A methodology for the assessment of unit cost drivers for commercial aircraft

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ABSTRACT

Presented in this paper are the prerequisite steps in a methodology for the identification and assessment of unit cost drivers for use in the development of a new design-oriented unit cost estimation methodology for large commercial jet aircraft with minimum seating capacity of 100 passengers. The work presented here focuses on unit cost, which is a significant element of the total aircraft cost and for the initial aircraft design process in particular. The methodology aims to investigate how aircraft design properties could influence cost. Cost estimation relationships, containing a wide range of the most highly correlated parameters, are retrieved from detailed regression analysis conducted on two different aircraft generation categories. Since the methodology is based on actual cost and technical data, it is accurate both in terms of predicting the aircraft unit cost or conducting cost-comparative studies between different aircraft concepts. The emphasis in this paper is mainly on the development approach and parameter assessments, adopted towards the final unit cost estimation methodology.

NOMENCLATURE

AR	wing aspect ratio
bpr	engine bypass ratio
bwing	wing span, in m
C_T-Tail	conventional or T-Tail, option switch
d	mean fuselage width at the horizontal stabiliser location, in m
Engine_FUS	fuselage-mounted engine, option switch
Engine_VS	vertical stabiliser integrated engine, option switch
Fuel_Not	horizontal stabiliser fuel tank, option switch
Loverall	overall fuselage length, in m
M_bHS	span of horizontal stabiliser, measured from blueprints, in m
M_bVS	span of vertical stabiliser, measured from blueprints, in m
Mcruise	cruise Mach number
M_SHS	total area of horizontal stabiliser, measured from blueprints, in m^2
M_Srudder	total rudder area, measured from blueprints, in m^2

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M_SVS	total area of vertical stabiliser, measured from blueprints, in m^2
Ncontrsurf	total number of wing control surfaces
Nengines	number of engines
NHScontrsurf	number of horizontal stabiliser control surfaces
Npass_1	number of passengers in a single class configuration
Npass_2	number of passengers in a two-class configuration
Npylons	number of engine pylons on the wing
Nundercarr	total number of undercarriage legs
NVScontrsurf	number of vertical stabiliser control surfaces
Nwheels	total number of wheels
Nwpanels	number of wing panels (segments)
R^2 *(or R^2)*	regression coefficient, (percentage)
S	standard error deviation in regression analysis
Sw	total wing area, in m^2
Sweepback	wing sweepback at quarter chord, in degrees
T	total Engine thrust, in lb
WfusEXT	max external fuselage width, in m
WfusINT	max internal fuselage width, in m
Winglets	winglet, option switch

Categories

ENG	engines
FUS	fuselage
HS	horizontal stabiliser
UND	undercarriage
VS	vertical stabiliser
W	wing

1.0 INTRODUCTION

System cost calculation is practically the result of a combination of parametric, engineering buildup and analogy techniques applied during different programme phases[1]. The engineering buildup technique provides information regarding what costs how much and therefore is a more detailed approach, applicable to later phases of the programme progression. Applying this technique requires thorough design details for all aircraft components and cost accounting data for all manufacturing and production stages. Its accuracy relies on the knowledge, time and money devoted to create the technical and cost database. Estimation by analogy is a similar approach to the engineering buildup, mainly applicable in an evolutionary rather than a revolutionary system development. The analyst applies an engineering buildup technique already conducted for a system to the new system under study, after adjusting some of its properties to reflect their differences. The analogous approach saves time, since there is no need to create the detailed breakdown structure for the new system, but, as a drawback, its validity is frequently compromised because of the subjective nature of the adjustment the analyst has to make in order to differentiate the original from the new system. The parametric approach is based on statistical techniques that correlate cost as the dependent variable with several other potential cost-driving factors, included as independent variables. Unlike the previous two approaches, there is no need for detailed information for the system under study, but selective technical expertise and judgement is required to form the objectives of the analysis or to filter the results. The correlation between cost and the independent variables is usually established through regression analysis, or, stated differently, by the development of cost estimation relationships (CER).

Most of the existing aircraft cost estimation methodologies are either detailed cost accounting methods[2], or parametric techniques optimised for minimum cost (especially direct operating cost)[3-8]. The nature of the detailed cost accounting approach prevents its application in the initial design phase, during which aircraft designers have to make some critical decisions before continuing to the detailed design process. Existing parametric approaches are focusing on the extensive use of weight-based CER, neglecting some other critical design parameters and their effect on cost[9].

The use of weight as a predictor provides an accurate initial estimate of cost, in relation to aircraft size, as long as the aircraft is relatively conventional in terms of materials and other technologies. But an increment in weight is interpreted as an increment in cost, which is not always true in the contemporary aviation industry; the weight of composite or smart materials which are nowadays extensively used in aircraft structures can not simply be proportional to cost. On the contrary, reductions in aircraft weight in such cases could entail a substantial rise in costs.

1.1 The new unit cost estimation approach

A new methodology that is aircraft design oriented but without focusing on weight in order to calculate cost while remaining independent of economic terms, is highly desirable. This new approach, presented in this paper, aims to study the economics of commercial aircraft production and to analyse the correlation between aircraft design and cost. Its primary objective is the identification and assessment of the actual unit cost drivers of an aircraft, and hence investigate how aircraft design properties affect cost.

Due to the lack of aircraft manufacturing cost data within the public domain, the data on which this new methodology is based, represent aircraft recommended prices obtained from reliable sources. The relationship between cost and price can be affected by several economic, pre-launch and corporate factors, as well as customer relationships. The resulting unit cost estimates should therefore accurately reflect the aircraft unit cost for the buyer rather than the manufacturer. This is indeed the primary aim of this new methodology which is intended to provide aircraft designers with the capability to predict reasonably accurately the selling price of a future aircraft, right from the early stages of the design process. Pricing information often needs to be made available to potential customers well before the launch of a new aircraft project. The derivation of the methodology is also based on design parameters which influence the manufacturing cost, either directly or indirectly. Hence, assuming that for the same aircraft manufacturer, the relationship between unit manufacturing cost and unit price remains roughly constant for the same time period, then the resulting price predictions, could also enable aircraft designers to carry out reasonable quantitative comparisons of the projected manufacturing unit cost amongst candidate design proposals, competing for the same requirements. However, within the context of this new methodology and the work presented in this paper, the term unit cost is used with reference to the buyer.

The results of the above approach have led to a new accurate unit cost estimation methodology, which is based on actual cost and technical data. This was designed from the outset to be easily applicable during the initial phase of the aircraft design process, as well as in later stages of the development of a new aircraft. Furthermore, it is flexible in terms of choosing which and how many of the design properties to include, depending on technical reference, availability of information and cost analysis requirements. The most important benefit from this method is its capability to provide realistic cost estimates as well as accurate comparisons between different design concepts.

