METHODOLOGY FOR COST ESTIMATION AND MANUFACTURING FRAMEWORK FOR THE MODIFICATION OF ABT-18 AIRCRAFT TO AN UNMANNED AERIAL VEHICLE

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Abstract

The ABT-18 Air Beetle has been the ab-initio trainer of the Nigerian Air Force (NAF) since 1993. As the aircraft reaches the end of its service life, the service seeks to modify the aircraft into an Unmanned Aerial Vehicle (UAV) as a life extension programme. This study examined the various costs involved in the modification and remanufacturing of the ABT-18 and its modification to an Unmanned Aerial Vehicle as well the various manufacturing methodologies involved. This study used various cost analysis models to predict the likely costs of various possible programme components of developing the UAV. It was determined that the avionics components particularly the sensor payload constitute 84% of the total cost of the modification and therefore cost reduction efforts should be aimed in this direction. A basic programme workflow and staffing template was designed which can be further developed as the project advances.

Keywords: *Cost Estimation, Cost Estimation Relationship (CER), Parametric model, Analogous model, Bottom-up Analysis.*

1. INTRODUCTION

The ABT-18 Air Beetle aircraft (Figure 1) is a two-seater, low wing primary trainer aircraft derived from the Van's RV-6. It was incorporated into the inventory of the Nigerian Air Force (NAF) in June 1994 to replace the Scottish Aviation Bulldog 123 aircraft which had suffered from high operating costs. It is powered by a single Lycoming O-360 four cylinder, four stroke, air cooled and horizontally-opposed aircraft engine producing 180 housepower.

However, throughout its service, the ABT-18 has suffered from significant maintainability, reliability and safety issues that have significantly reduced the fleet's service life. The most notable of these issues include buckling of the nose landing gear, high cylinder head temperature and poor fuel quality (Udu, 2014)

This has caused the NAF losses in terms of continued parts replacement, lost hours of pilot training and air crashes claiming the lives of experienced instructors and young students. Consequently, the NAF was forced to send its trainee pilots to other countries for initial training at huge expenses. Furthermore, the NAF had to acquire the Diamond DA40 aircraft for the training of its pilots. This has occurred before the normal expected service life of the ABT-18 was achieved (DAE, 2014)

Figure 1: ABT-18 Air Beetle [1]

As the NAF looks to phase out the ABT-18 as its ab-initio trainer, the Air Force Institute of Technology (AFIT), through the Department of Aircraft Engineering has decided to explore the possibility of converting the ABT-18 (Standard Version) into an Unmanned Aerial System (UAS) for surveillance and intelligence gathering purposes (DAE, 2014). If successful, the project will serve as a life extension program for the ABT-18 fleet, allowing it to provide useful service to the NAF for many more years while correcting some of the problems that have plagued the fleet during its service as a primary trainer.
This paper aims to study the possible cost implication of the project. It will also look to create a basic management template that will be used to run the project successfully.

The following will serve as primary design drivers:

a. Utilization of available facilities;
b. Robustness of design;
c. Low weight;
d. Safety;
e. Cost;
f. Reliability;
g. Maintainability;
h. Aviation standards and best practices; and
i. Lessons learned from previous and ongoing R&D projects in the NAF.

Some of the project specification include (DAE, 2014):

Max take-off weight:	841kg (Subject to change)
Empty weight:	596 kg (Subject to change)
Endurance:	12 h (minimum)
Service ceiling:	25,000 ft
Cruise speed:	51.4 m/s

The cost of an aircraft can be defined as the totality of the resources, quantified in monetary value, which goes into the manufacturing of an aircraft. The price of the aircraft is the amount paid by the customer for that aircraft. The profit (or loss) is the difference between the price paid and the cost of the aircraft (Roskam, 1990)

In analysing the cost of any aircraft programme, designers normally use accepted models to evaluate the possible estimates. Generally, there are 3 possible alternatives in determining costs. These include the parametric model, the analogous model and the bottom up approach. The parametric model uses Cost Estimation Relationships (CERs) in their calculations. Past experience is used to determine cost by creating mathematical equations to represent different cost elements based on the project specification. This approach allows the designers to define a cost target at the concept phase of the project. Additionally, this allows designers and sponsors to decide if the project is achievable giving the available resources or should be scaled back appropriately. However, this method does not take into consideration the local particulars of individual projects. It often also assumes that the research and development for the project will be done from scratch and will not include modifications to already proven technology or designs and ideas from previous projects (Anderson, 1999)

The analogous method makes comparisons with past projects to create an idea of the final cost of project. The use of this approach will create an idea of what the project sponsor will expect to pay for the project based on his experience and guide the designers accordingly. This will help in reducing the risk of optimism bias, especially when using proven systems or technology already deployed on existing platforms.

The Bottom-up approach seeks to use all the cost components of the aircraft as selected by the designers as well as other overhead costs to determine the likely cost of the platform. While this method will produce a more realistic cost figure, this can only be done after the preliminary design and system integration has been accomplished. This implies that the manufacturer has already made significant investments in Research and Development. The scrapping of the project at this point (or its rejection by potential customers) will result in losses borne by the manufacturer. This is usually mitigated by the sponsor awarding a contract for initial development or data generated by the programme transferred to other projects. It should however be noted that the freedom of manufacturers to set prices will be limited by the cost of already existing or proposed aircrafts with similar characteristics or performing those roles. Also, the length of most modern aircraft development process makes it likely that disruptive technologies, economic forces or changing customer needs will move against the project. This will force the manufacturer to rework their designs, driving up the costs of the programme to the point of economic unviability or technological obsolescence (Assler, 2006).

