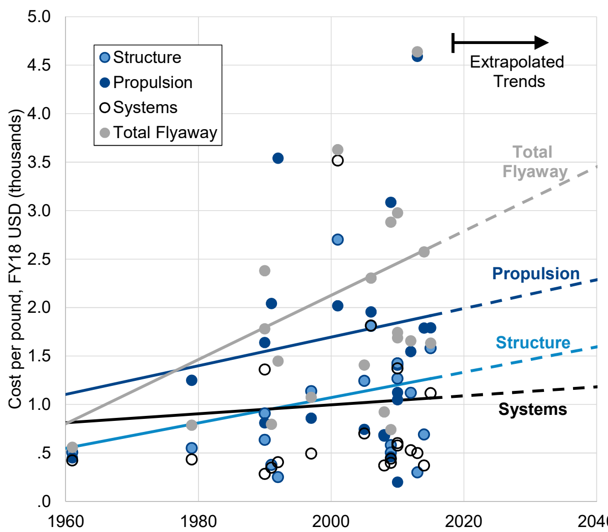

Figure 8: Predicted historical trends in component cost drivers in dollar per pound prices

As with any empirical model, conceptual analysis of procurement cost retains the inherent dilemma of attempting to predict future trends based on historical evidence which new technologies propose to defy based on confident assertions of future innovation and efficiency. Ultimately, the most useful aspect of a high fidelity procurement assessment capability in this sense likely resides in its ability to identify and quantify opportunities for affordability improvement. From this perspective, the work of conceptual design becomes the

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synthesis of feasible technologies which produce an aircraft satisfying the customer's requirements while also minimizing the technical characteristics identified in the cost equations. The pinnacle of this approach would be a future conceptual cost model which provides sufficient certainty to both the customer and the manufacturer such that the procurement price of a new clean-sheet design aircraft could be contractually finalized without any contingency reserve prior to the commencement of production. While this goal is likely unrealistic in its ambition, cost modeling and testing must nevertheless press on toward the goal of improving aircraft affordability.

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A. COST ESTIMATING RELATIONSHIPS

Each equation estimates the unit price of the component for the Nth production unit aircraft in thousands of FY18 US Dollars where N_p represents the number of units previously produced $(N-1=N_p)$ and N_q represents the number of units delivered in the production lot containing the Nth unit.

Wing:

(6)

$$\hat{c}_{wing} = 1.4401\, w_{wing}^{0.5176} \left(\frac{f_{wing} WMTO}{S}\right)^{0.9963} AR^{0.5478} \sigma_{wing}^{-0.2742} \left(Yr - 1986\right)^{-0.3050} N_q^{-0.0813} N_p^{-0.1125}$$

Where σ_{wing} is the wing weight per planform area in pounds per square foot

$$\sigma_{wing} = \frac{w_{wing}}{S}$$

Rotor:

(7) $$\hat{c}_{rotor} = 187.99\, w_{rotor}^{0.7127} N_{bl}^{1.5546} AR_{bl}^{-1.3931} f_{MRhub}^{2.4423} (Yr - 1968)^{0.0944} N_q^{-0.0130} N_p^{-0.1572}$$

Where f_{MRhub} is the hub's fraction of the main rotor weight. $f_{MRhub} = \dfrac{w_{MRhub}}{w_{MRhub} + w_{MRblades}}$

Fuselage:

(8) $$\hat{c}_{fuse} = 19.584\, w_{fuse}^{0.5232}\, f_{sec}^{-1.2330} \sigma_{fuse}^{-0.1131} \left(Yr - 1986\right)^{0.2788} N_q^{-0.0367} N_p^{-0.1054} \times H_{fuse}$$