The inherent nature of the parametric estimation technique is closely associated with the scope of this new approach to identify the aircraft design properties affecting cost. A CER retrieved from a parametric analysis is the ultimate tool to answer several 'what if' questions concerning not only the economic aspects accomplished, but also a wide range of pending design procedures. A designer or manufacturer can use the CERs to make decisions for cost reduction in either a simple or complex manner, depending on the complexity of the selected CER and the pertinent programme needs.

Table 1
Selection criteria for multivariate dependence methods

METHOD		VARIABLE			
		DEPENDENT		INDEPENDENT	
NAME	EQUATION TYPE	TYPE	NUMBER	TYPE	NUMBER
Canonical Correlation	Y1+...+Yn = X1+...+Xn	Metric, Nonmetric	1...n	Metric, Nonmetric	1...n
Multivariate Analysis of Variant	Y1+...+Yn = X1+...+Xn	Metric	1...n	Nonmetric	1...n
Analysis of Variant	Y1 = X1+X2+...+Xn	Metric	1	Nonmetric	1...n
Multiple Discriminant Analysis	Y1 = X1+X2+...+Xn	Nonmetric	1	Metric	1...n
Multiple Regression Analysis	Y1 = X1+X2+...+Xn	Metric	1	Metric, Nonmetric	1...n
Conjoint Analysis	Y1 = X1+X2+...+Xn	Nonmetric, Metric	1	Nonmetric	1...n
Structural Equation Modelling	Y1 = X11+X12+...+X1n Y2 = X21+X22+...+X2n Ym = Xm1+Xm2+...+Xmn	Metric	(1...m)*1	Metric, Nonmetric	(1...m)(1...n)

1.2 Data analysis approach

The way the problem is formulated with cost as the only dependent variable to be examined versus multiple metric and non-metric independent variables (design properties), regression analysis appears as the most appropriate method to use, from those illustrated in Table 1[10].

What is cited as a major disadvantage of the regression analysis is the fact that, it cannot be used to confirm causality but rather to measure the associative influences of the independent variables on the dependent variable. If, for instance, regression provides a CER that highly correlates aircraft cost with the maximum Mach number, it can only be stated that, higher costs are related with higher (or lower) Mach numbers. There is no obvious reason to claim that, the origin or the actual cause for this cost is the Mach number itself. A different wing configuration, for example, could lead to changes in aircraft production and operating cost due to the use of a different type of material or the different manufacturing techniques applied, and at the same time wing planform changes could result in a different cruise Mach number. In this case, although cost could be highly correlated to Mach number, the material change is one of the actual reasons for the variation of the cost.

This causality disadvantage, as described above, applies only on how the results are interpreted by the analysts. The way the variables under investigation were chosen and the approach based on aircraft design standards ensure that there is a clear technical association amongst cost and the independent variables.

Finally, an acceptable limitation of the regression analysis is its fundamental weakness to reliably predict values for the dependent variable beyond the analysed range of the independent parameters. In practise, a plus or minus 20% extrapolation is generally acceptable and that is considered adequate for this particular case.

1.3 Theoretical framework

The Unit Cost analysis is literally a combined study of two different fields which are both following similar steps in their approach: these are the engineering and the economic parts (Fig. 1). It is the role of the parametric estimation to connect these parts by providing the statistical framework and the regression approach from which the cost estimation relationships for modelling aircraft cost will be extracted. These models are in turn implemented into a software routine (unit cost program) flexible enough to conduct cost analyses and comparisons amongst different aircraft types.

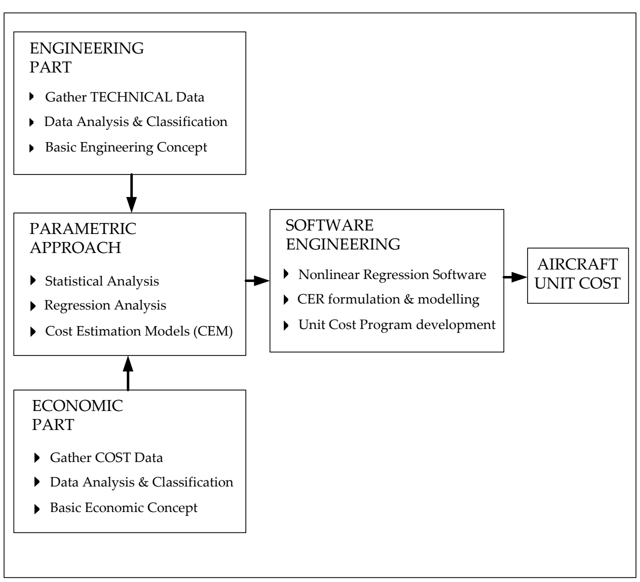

Figure 1. The main concepts for the development of the unit cost methodology.

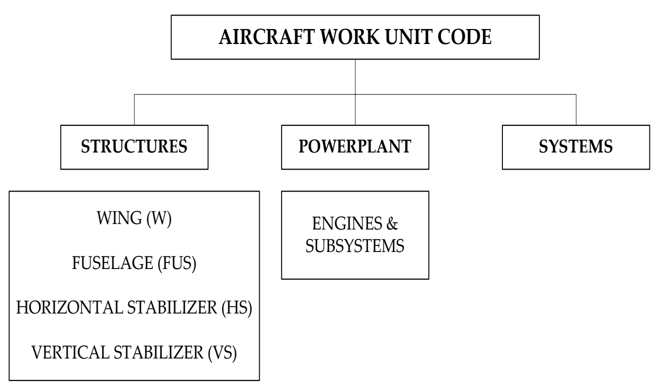

Figure 2. Modified work unit code used in unit cost methodology.

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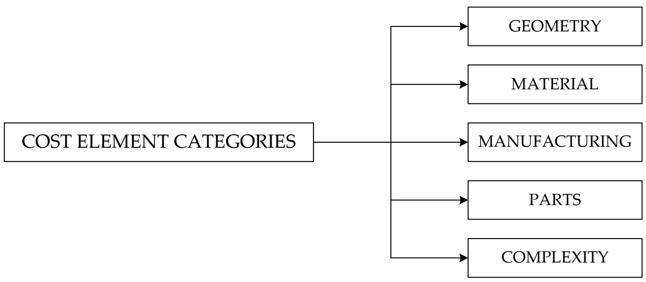

Figure 3. Basic cost element categories.