It is essential that consideration for manufacturing must be made during design. This involves integrating several engineering and management techniques into design and manufacture in order to ensure efficiency of inputs. Some of these techniques include (Kundu, 2010):

a. Design Built Team (DBT)
b. Design for Manufacture and Assembly (DFM/A)
c. Integrated Product and Process Development (IPPD) or Concurrent Engineering
d. Design for Six Sigma (DFSS)
e. Lean and Agile Manufacturing (LAM)
f. Product Life-Cycle Management (PLM)
g. Manufacturing Process Management (MPM)
h. Product, Process and Resource (PPR)
i. Design to Cost

2. ANALYSIS

In analysing the potential costs of the Unmanned Aerial System (including both the UAV and the Ground Control Station), the following approaches were adopted.

a. Dr Jan Roskam Life Cycle Cost Analysis
b. Modified Rand DAPCA IV Cost Model
c. Unmanned Aerial System Roadmap Capability and Performance Metrics
d. Bottom up calculation of selected components.

Jan Roskam Life Cycle Cost Analysis

Jan Roskam proposed a model to predict the cost of aircraft programmes using the relationship (Roskam, 1990):

$$LCC = C_{RTDE} + C_{ACQ} + C_{OPS} + C_{DISP} \quad (1)$$

Where LCC is the life cycle cost, C_{RTDE} is the Research, Development, Testing and Evaluation cost, C_{OPS} is the operating cost and C_{DISP} is the disposal cost.

However, since this research is limited in scope to just the cost of modification, then only the 'price' of the modified aircraft, will be examined. Thus

$$Programme\ Cost\ per\ plane = \frac{C_{RTDE} + C_{ACQ}}{N_{programme}} \quad (2)$$

Where $N_{programme}$ is the number of aircrafts to be built during the programme.

The C_{RTDE} is incurred to move the aircraft from a paper concept to full flight testing and certification as well as production. This cost is evaluated using

$$C_{RTDE} = C_{aed_r} + C_{dst_r} + C_{fta_r} + C_{fto_r} + C_{tsf_r} + C_{pro_r} + C_{fin_r} \quad (3)$$

C_{aed_r} is the Airframe Engineering and Design Cost, C_{dst_r} is the Development Support and Testing Cost, C_{fta_r} is the Flight Test Airplanes Cost, C_{fto_r} is the Flight Test Operations Cost, C_{tsf_r} is the Test and Simulation Facilities Cost, C_{pro_r} is the Research Testing Development and Evaluation Profit and C_{fin_r} is the Cost to finance the RTDE phase.

$$C_{aed_r} = MHR_{aed_r} \times R_{e_r} \quad (4)$$

MHR_{aed_r} is the Engineering man hours required to complete Aircraft Engineering and Design and R_{e_r} is the Engineering Dollar Rate per hour

$$MHR_{aed_r} = 0.0396 \left(W_{ampr}\right)^{0.791} (V_{max})^{1.526} (N_{rtde})^{0.183} \left(F_{diff}\right)(F_{cad}) \quad (5)$$

W_{ampr} is the Aeronautical manufacturers' Planning Weight, V_{max} is the maximum level speed at sea level, N_{rtde} is the number of airplanes produced for the RTDE, F_{diff} is a judgement factor accounting for the difficulty of the programme and F_{cad} is the judgement factor accounting for the effect of computer-aided design (CAD) capability.

$$W_{ampr} = invlog \left(0.1936 + 0.8645(\log W_{TO})\right) \quad (6)$$

W_{TO} is the aircraft take-off weight

$$\left(R_{e_r}\right)_{2015} = \left(R_{e_r}\right)_{1989} \left(\frac{CEF_{2015}}{CEF_{1989}}\right) \quad (7)$$

CEF is the Cost Escalation Factor

$$C_{dst_r} = 0.008325 \left(W_{ampr}\right)^{0.873}(V_{max})^{1.89}(N_{rtde})^{0.346}(CEF)\left(F_{diff}\right) \quad (8)$$

$$C_{fta_r} = C_{(e+a)_r} + C_{man_r} + C_{mat_r} + C_{tool_r} + C_{qc_r} \quad (9)$$

$C_{(e+a)_r}$ is the cost of engine and avionics, C_{man_r} is the manufacturing labour cost, C_{mat_r} is the manufacturing materials cost, C_{tool_r} is the tooling cost and C_{qc_r} is the quality control cost.

$$C_{(e+a)_r} = \left(C_{e_r}N_e + C_{p_r}N_p + C_{avionics_r}\right)(N_{rtde} - N_{st}) \quad (10)$$

C_{e_r} is the cost of each engine, N_e is the number of engines per aircraft, C_{p_r} is the cost per propeller, N_p is the number of propellers per aircraft, $C_{avionics_r}$ is the cost of avionics per aircraft and N_{st} is the number of static test airplanes.