Where

$$\sigma_{fuse} = \frac{w_{fuse}}{2\pi r_{fuse} L_{fuse}}$$

and f_{sec} is the fraction of secondary fuselage weight, $w_{fuse} = w_{prim} + w_{sec}$, $f_{sec} = \dfrac{w_{sec}}{w_{prim} + w_{sec}}$

$$H_{fuse} = \kappa_{boom} \kappa_{dev}$$

$$\kappa_{boom} = \begin{cases} 0.6290 & \text{Fuselage includes tailboom} \\ 1.0 & \text{No tailboom} \end{cases}$$

$$\kappa_{dev} = \begin{cases} 2.7470 & \text{Early LRIP of clean sheet design} \\ 1.0 & \text{otherwise} \end{cases}$$

Turboshaft Engine: (Unit cost of one turboshaft engine rated to SHP_{eng})

Eqn. (9) is adapted from a previous parametric engine cost study[11] and estimates the full unit procurement cost of turboshaft engines for VTOL applications.

(9) $$\hat{c}_{eng} = 5.6920\, SHP_{eng}^{0.8152} SP^{0.8304} Pr_{avg}^{0.7557} TBO_{eng}^{0.3657} (Yr - 1955)^{-0.2475} N_p^{-0.0759} \times H_{eng}$$

Where $H_{eng} = \kappa_{mar} \kappa_{FADEC}$

$$\kappa_{mar} = \begin{cases} 1.1644 & \text{Marinized engine} \\ 1.0 & \text{Non-marinized engine} \end{cases}$$

$$\kappa_{FADEC} = \begin{cases} 0.7298 & \text{FADEC equipped engine} \\ 1.0 & \text{Non-FADEC equipped} \end{cases}$$

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For non-rotorcraft / VTOL applications, Eqn. (10) for turboprops and high performance aviation recip-rocating engines and Eqn. (11) for propellers are adapted from the fixed wing propulsion section cost assessment methods in Roskam[10].

Turboprop Engine: (Unit cost of one turboprop engine rated to SHP_{eng})

(10) $\hat{c}_{eng} = 1.1786\, SHP_{eng}^{0.9465}$

Propeller: (Unit cost of one propeller rated to a transmission output of $SHP_{propeller}$)

(11) $\hat{c}_{propeller} = 0.0209\, SHP_{propeller}^{1.1432}$

Drive:

(12) $\hat{c}_{xmsn} = 1.2092\, w_{xmsn}^{0.4309} N_{gb}^{2.2692} r_{xmsn}^{0.2745} (Yr - 1968)^{-0.1566} N_q^{-0.0501} N_p^{-0.0281} \times H_{xmsn}$

Where r_{xmsn} is the overall reduction ration of the transmission system

$$r_{xmsn} = \Omega_{eng}/\Omega_{MR}$$

and $H_{xmsn} = \kappa_{rg}\kappa_{mar}$

$$\kappa_{rg} = \begin{cases} 0.3241 & \text{Engine group includes reduction gearbox} \\ 1.0 & \text{Transmission input direct from engine shaft} \end{cases}$$

$$\kappa_{mar} = \begin{cases} 2.0203 & \text{Marinized transmission system} \\ 1.0 & \text{Non-marinized transmission} \end{cases}$$

Avionics: (Unit cost of base avionics package which includes an automatic flight control system (afcs), communication & navigation systems, vehicle management and HUMS systems (if installed), but not specialized mission equipment such as survivability, imaging, or fire control.)

(13) $\hat{c}_{av} = 0.0269\, w_{av}^{1.6050} f_{afcs}^{0.4948} (Yr - 1970)^{0.1141} \times H_{av}$

Where w_{av} is the weight of the base avionics package and f_{afcs} is the afcs system's fraction of the total base avionics

$$w_{av} = w_{afcs} + w_{comm} + w_{nav} + w_{vms} + w_{HUMS}$$

$$f_{afcs} = \frac{w_{afcs}}{w_{afcs} + w_{comm} + w_{nav} + w_{vms} + w_{HUMS}}$$

and $H_{av} = \kappa_{dev}\kappa_{UAV}$

$$\kappa_{dev} = \begin{cases} 5.1690 & \text{Early LRIP of new avionics package} \\ 1.0 & \text{otherwise} \end{cases}$$

$$\kappa_{UAV} = \begin{cases} 3.3230 & \text{Unmanned medium to long endurance aircraft} \\ 1.0 & \text{otherwise} \end{cases}$$