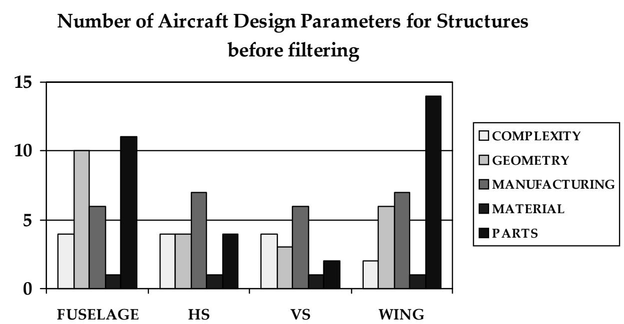

Figure 4. Summarised structures design parameters before filtering.

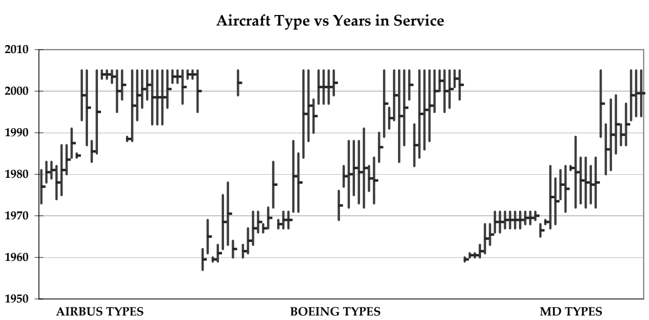

Figure 5. Life cycle of all commercial aircraft by Airbus, Boeing and McDonnell Douglas.

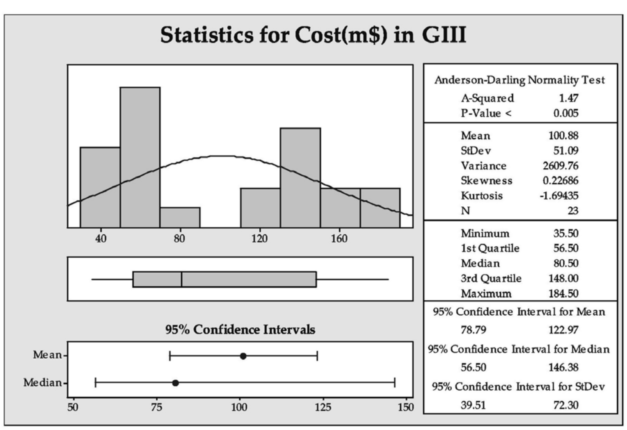

Figure 6. GIII cost data descriptive statistics.

1.4 Engineering part

The first stage of the engineering part of the project includes the development of a top-down methodology aiming to identify the actual aircraft cost drivers, thus revealing the contribution of any design changes on aircraft unit cost.

Following a standard work unit code (WUC), but appropriately simplified for the needs of this analysis, the aircraft is broken down into its major parts and systems (Fig. 2). This simplified WUC was adopted, since a fully-detailed breakdown could easily prove prohibitive in terms of data gathering and contrary to the initially set objectives.

The Powerplant category will basically provide the parameters describing the aircraft engines. The engine subsystems are essentially standardised for large commercial aircraft and hence it is difficult to establish any parameter that reveals a design distinction between them. Similarly, establishing parameters that could correlate cost with aircraft systems and finding data for them is even more complicated and literally unmanageable. Besides, all aircraft of the same generation are normally equipped with standard systems, because of safety regulations, operational requirements and the need to use competing state of the art technology. Furthermore, aircraft values used for the analysis should reflect a standard version of each aircraft type and should not include any additional or specialised demands in terms of systems, which obviously increase the aircraft price.

What is defined as aircraft unit cost is largely made up from contributions from the research, design, test, evaluation, manufacturing and acquisition phases of the life cycle of the aeroplane. A detailed task assessment to estimate costs during these phases is against the philosophy of the proposed methodology. Hence, to comprise both aspects, five representative cost element categories are established to classify all parameters for the aircraft structures under investigation (Fig. 3).

These categories are primarily controlled by the design and not by financial fluctuations. In other words, the selection was based strictly on engineering criteria. It has been therefore attempted to include as many parameters as possible to adequately represent the aircraft and to enhance design sensitivity. The setup of the cost element categories aims to facilitate the data collection process. Therefore, some design properties may be used to describe more than one category. The strategy adopted at this point is to select for each aircraft part the most representative aircraft design properties under each cost element category. The selected parameters should be reconciled with the aircraft design standards and in fact the most technically relevant for each cost element category. Furthermore, it is important to select an adequate number of parameters in terms of describing and distinguishing different aircraft. Bearing in mind the rules of the forthcoming regression analysis, any correlations between the parameters themselves should be detected from the start and their simultaneous use should be avoided.

Following the above criteria, a fully detailed technical database was created containing all possible aircraft design parameters that could influence cost. A total of 97 parameters (Fig. 4) could be analysed under different categories, aiming to identify the actual aircraft cost drivers. Inevitably, data were not available for all of these parameters and therefore the technical database finally used was downsised.

1.5 Economic part

All commercial aircraft with a seating capacity of more than 100 passengers (approximately 60 aircraft in total) were analysed for the duration of their whole life cycle, and classified further in accordance with the year of entering into service. A representative diagram is shown in Fig. 5. In this diagram, the year 2005 is set as a fictitious upper limit for those aircraft which are still in operation, while the dots indicate a mean year of reference for each aircraft.

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The creation of this diagram facilitates the normalisation technique of dividing these aircraft into different generations. The distribution of the reference years is consistent with the initial intention to divide the different aircraft types in terms of the decade within which their production started. The sample is adequate to provide data for aircraft in three generations as shown in Table 2. That criterion, however, is in some cases deliberately relaxed, e.g. 747-400 which strictly speaking should be in generation GII. But since it is newer and more advanced in terms of technology than the 747-300 of the same generation, it was considered more reasonable to place it in GIII. The same exception applies for MD-81 and MD-11.

The developed unit cost methodology focuses on the study of the contemporary generations GII and GIII. In addition, the lack of reliable cost information for the aircraft in GI led inevitably to the a priori elimination of these older aircraft types. Although it is not intended to use the GII analysis results to evaluate GIII aircraft, having similar results for both generations would undoubtedly strengthen the validity of our concept.