$$C_{man_r} = MHR_{man_r}R_{m_r} \quad (11)$$

$MHR_{man_r}$is the number of manufacturing man hours required during RTDE and R_{m_r} is the manufacturing labour rate.

$$MHR_{man_r} = 28.984 \left(W_{ampr}\right)^{0.74}(V_{max})^{0.543}(N_{rtde})^{0.524}\left(F_{diff}\right) \quad (12)$$

$MHR_{man_r}$is the manufacturing man hours required for tooling

$$R_{m_r} = \left(R_{m_r}\right)_{1989}\left(\frac{CEF_{2015}}{CEF_{1989}}\right)$$

$$C_{tool_r} = MHR_{tool_r}R_{t_r} \quad (13)$$

$R_{t_r}$is the tooling labour rate.

$$MHR_{tool_r} = 4.0127\left(W_{ampr}\right)^{0.764}(V_{max})^{0.899}(N_{rtde})^{0.178}\left(N_{r_r}\right)^{0.66}\left(F_{diff}\right)$$

$$R_{t_r} = \left(R_{t_r}\right)_{1989}\left(\frac{CEF_{2015}}{CEF_{1989}}\right) \quad (14)$$

$$C_{fto_r} = 0.001244\left(W_{ampr}\right)^{1.160}(V_{max})^{1.371}(N_{rtde} - N_{st})^{1.281}(CEF)\left(F_{diff}\right)(F_{obs}) \quad (16)$$

$$C_{q_r} = 0.13\left(C_{man_r}\right) \quad (15)$$

F_{obs} is a judgement factor depending on the importance of 'stealth'

$$C_{fin_r} = \left(F_{fin_r}\right)(C_{RTDE}) \quad (17)$$

$F_{fin_r}$is the factor determined by interest rate

$$C_{pro_r} = \left(F_{pro_r}\right)(C_{RTDE}) \quad (18)$$

F_{pro_r} is the factor based on the profit to made at the Research, Development, Testing and Evaluation phase

The C_{ACQ} is the cost of manufacturing the airframes in the programme as well as the manufacturer's profit. This implies that

$$C_{ACQ} = C_{MAN} + C_{PRO} \quad (19)$$

C_{MAN} is the manufacturing cost while C_{PRO} is the manufacturer's profit.

$$C_{MAN} = C_{aed_m} + C_{apc_m} + C_{fto_m} + C_{fin_m} \quad (20)$$

C_{aed_m} is the Airframe Engineering and Design Cost, C_{apc_m} is the Airplane Production Cost, C_{fto_m} is the Production Flight Test Operations Cost and C_{fin_m} is the Cost of financing the manufacturing phase

$$C_{aed_m} = \left(MHR_{aed_{programme}}\right)\left(R_{e_m}\right) - C_{aed_r} \quad (21)$$

$MHR_{aed_{programme}}$ is the total amount of engineering man hours needed for the entire airplane programme (Raymer, 1992; Bowen, 1967)

$$MHR_{aed_{programme}} = 0.0396 \left(W_{ampr}\right)^{0.791}\left(V_{max}\right)^{1.526}\left(N_{programme}\right)^{0.183}\left(F_{diff}\right)\left(F_{cad}\right) \quad (22)$$

$$R_{e_m} = \left(R_{e_r}\right)_{1989}\left(\frac{CEF_{2015}}{CEF_{1989}}\right)$$

$$C_{apc_m} = C_{(e+a)_m} + C_{man_m} + C_{mat_m} + C_{int_m} + C_{tool_m} + C_{qc_m} \quad (23)$$

$$C_{man_m} = \left(MHR_{man_{programme}}\right)R_{m_m} - C_{man_r} \quad (24)$$

$$MHR_{man_{programme}} = 28.984 \left(W_{ampr}\right)^{0.74}\left(V_{max}\right)^{0.543}\left(N_{prog\ ramme}\right)^{0.524}\left(F_{diff}\right)$$

$$\left(R_{m_m}\right)_{2015} = \left(R_{m_r}\right)_{1989}\left(\frac{CEF_{2015}}{CEF_{1989}}\right) \quad (25)$$

$$C_{tool_m} = \left(MHR_{tool_{programme}}\right)R_{t_m} - C_{tool_r} \quad (26)$$

$$MHR_{tool_{programme}} = 4.0127\left(W_{ampr}\right)^{0.764}\left(V_{max}\right)^{0.899}\left(N_{programme}\right)^{0.178}\left(F_{diff}\right) \quad (27)$$

$$C_{fto_m} = N_m\left(C_{ops/hr}\right)\left(t_{pft}\right)\left(F_{ftoh}\right) \quad (28)$$

Where $C_{ops/hr.}$ is the airplane operating cost per hour, t_{pft} is the number of flight test hours flown by the manufacturer before delivery, and F_{ftoh} is the overhead factor associated with production flight test.

$$C_{ops/hr} = N_{cj}SAL_j\left(\frac{CEF_{then\ year}}{CEF_{1990}}\right) + FP.FC \quad (29)$$

N_{cj} is the number of crew, SAL_j is the crew salary, FP is the fuel price and FC is the engine fuel consumption per hour

$$C_{fin_m} = \left(F_{fin_m}\right)(C_{MAN}) \quad (30)$$

F_{fin} is the factor depending in the interest rate required to finance the cost of manufacturing