Empennage, Nacelle, and Landing Gear: As the assumed smaller components of airframe structure weight and cost, landing gear, and nacelle costs are estimated together. Though not directly considered, adjustment would likely be warranted for non-conventional tails or nacelle/air induction configurations.
Fixed Landing Gear:

(14) $\hat{\rho}_{emp+nac+LG} = \dfrac{\hat{c}_{emp+nac+LG}}{w_{emp+nac+LG}} = 772\, w_{emp+nac+LG}^{-0.2116}$

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Retractable Landing Gear:

$$(15)\quad \hat{\rho}_{emp+nac+LG} = \frac{\hat{c}_{emp+nac+LG}}{w_{emp+nac+LG}} = 2,397\, w_{emp+nac+LG}^{-0.2252}$$

Auxiliary Power System, Fuel, and Propulsion Systems: The auxiliary power group is considered in a single element along with the fuel system, exhaust system, and propulsion controls & accessories are considered together using a dollar per pound relationship. ($/lb, FY18 USD, not in thousands).

$$(16)\quad \hat{\rho}_{aux+fuelsys+propsys} = \frac{\hat{c}_{aux+fuelsys+propsys}}{w_{aux+fuelsys+propsys}} = 3.4379\, w_{propsys}^{0.9630},\ \$/\text{lb}$$

Where $w_{propsys}$ refers to the weight of the engine exhaust, engine starting & control systems, and the propulsion accessories.

Flight Controls, Instruments, and Hydraulic Systems: In keeping with the MIL-STD-881C WBS, the automatic flight control system is considered part of the avionics group, not the flight control group. Flight controls weight in this group denotes the weight of the system controls and the cockpit controls $w_{FC} = w_{FC,Sys} + w_{FC,CC}$

$$(17)\quad \hat{c}_{FC+Inst+hyd} = 1.8557(w_{FC,Sys} + w_{FC,CC} + w_{inst} + w_{hyd})^{0.84757}$$

Electrical: The cost of the electrical group is predicted using a dollar per pound relationship which is in turn estimated from the cost of the avionics and environmental groups. The predicted dollars per pound of electrical weight $\hat{\rho}_{elec} = \frac{\hat{c}_{elec}}{w_{elec}}$ in FY18 USD (not in thousands in this case) is:

$$(18)\quad \hat{\rho}_{elec} = 0.01503\,(c_{av} + c_{env})^{0.6353},\ \$/\text{lb}$$

Environmental: The environmental group in 881C includes the anti-ice and air conditioning groups. The environmental group is estimated as 3% of the parametric prime equipment components.

$$(19)\quad \hat{c}_{env} = f_{env}(c_{wing} + c_{fuse} + c_{rotor} + c_{drive} + c_{eng} + c_{av})$$

Where $f_{env} \approx 0.03$ for conventional transport aircraft.

Armament, Furnishings, Load and Handling: The armament provisions, furnishings, and load and handling groups are estimated as a fraction of the fuselage cost.

$$(20)\quad \hat{c}_{arm+furn+LH} = f_{arm+furn+LH}\, c_{fuse},$$

Where $f_{arm+furn+LH} \approx 0.12$ for conventional transport aircraft.

Integration & Assembly, Systems Engineering, and Profit: Based on the observed history of US government aircraft procurement, the costs of integration & assembly, systems engineering, and prime manufacturers' profit are estimated as a function of the production cost of the prime equipment c_{pq}. Note that the engine group as assessed in 9 or 10 is included as a component of prime equipment, and already includes the cost of assembly and profit.

$$(21)\quad c_{int+SE} = 7.8271\, c_{pq}^{0.6897}$$

$$(22)\quad c_{profit} = 5.2003\, c_{pq}^{0.6749}$$

For commercial and civil aircraft, integration & assembly, systems engineering, and profit were collectively estimated as a percentage of prime equipment

$$(23)\quad c_{int+SE} + c_{profit} = f_{int+SE+profit}\, c_{pq}$$

Where $f_{int+SE+profit} \approx 0.25$

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B. MODIFIED HARRIS-SCULLY COST MODEL