Table 2
Commercial Aircraft classification into Generations

GI 1980	GII 1990	GIII 2000
A300B2-100	A300-600	A319
A300B2-200	A300-600R	A321-100
A300B2-300	A310-200	A321-200
A300B4-100	A310-300 IGW	A330-200
A300B4-200	A320-200	A330-300
727-200 ADV	737-300	A340-200
737-200 ADV	737-400	A340-300
747-100B	737-500	A340-300ER
747-200B	747-300	717-200
747SP	757-200	737-600
747SR	767-200	737-700
DC-9-30	767-200ER	737-800
DC-9-40	767-300	737-900
DC-9-50	767-300ER	747-400
DC-10-10	MD-81	757-300
DC-10-30	MD-82	767-400ER
DC-10-30ER	MD-83	777-200
DC-10-40	MD-87	777-200ER IGW
	MD-88	777-300
		MD-11
		MD-90-30
		MD-90-30ER
		MD-90-50

2.0 DATA COLLECTION AND PROCESSING

2.1 Technical database

Selecting a single and reliable data source[11] is of great importance for the credibility of the parametric approach. Providing that the data collection technique is the same for all aircraft in the sample, the statistical error in the analysis will be consistent. Some of the basic dimensional parameters like the wing and tail total area and span (denoted with '*M_*' in their label) were measured from the scaled blueprints, since no values were directly recorded in the database. In this way, although the measured values may not be exactly the same with the real values, the associated error is of the same scale for all aircraft.

2.2 Cost database

Normalisation of cost data was achieved by classifying the aircraft into different predefined generations and collecting cost data for each generation individually. The data analysis was also conducted individually for each generation. This classification reflects the different technology levels and hence cost is more coherent within each generation making the parametric analysis more reliable.

The collected cost data for the two generations (GIII and GII) were based on two different years of reference (2000 and 1990 respectively). This approach was adopted in order to safely exclude the effects of inflation, which could otherwise undermine the robustness of the results. By conducting two individual analyses with aircraft prices in the same currency but for different years of reference, cost was directly correlated with aircraft design properties without being affected by economic factors.

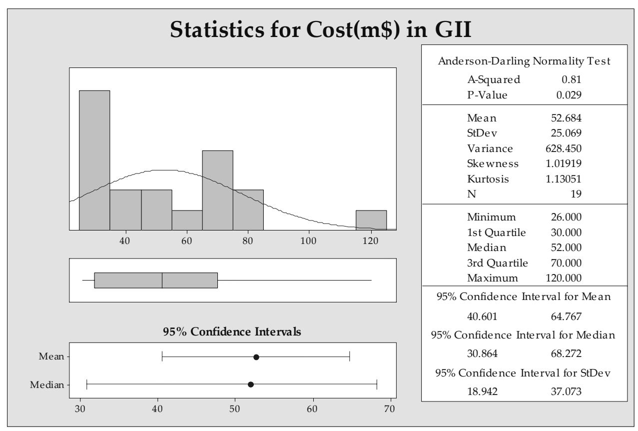

Figure 7. GII cost data descriptive statistics.

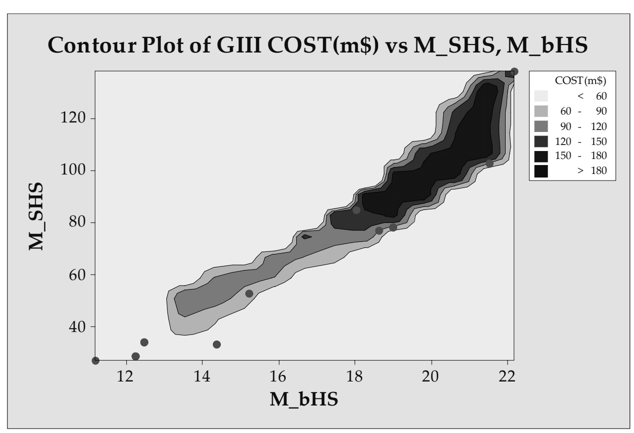

Figure 8. Contour plot of GIII Cost for HS sub-assembly.

3.0 STATISTICAL ANALYSIS

3.1 Descriptive statistics

The use of descriptive statistics concerns the representation of the essential features and the graphical visualisation of the basic calculations for the data under study. The most common data characteristics to present are measures of central tendency (sum, mean, median), and measures of dispersion or variability (standard deviation, variance, etc.).

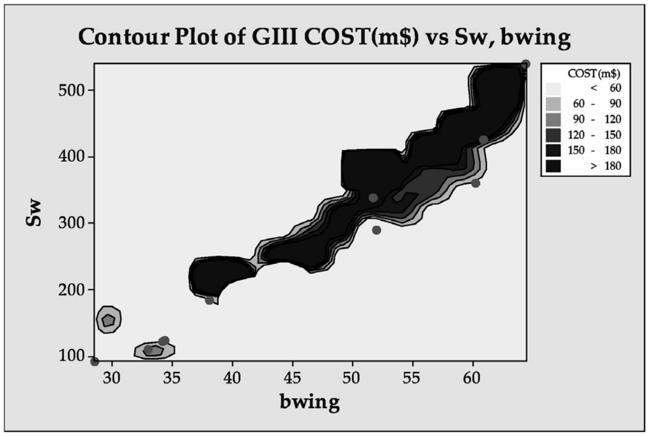

Figure 9. Contour plot of GIII Cost for WING sub-assembly.

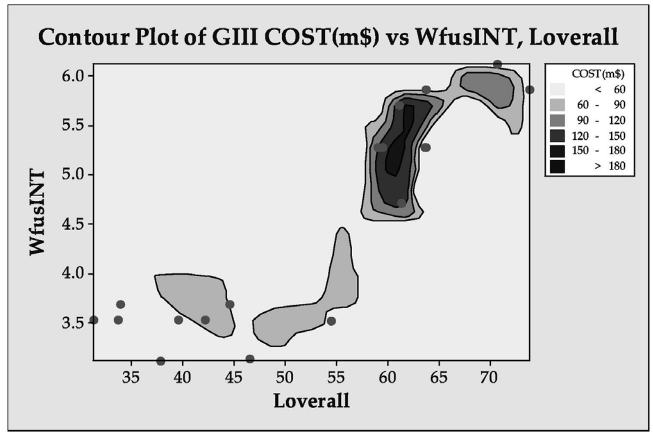

Figure 10. Contour plot of GIII Cost for FUS sub-assembly.