Modified Rand DAPCA IV Model

The Development and Procurement Costs of Aircraft (DAPCA) model was first set out in February 1967 by H. E. Boren Jr. of the Rand Corporation (Raymer, 1992; Bowen, 1967). It is a computer program for the USAF Project Rand to calculate the costs of major aircraft systems. The version used in this research combines the notes of (Serkan Özgen) and the modifications made to the model by (C. N. Eastlake and H. W. Blackwell) specifically for general aviation aircraft, the class to which the ABT-18 falls.

$$\begin{aligned}\textit{Programme Cost} &= RTD\&E + \textit{production cost} \\ &= H_eR_e + 0.125(H_tR_t) + 0.111\,(H_mR_m) \\ &+ 0.111\left(H_qR_q\right) + C_D + C_F + 0.3125(C_M) \\ &+ C_{eng}N_{eng} + C_{avionics} - F_{FLG} \\ &+ C_{PRO}\end{aligned} \quad (31)$$

H_e, Ht, Hm and Hq are the engineering, tooling, manufacturing and quality control hours respectively. C_F is the flight test costs, FTA is the number of flight test airplanes, C_{eng} is the engine production cost, N_{eng} is the total number of engines required, $C_{avionics}$ is the cost of avionics, C_{PRO} is the manufacturer's profit, F_{FLG} is the factor for fixed landing gear and R_e, R_t, R_m and R_q are the engineering, tooling, manufacturing and quality control wrap rates respectively. These cover employee salary, benefits, overhead and administrative costs.

$$H_e = 7.07{W_e}^{0.777}V^{0.777}Q^{0.163} \quad (32)$$

$W_e$is aircraft empty weight, V is the maximum velocity, and Q is the production quantity.

$$H_t = 8.71\left({W_e}^{0.777}\right)(V^{0.696})(Q^{0.263}) \quad (33)$$

$$H_m = 10,72\left({W_e}^{0.82}\right)(V^{0.484})(Q^{0.641}) \quad (34)$$

$$H_q = 0.133H_m \quad (35)$$

$$C_D = 66{W_e}^{0.63}V^{1.3} \quad (36)$$

$$C_F = 1807.1{W_e}^{0.325}V^{0.325}FTA^{1.21} \quad (37)$$

In 2015 value,

$$\textit{Programme Cost}_{2015} = \textit{Programme Cost}_{1999}\frac{CEF_{2015}}{CEF_{1999}} \quad (38)$$

$$\textit{Unit Value of Aircrafts} = \frac{\textit{Programme Cost}_{2015}}{N_{programme}}$$

Unmanned Aircraft Systems Roadmap

In 2005, the Office of the Secretary of Defence of the United States of America released a report (OOSD, 2005) in which an analogy cost relationship was established which was derived for the UAV performance metrics. This was done by comparing the capabilities and characteristics of historic United States UAV programmes. The results were logarithmic graphs that equated those examined abilities with their costs in 2002 dollars. These graphs were used to correlate potential capability of the ABT-18 UAV with its expected cost.

Bottom up Analysis

The bottom up analysis was done by collating all the components to be the added to the UAS. Then a market survey was done by contacting as many of the parts suppliers as possible. As internet searches were done checking various internet sources like aircraftspruce.com and qualityaircraftasccessories.com amongst others.

RESULTS

The following results were generated when the various models were applied to the project parameters. It was assumed that 15 aircrafts will be acquired at this stage of the programme.

Cost Estimation

A comparison of the results of the various cost estimation models is shown in the Figure 1 below. For security purposes, the actual costs cannot be revealed in this report.

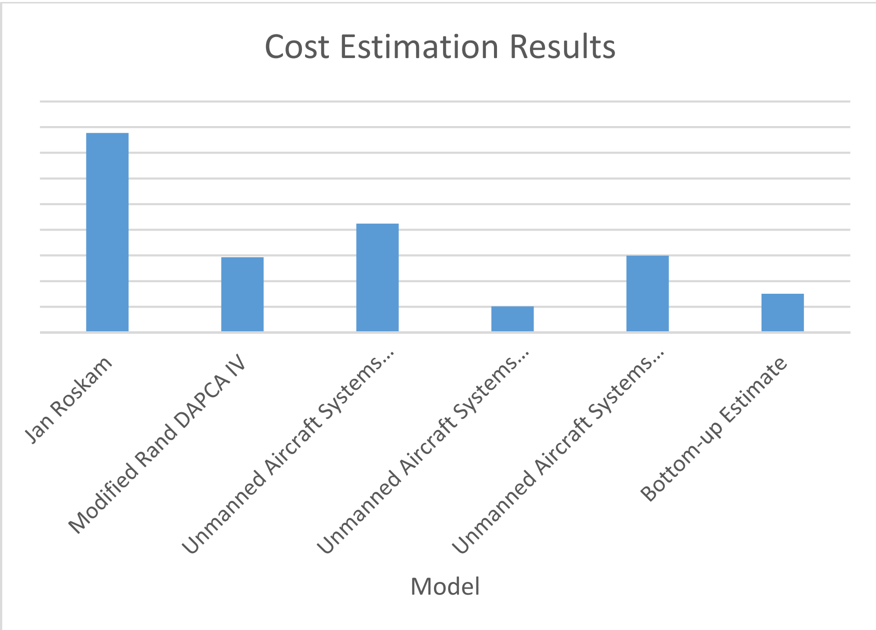

Figure 2: Comparison of Cost Estimation Results of Different Models

From Figure 2, it can be seen that Jan Roskam model produced the highest cost estimate almost twice the estimate of the next model (Unmanned Aerial System Report Empty Weight). The Unmanned Aircraft Systems Payload Weight Cost Relationship resulted in the lowest cost estimate. However, it must be noted that the Jan Roskam model is optimised for manned military aircrafts. The need for greater safety considerations, life support system, need for onboard human-machine interface as well as the distortions generated by adjustments for inflations may explain some of this gap.