(24) $\hat{c}_{FA} = 638.79\, f_{H-S} N_{bl}^{0.1463} \kappa_{eng} \kappa_{turb} \kappa_{LG} \kappa_{rotor}$

Where f_{H-S} is the Harris-Scully size factor, $f_{H-S} = WE^{0.4638} SHP_{inst}^{0.5945}$ and SHP is the installed horse-power of the aircraft, $SHP = N_{eng} SHP_{eng}$

$$f_{H-S} = WE^{0.4638} SHP^{0.5945}$$

$$\kappa_{eng} = \begin{cases} 1.0 & \text{Single engine} \\ 1.344 & \text{Multi-engine} \end{cases}$$

$$\kappa_{turb} = \begin{cases} 1.0 & \text{Piston} \\ 1.794 & \text{Turbine} \end{cases}$$

$$\kappa_{LG} = \begin{cases} 1.0 & \text{Fixed landing gear} \\ 1.115 & \text{Retractable} \end{cases}$$

$$\kappa_{rotor} = \begin{cases} 1.0 & \text{Single Main Rotor} \\ 1.031 & \text{Multiple Main Rotors} \end{cases}$$

Eqn. 25 modifies the Harris-Scully model for the prediction of flyaway costs of modern fixed wing aircraft. It retains the basic form and engine & landing gear complexity factors, but does not consider number of propeller blades. Additionally the cost trend is shifted by a constant factor developed from the survey of aircraft types shown in 1.

(25) $\hat{c}_{FA,FW} = 351.33\, f_{H-S} \kappa_{eng} \kappa_{turb} \kappa_{LG}$

Eqn. 26 modifies the Harris-Scully model for the prediction of flyaway costs of modern unmanned aerial vehicles.

(26) $\hat{c}_{FA,UAV} = 154,458\, f_{H-S}^{0.6138}$

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C. NOMENCLATURE

c	Actual cost
$\hat{c}$	Predicted cost
ϵ	Residual of predicted cost
ρ	Cost per weight, \$/lb
Yr	Fiscal year of procurement
N	The production unit corresponding to the estimated cost, $\hat{c}(N)$
N_p	The number of units previously produced, $N - 1 = N_p$
N_q	The number of units delivered in the production lot containing the Nth production unit

Wing

w_{wing}	Wing weight, lb.
AR	Wing aspect ratio
S	Wing planform area, sq. feet
f_{wing}	Design lift share fraction of wing in cruise ($f_{wing} = 1.0$ for fully wing-borne forward flight)

Rotor

w_{rotor}	Rotor weight, lb.
AR_{bl}	Rotor blade aspect ratio
N_{bl}	Number of blades per main rotor

Fuselage

$w_{fuselage}$	Fuselage weight, lb.
L_{fuse}	Fuselage length, ft.
r_{fuse}	Fuselage half-width at point of maximum fuselage diameter, ft.

Engine and Propeller

SHP_{eng}	Engine maximum rated power (MRP), hp
SHP_{prop}	Propeller shaft maximum rated power, hp
SP	Engine specific power, $SP = \frac{SHP_{eng}}{\dot{m}}$ where $\dot{m}$ is the design mass flow of the engine at the MRP rating, $\frac{\text{hp}}{\text{lb}_m\text{/sec}}$
Pr_{avg}	Stage-averaged engine compressor pressure ratio, $Pr_{avg} = OPR^{1/N_{st}}$, where OPR is the compressor's overall pressure ratio and N_{st} is the number of compressor stages
TBO_{eng}	Engine design-specified time between overhaul in flight hours

Drive

w_{xmsn}	Drive system weight, lb.
N_{gb}	Drive system number of gearboxes
Ω_{eng}	Engine output shaft design speed, RPM
Ω_{MR}	Main rotor shaft design speed, RPM

Avionics

w_{av}	Base avionics weight, lb.
f_{afcs}	Weight fraction of automatic flight control system in avionics weight

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