Table 3
Simple Linear Regression Table

	GIII			GII		
PARAMETER (P)	R^2 (%)	S	EQUATION	R^2 (%)	S	EQUATION
Sw	96.3	10.01	Cost = 13.2 + 0.351 * P	95.4	5.54	Cost = 6.82 + 0.230 * P
Sweepback	85.9	19.66	Cost = - 243 + 12.2 * P	86.9	9.33	Cost = - 123 + 6.38 * P
Mcruise	84.9	20.39	Cost = - 1247 + 1680 * P	81.3	8.75	Cost = - 478 + 674 * P
Nwpanels	74.8	26.23	Cost = - 80.4 + 75.8 * P	15.4	23.72	Cost = 0.7 + 23.5 * P
bwing	94.1	12.69	Cost = - 68.9 + 3.69 * P	91.2	7.65	Cost = - 56.5 + 2.76 * P
Ncontrsurf	59.7	33.20	Cost = - 72.7 + 5.46 * P	70.1	14.11	Cost = - 33.6 + 2.76 * P
Npylons	38.5	41.01	Cost = 48.3 + 26.3 * P	59.1	16.49	Cost = 24.3 + 18.0 * P
d	53.7	35.59	Cost = 30.2 + 27.5 * P	60.6	16.2	Cost = 23.1 + 12.9 * P
NHScontrsurf	19.6	46.88	Cost = 140 - 11.2 * P	26.7	22.08	Cost = 76.9 - 5.48 * P
NVScontrsurf	5.8	50.75	Cost = 75.3 + 16.8 * P	27.1	22.03	Cost = 82.0 - 17.4 * P
Loverall	91.2	15.54	Cost = - 100 + 3.84 * P	76.7	12.45	Cost = - 59.5 + 2.41 * P
WfusEXT	95.4	10.51	Cost = - 110 + 44.2 * P	79.1	9.75	Cost = - 42.0 + 20.4 * P
WfusINT	94.4	12.39	Cost = - 98.6 + 45 * P	82.1	10.92	Cost = - 44.9 + 23.3 * P
Npass_1	96	10.45	Cost = - 0.16 + 0.324 * P	94.9	5.85	Cost = - 3.62 + 0.221 * P
Npass_2	95.2	11.48	Cost = - 3.79 + 0.405 * P	93	5.35	Cost = - 12.7 + 0.328 * P
Nengines	31.1	43.40	Cost = 13.8 + 36.4 * P	42.3	19.6	Cost = - 22.1 + 35.5 * P
Nundercarr	41.3	40.08	Cost = - 90.9 + 57.3 * P	42.3	19.6	Cost = - 57.6 + 35.5 * P
Nwheels	93.1	13.69	Cost = - 24.5 + 13.2 * P	91.1	7.68	Cost = - 14.4 + 7.86 * P
M_SHS	93.3	13.56	Cost = 7.55 + 1.53 * P	92.8	6.93	Cost = 5.82 + 0.866 * P
M_bHS	92.4	14.39	Cost = - 118 + 13.4 * P	90.5	7.95	Cost = - 65.2 + 7.76 * P
M_SVS	87.9	18.22	Cost = - 11.4 + 2.81 * P	94.5	6.03	Cost = - 2.11 + 1.55 * P
M_bVS	80.9	22.85	Cost = - 80.3 + 23.3 * P	78.4	11.99	Cost = - 28.0 + 11.1 * P
M_Srudder	87.8	18.29	Cost = - 2.42 + 8.78 * P	90.3	8.03	Cost = 0.56 + 4.63 * P
Winglets	5.9	50.72	Cost = 87.1 + 24.5 * P	3.8	25.31	Cost = 49.9 + 10.7 * P
C_T-tail	20.8	46.54	Cost = 111 - 60.1 * P	33.6	21.01	Cost = 61.1 - 32.1 * P
Fuel_Not	38.9	40.87	Cost = 80.3 + 67.7 * P	7.8	24.77	Cost = 50.4 + 22.1 * P
Engine_FUS	10.3	49.53	Cost = 109 - 38.8 * P	33.6	21.01	Cost = 61.1 - 32.1 * P
Engine_VS	4	51.24	Cost = 98.8 + 48.7 * P	-	-	-
AR	39.7	40.60	Cost = 322 - 46.0 * P	-	-	-
T	54.6	33.60	Cost = 42.3 + 0.00154 * P	76.7	12.44	Cost = 3.87 + 0.00128 * P
bpr	28	42.30	Cost = - 51.8 + 32.1 * P	28	21.89	Cost = 16.0 + 8.88 * P

As shown in Fig. 6, cost data for the aircraft in GIII have a mean value of \$100·88m (million dollars), a standard deviation of \$51·09m and for 95% level of confidence they do not follow a normal distribution, since *p*-value (<0·005) is less than the value of 0·05 for the 95% confidence level. The negative value of Kurtosis denotes that GIII cost data distribution has a flatter peak and smaller (thinner) tails than the normal distribution. The positive value of Skewness shows that the distribution is not symmetrical with the presence of skewness to its right side.

The results for the cost data of GII aircraft are similar (Fig. 7). The existence of 747-300 in this generation is the reason for the positive Kurtosis (extended left tail), since its cost value is considerably higher in comparison to the rest of the aircraft. The latter point could also be considered as an early indication of the characterisation of the specific aircraft as an outlier ('atypical' observation with considerably different value in a given data set), but the validity of this argument has to be verified during the regression analysis.

3.2 Qualitative examination

In the contour plot in Fig. 8, the total area of the horizontal stabiliser (*HS*), as measured from the GIII aircraft blueprints (*M_SHS*), is plotted against its span (*M_bHS*), as indicated by the dots. Cost is the *z*-variable on the same diagram varying in a spectrum from 0 to its max value.

This contour plot is, in fact, the most representative diagram showing the effect on cost of *M_SHS* and *M_bHS* as typical parameters of the Geometry and Material categories. A linear association is clear between the variables on *x* and *y* axis, while an area of intense cost concentration alongside this linear pattern converges towards the upper right corner of the diagram. This means that higher values of *M_SHS* and *M_bHS* are correlated with more expensive aircraft. In other words, there is a trend to have higher aircraft costs with bigger horizontal stabilisers. Providing that *HS* is a structural part with no obvious unconventional characteristics for the aircraft in our sample, it can be argued that, size and material rather than complexity are driving aircraft cost in this case.

On the contrary, plotting the same parameters for the wing (Fig. 9), reveals that cost is equally distributed alongside the linear evolution of total wing area versus wing span. The fact that there are expensive aircraft with smaller wings (lower values of *Sw* and *bwing*), simply denotes that complexity and manufacturing have a primary role in determining aircraft cost, as far as the wing is concerned. Size is not the main factor that affects cost and this reflects a distinctive difference in the design of the aircraft wing and the *HS*, with the former component to consist of more complicated parts than the latter.