Jan Roskam Model

The Research, Testing Development and Evaluation (RTDE) Cost are those costs associated with activities to take the aircraft from planning and conception to certification. These include design, construction, ground and flight testing of static and flight test aircrafts. The cost components are represented in Figure 3.

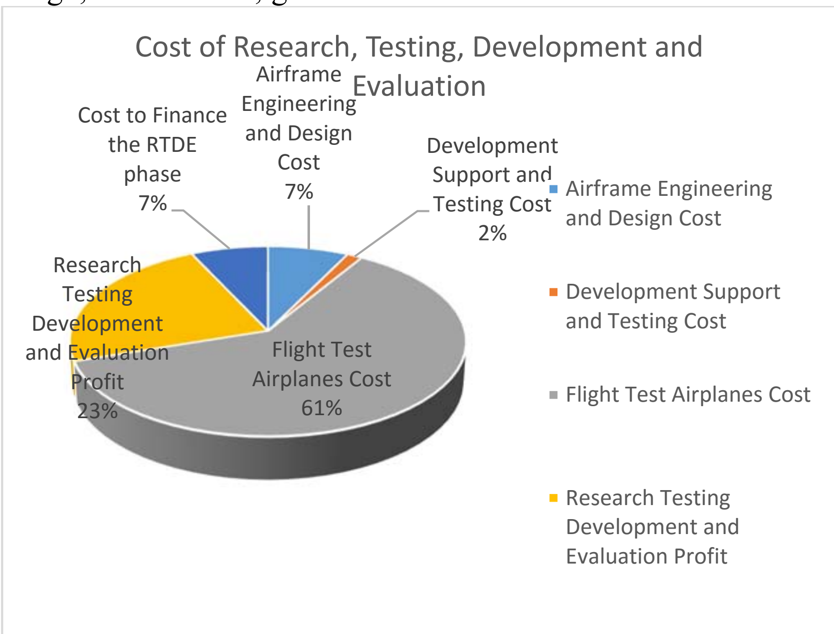

Figure 3: Jan Roskam's Cost of Research, Testing Development and Evaluation

The acquisition cost of the aircraft is the actual cost of building the specified number of production aircrafts to standard. The proportion of the acquisition cost components are shown in Figure 4.

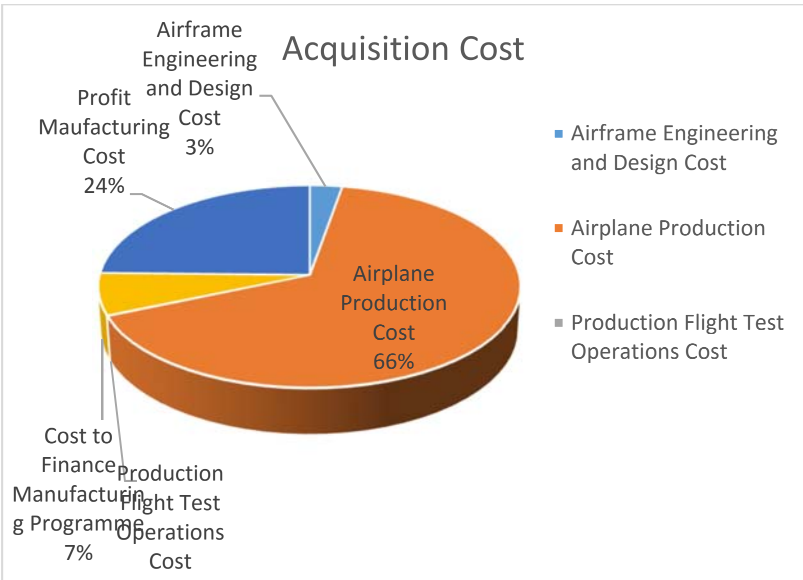

Figure 4: Jan Roskam Acquisition Cost

Modified DAPCA IV Model

The proportions of the cost components of the modified DAPCA IV Model are illustrated in Figure 5.