This difference also justifies the selection of variables that represent wing complexity and parts, such as the *Sweepback*, *Ncontrsurf* and *Nwpanels*. The limited selection of the geometrical parameters for the *HS* are deemed, in contrast, as adequate, to study their contribution to aircraft cost.

The validity of the above arguments is verified by the same contour plots for *GII*, which were well in accordance with the corresponding plots for *GIII*, although they were derived from a completely different cost sample.

The necessity of including an adequate number of parameters that best represent each established cost element category, is clear from a similar contour plot with parameters describing the Fuselage category. The non linear association between the overall length of the fuselage and its internal width dimension is noticeably depicted in Fig. 10. Narrow-body aircraft occupy the lower left side of this plot, while the bigger and most expensive wide-body aircraft are located in the upper right corner of the same diagram.

Finally, a similar diagram, containing two of the most representative variables for the overall aircraft (Fig. 11), exposes two important issues. First is a provisional correlation between maximum number of passengers (*Npass_1*) and cruise Mach number (*Mcruise*), with a line that is constantly increasing – possibly a straight line with

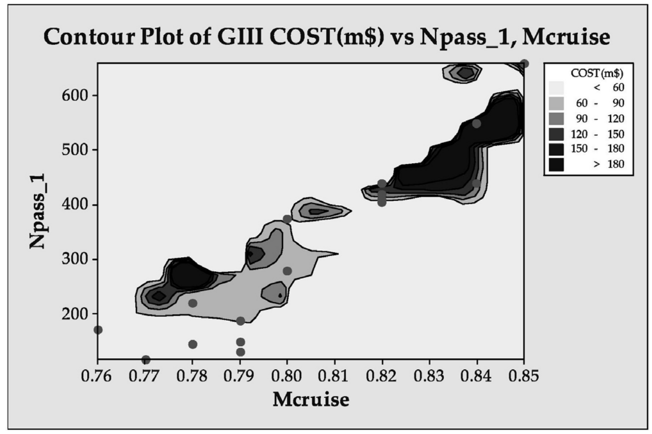

Figure 11. Contour plot of GIII Cost for parameters representing the overall aircraft.

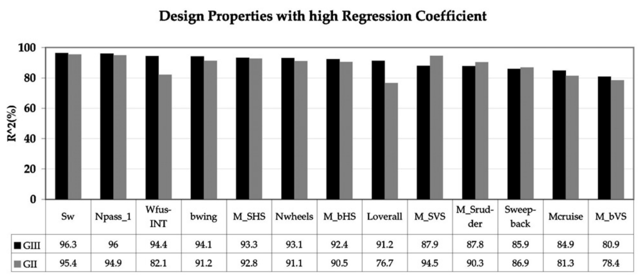

Figure 12. Most highly correlated parameters against cost after individual analysis.

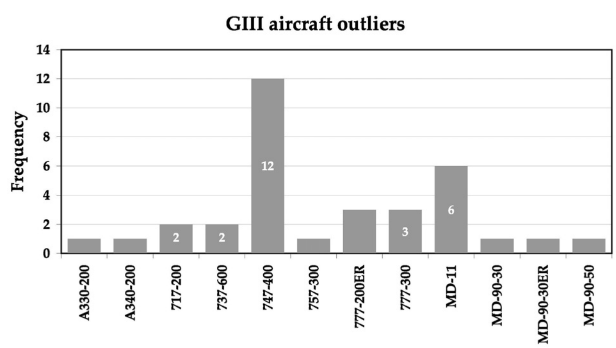

Figure 13. Outliers in simple linear regression in GIII.

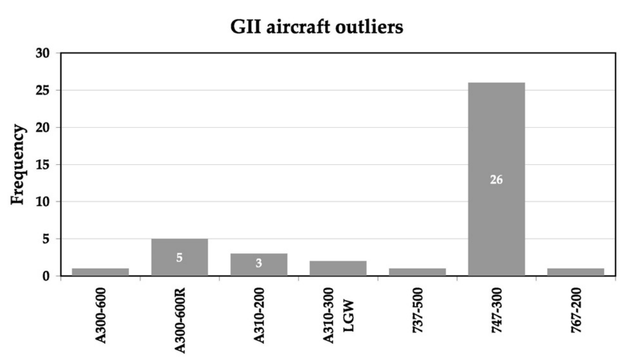

Figure 14. Outliers in simple linear regression in GII.

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Table 4
Best subset analysis for GIII aircraft under HS category

VARIABLES					CRITERIA			
Vars	M_SHS	M_bHS	d	NHScontrsurf	R^2 (adj)	Mallow C-p	S	R^2 (%)
4	X	X	X	X	94.0	5.0	12.516	95.1
3	X	X	X		94.2	3.3	12.269	95.0
2	X	X			94.1	2.6	12.390	94.7
3	X	X		X	93.8	4.5	12.681	94.7
3	X		X	X	92.4	9.0	14.082	93.4
1	X				93.0	5.7	13.564	93.3
2	X			X	92.6	7.5	13.860	93.3
2	X		X		92.6	7.6	13.876	93.3
2		X	X		92.1	9.3	14.357	92.8
3		X	X	X	91.7	11.3	14.730	92.8
2		X		X	91.8	10.2	14.599	92.6
1		X			92.1	8.8	14.394	92.4
1			X		51.5	150.8	35.591	53.7
1				X	15.8	275.6	46.879	19.6

Table 5
Best subset analysis for GII aircraft under HS category

VARIABLES					CRITERIA			
Vars	M_SHS	M_bHS	d	NHScontrsurf	R^2 (adj)	Mallow C-p	S	R^2 (%)
4	X	X	X	X	94.0	5.0	6.159	95.3
3	X		X	X	93.5	5.0	6.370	94.6
3	X	X		X	93.3	5.7	6.502	94.4
2	X			X	93.6	3.9	6.329	94.3
3		X	X	X	92.4	8.0	6.928	93.6
3	X	X	X		92.1	8.5	7.024	93.5
2	X		X		92.6	6.6	6.818	93.4
2	X	X			92.3	7.4	6.949	93.2
1	X				92.3	6.5	6.934	92.8
2		X		X	89.9	13.7	7.960	91.0
1		X			89.9	13.4	7.954	90.5
2		X	X		89.3	15.3	8.193	90.5
1			X		58.3	102.6	16.197	60.6
1				X	22.4	203.5	22.083	26.7

Table 6
Aircraft properties finally selected for the nonlinear regression approach

HS	VS	FUS	UND	ENG	WING
M_SHS	*M_SVS*	*Loverall*	*Nundercarr*	*T*	*Sweepback*
M_bHS	*M_bVS*	*WfusINT*	*Nwheels*	*bpr*	*Mcruise*
d	*M_Srudder*	*Npass1*		*Nengines*	*bwing*
		Nwheels			*Npylons*
					Sw
					Ncontrsurf
					Nwpanels

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positive slope. Although this association cannot be designated with a direct relationship derived from the aircraft design process theory, it reflects the tendency to design the bigger aircraft for higher cruise Mach numbers, in order to achieve better performance efficiency.