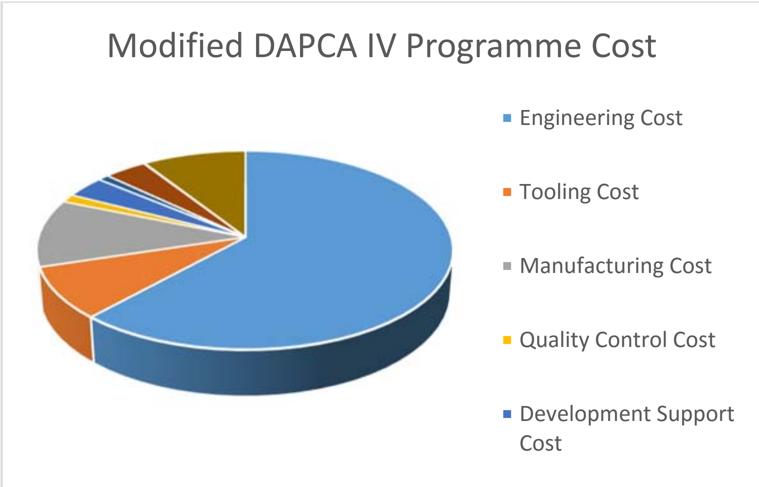

Figure 5: Modified DAPCA IV Programme Cost

Unmanned Aircraft Systems Roadmap.

Figures 6 and 7 illustrates the various relationships between aircraft specifications and their cost. The points marked with yellow stars are those points corresponding to the ABT-18 UAV as determined by other programme designers.

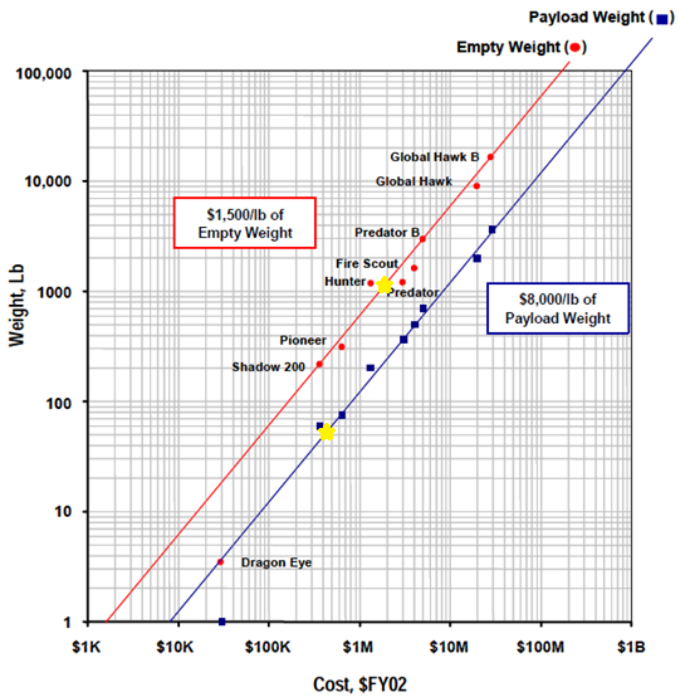

Figure 6: UA Capability Metric: Weight V. Cost (OOSD, 2005)

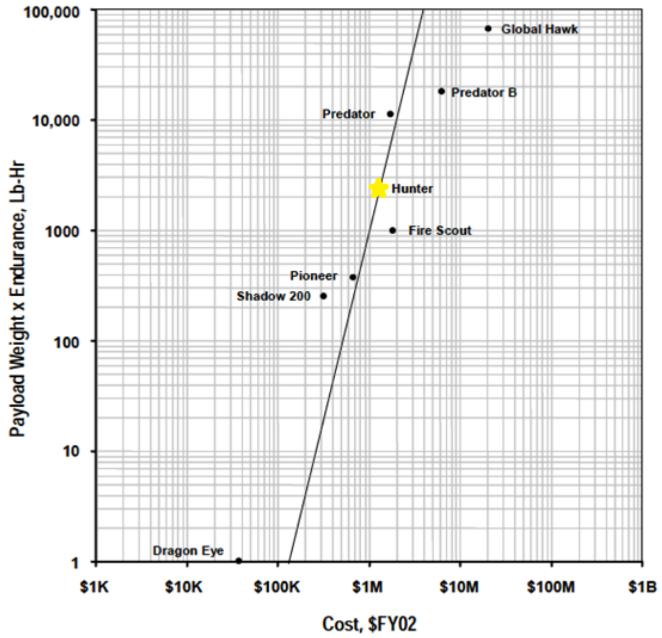

Figure 7: UA Performance Metric: Endurance V. Cost (OOSD, 2005)

From Figure 6, it can be inferred that the current payload weight of the proposed ABT-18 UAV is against historic empty weight trends. While this is offset by a higher than normal endurance which brings its overall performance (Figure 7) in line with comparative UV systems, more research is needed to better optimise its payload capability to allow for heavier and more capable payloads without unduly sacrificing its current endurance. However, the estimates from this report can be used as a guide to determine an acceptable cost of the project to the NAF.

This model uses a census of the selected components as well as the personnel cost of the project. These cost components are shown in Figures 8 and 9. It can be seen that 84% of the estimated project cost is in Avionics of which 95% of avionics cost is the camera selected. This implies that 80% of programme cost is incurred by the cost of the camera selected.

Bottom-up Estimate

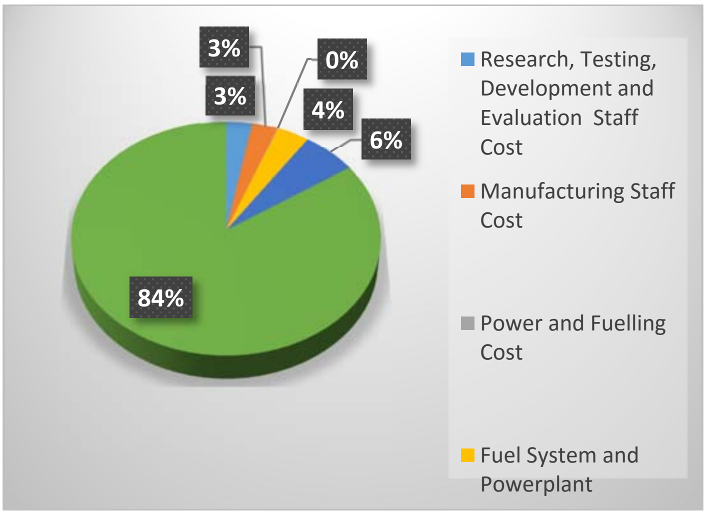

Figure 8: Cost Components of the Bottom-Up Method

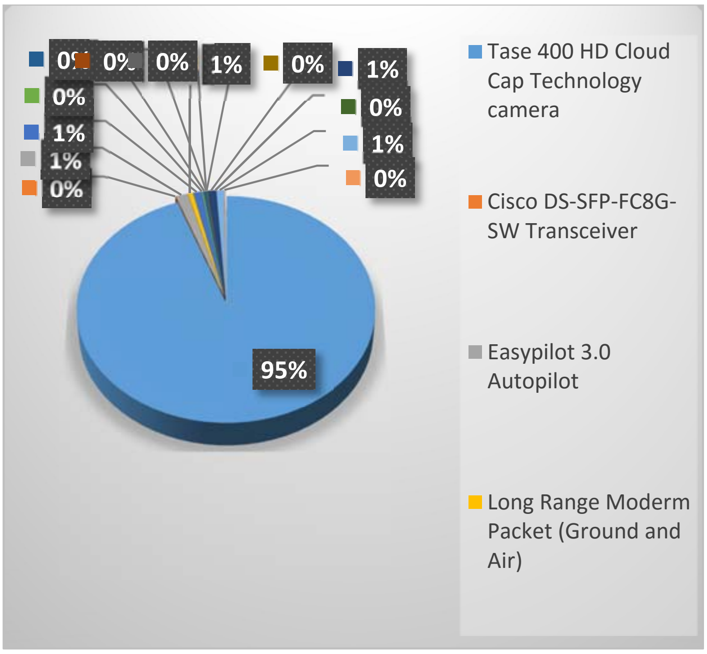

Figure 9: Avionics Cost Components

It must be stressed at this point that the components of the UAV were priced at their unit cost. It is anticipated that most suppliers will offer significant discounts for bulk orders and negotiated supply contracts. Some of the components may also be designed and produced locally, generating even more savings. Also, the cost of several services, e.g. surface finishing and painting were not included in the current estimate as they were outside the scope of the current project group. However, it is believed that the anticipated cost savings should cover the current unanticipated costs. Costs arising from currency fluctuations were not covered by this study.

Manufacturing Methodology.

For the purpose of this study, manufacturing of the aircraft was planned to occur using local Air Force Facilities and personnel. It is anticipated that the research and manufacturing phases will be co-located within the Nigerian Air Force Base, Kaduna which already has existing facilities and where similar activities are already ongoing. The presence of the military airfield within the complex will facilitate the transportation and delivery of project components directly on site.

The project is scheduled to run for 15 months. This will consist of:

a. Research, Testing Development and Evaluation phase: 8 months
b. Manufacturing phase: 7 months

However, it must be stressed that the schedule is not rigid as initial manufacturing procedures may commence as soon as the verification of their methods have been concluded.

Figures 10 and 11 illustrate the recommended organograms for the various phases.