Another important characteristic of the same plot is the two biased areas of cost distribution. *Npass_1* is the potential capacity limit of the aircraft, strongly affecting its size and structural weight in a proportional way. Differences in *Mcruise*, on the other hand, can be easily interpreted with a number of complexity factors regarding mainly the wing configuration. Consequently, this disproportionate cost distribution on the *x-y* system of *Npass_1* and *Mcruise*, suggests that aircraft cost increment is not solely caused by weight or size increment. Studying the effect of the chosen parameters under the adopted cost element categories is imperative, in order to identify the actual aircraft cost drivers.

3.3 Simple linear regression

A simple linear regression approach was implemented in this part of the analysis to point out the most highly correlated parameters against cost (Table 3).

Equations with lower standard error deviation (S) and consequently higher regression coefficient (R^2) incorporate a better individually correlated parameter against cost. These equations, however, can not be used to justify the way cost responds to any variations of that parameter. They simply form the mathematical expression of the best fit based on the sample data, and this is particularly rational for categorical variables (switches). For example, by analyzing the regression equation between cost and *NHScontrsurf*, it is not valid to claim that an increment in the number of *HS* control surfaces will cause a cost reduction as the equation suggests. On the contrary, based on common sense and aircraft design standards it will be more realistic to expect it to cause a cost increase. What is reliable, though, to deduce from this equation is the fact that, *NHScontrsurf* is not highly correlated with cost, since the value of regression coefficient is considerably smaller than one.

Figure 12 exhibits the aircraft design properties with regression coefficient greater than 80%, after a simple linear regression analysis for the aircraft in both generations. The observed coherence of the results for both generations verifies further that aircraft unit cost is highly influenced by these design properties.

3.4 Outliers

The diagrams depicted in Figs 13 and 14 were created with the intention of summarising the frequency of the aircraft that demonstrated some of their design properties as outliers during the analysis. The most frequently appearing aircraft were the 747-400 and MD-11 from GIII, and 747-300 from GII. The 747 differs from other aircraft in the sample due to its large size and upperdeck, while the MD-11 differs due to its VS-integrated engine.

It is crucial to identify outliers because they can have a significant effect on the fitting model and its accuracy. The observed outliers, however, highlight the link between cost and design properties, hence removing them from the sample without further consideration is not recommended. It was therefore deemed wise to leave the above aircraft in the sample for further analysis. The qualitative temperament these aircraft will grand to the methodology, is of more importance than the adjustment of the regression coefficient to the maximum possible value.

3.5 Best subsets

After identifying the most highly correlated parameters against cost, from the linear regression analysis conducted individually for each parameter, the most accurate combination of them was detected with the use of the best subsets approach. Under each aircraft subassembly category, all possible combinations of simple linear regressions between the variables and cost were ranked according to different selection criteria. Tables 4 and 5 demonstrate these principles for the *HS* of *GIII* and *GII* aircraft respectively.

The best subset analysis revealed that, the combination of the most highly correlated design properties can provide regression equations with exceptionally high goodness of fit statistic measures. By incorporating more variables in a model, the fitted equation has normally better regression coefficient, but choosing the number of variables to include in the models is quite flexible, since the difference in the R^2 value between alternative models is very small. Changes in the values of the mathematical criteria between alternative models are generally synchronised, and so, there is no contradiction in choosing any of them as the decisive factor for model selection. R^2 is mainly used for consistency reasons between the analysis steps.

3.6 Most highly correlated parameters

All the previously described analysis steps, based on linear regression techniques, were mainly focused on the qualitative investigation of the effect of the design properties on aircraft cost. They support with statistical measures the selection of the variables, which will be included in the unit cost methodology. The properties with the biggest influence on aircraft unit cost as derived from the analysis so far, are summarised in Table 6.

Based on the conclusions of the best subset analysis, the final choice of models can be very broad and flexible, as long as they contain these variables. Bearing in mind that nonlinear regression techniques are more efficient in terms of fitting more accurately a wider range of equations to the existing data, a higher accuracy and reliability should be expected from the forthcoming unit cost methodology.

3.7 Nonlinear regression

The objective of nonlinear regression is to fit the collected data to different types of equations, especially when neither the independent variables nor their mathematical conversions can be linearly associated with the dependent variable. Practically, it provides the ability to fit data to virtually any type of equation, while essentially the CER retrieved from the nonlinear approach can vary from very neat and handy to more complicated relationships involving several independent variables.

From a statistical point of view, the method of minimising the vertical distance between the observed data and the fitted surface (least squares) is used in nonlinear regression as a convergence criterion within an iterative process[12]: starting with an initial set of values for all the parameters in the equation, the first fitted surface is generated and the sum of squares are calculated. Then, with the use of several different algorithms, the variables are altered repeatedly to reduce the calculated sum of squares and, therefore, to obtain a better model for the given data set. The iterations stop when no further reduction in the sum of squares can be achieved by adjusting the regression parameters. The model containing the last set of variables is the equation of the surface that best fits to the analysed data.

The algorithms used to adjust the regression parameters are generally described as nonlinear estimating techniques and typically involve complicated matrix and derivative calculations. Three of the most commonly used techniques are the *Steepest Descent*, *Gauss-Newton* and *Marquardt-Levenberg* methods, which basically follow similar strategies[12,13].

The nonlinear regression approach followed in the developed methodology is based on the latter technique, since it is well established, more efficient and more widely accepted. Its algorithm is used by several commercial software packages used for the analysis, but it is also adopted in the new software (AUCER), that was developed specifically for this research programme to model aircraft unit cost by formulating and analysing CERs.

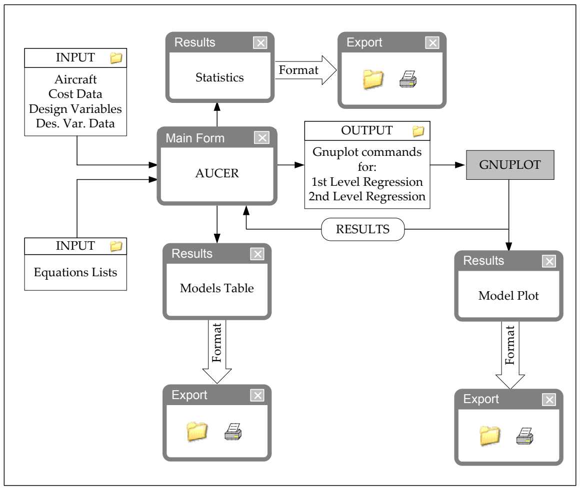

Figure 15. AUCER software architecture.