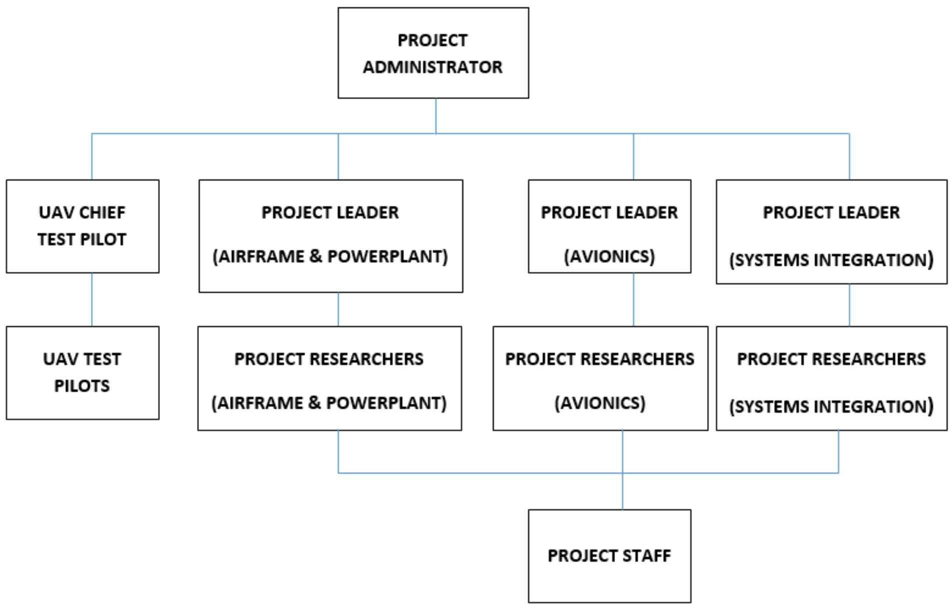

Figure 10: Organogram of RTDE Phase

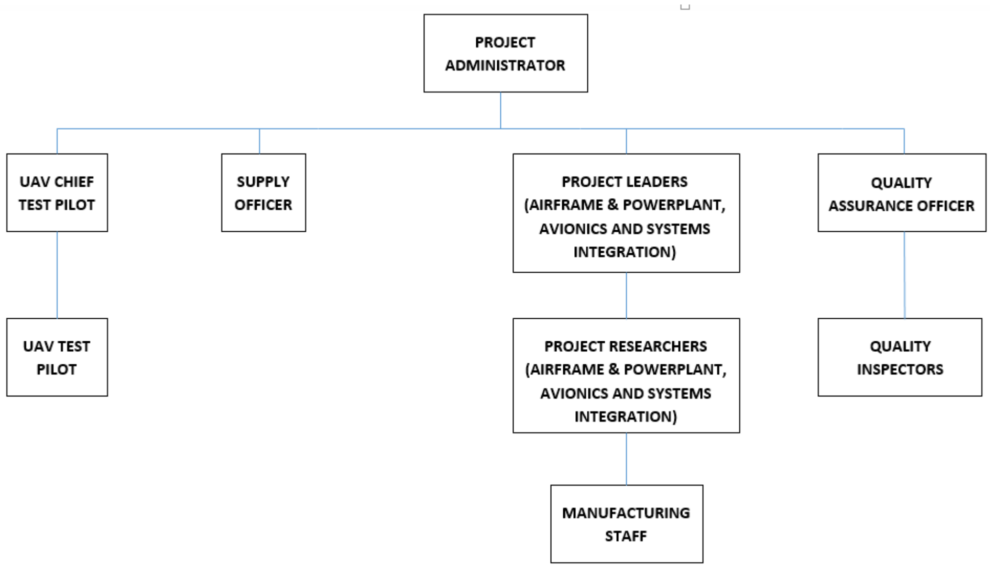

Figure 11: Organogram of Manufacturing Phase

The workflow of the manufacturing phase is also indicated in Figure 12. The workflow takes into consideration that most inputs will be supplied by external contractors. However, with project maturity, some of the foreign components may be replaced by local substitutes produced using in house facilities, other Air Force and military organisations or local contractors. However, only the final assembly and flight testing will be undertaken at the facility initially.

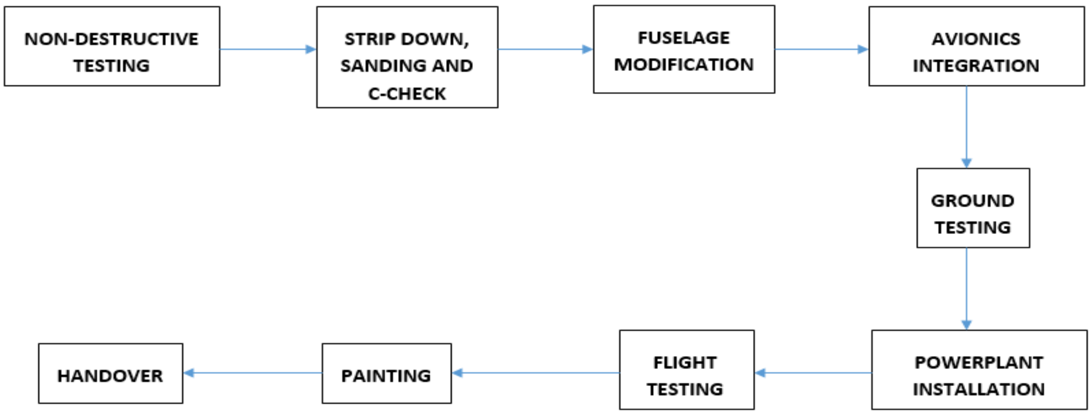

Figure 12: Workflow for the Modification of the ABT-18 to UAV

CONCLUSION

In this paper, the various approaches to calculating cost have been explored and applied to determining the potential costs of the programme. It has been defined that a suitable price range to serve as a baseline acquisition cost of the UAV during an initial production run of just 15 aircrafts as currently designed. This will allow the Nigerian Air Force develop the needed operational protocols for deploying the ABT-18 UAV. It will also expose any weaknesses not identified during Research and Development to be addressed during the next iteration of the project or in future UAV development. The cost of the avionics payload (the camera in particular) mounted on-board the UAV will significantly determine the final acquisition cost. Therefore the sponsor may wish to look into using a cheaper but still capable camera or may sacrifice some payload performance to bring the cost down while adjusting suitable operating procedures.

The manufacturing method adopted for the UAV takes into consideration all the prevailing attributes of the proposed development organisation as well as optimising already existing facilities. It also gives them the opportunity to generate and enhance institutional knowledge and skill. This will serve them well in future developments of the UAS concept in Nigeria.

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