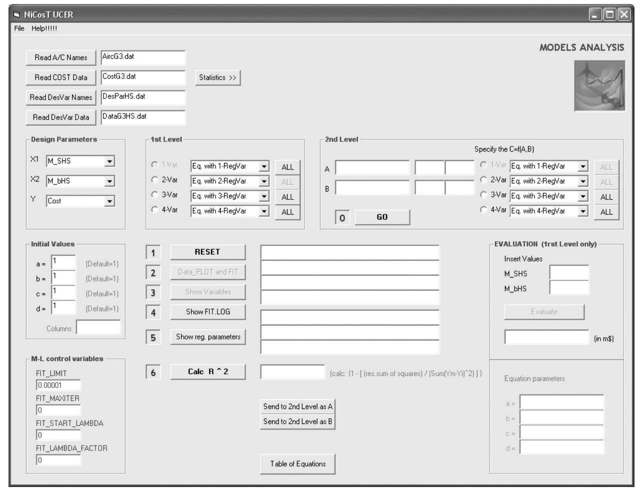

Figure 16. Aircraft unit cost estimation relationships (AUCER) software main form.

Table 7
Equations list according to number of regression variables

1-variable	2-variables	3-variables	4-variables
a**x1*	a**x1* +b	a*(*x1* **b)*(*x2* **c)	a*(*x1* **b)+(c*(*x2* **d))
x1 **a	a***x1* +b	a*(b***x1*)+(c***x2*)	a*(b***x1*)+(c*(d***x2*))
a***x1*	*x1* **a+b	a*(*x1* **b)+(c***x2*)	a*(*x1* **b)+(c*(d***x2*))
	a*(*x1* **b)	a*(b***x1*)+(*x2* **c)	a*(b***x1*)+(c*(*x2* **d))
	a*(b***x1*)	a*(b***x1*)*(*x2* **c)	(a+(b*(*x1* **x2*)**c))**d
	(*x1* **a)*(*x2* **b)	a*(b***x1*)*(c***x2*)	
	(a***x1*)*(*x2* **b)	a*(*x1* **b)*(c***x2*)	
	(a***x1*)*(b***x2*)	(*x1* **a)+(b*(*x2* **c))	
	(*x1* **a)*(b***x2*)	(a***x1*)+(b*(c***x2*))	
	(*x1* **a)+(*x2* **b)	(a***x1*)+(b*(*x2* **c))	
	(a***x1*)+(b***x2*)	(*x1* **a)+(b*(c***x2*))	
	(*x1* **a)+(b***x2*)	a*(*x1* **b)+(*x2* **c)	
	(a***x1*)+(*x2* **b)		
	a*((*x1* **x2*)**b)		
	a*((*x1* /*x2*)**b)		

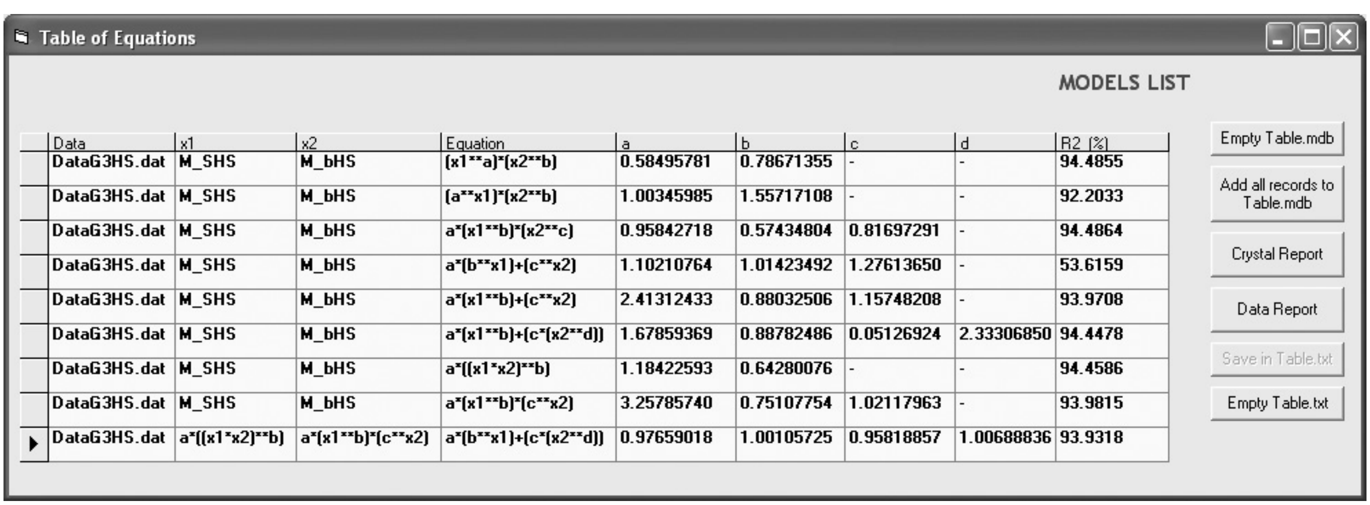

Figure 17. AUCER equations table form.

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4.0 AIRCRAFT UNIT COST ESTIMATION RELATIONSHIPS SOFTWARE (AUCER)

AUCER is a computer program that provides the ability to conduct basic statistical calculations, nonlinear regression and curve fitting in both 2D and 3D systems. It utilises certain benefits of the existing data analysis software that help towards the quick, simple and accurate development of cost estimation relationships from the aircraft design properties values retrieved from the technical database.

It is an autonomous, stand alone application designed for the analysis, formulation and filtering of aircraft cost estimation relationships. It can, however, be used as a platform to conduct nonlinear regression analysis and 2D or 3D curve fitting for any type of problem. The built-in equations are specifically selected to cover the needs of this particular unit cost analysis, although an unlimited number of equations can be incorporated and analysed. Therefore, the analysis can be fully adjusted to include from simple to more complicated models, in one or more program runs.

AUCER has its own user interface, although it utilises the freely available Gnuplot® code for all statistical computations and graphical representation of the results. Development of AUCER was based on Gnuplot's ability to run in batch mode with the use of files containing either the data to analyse or the commands for such an analysis. It was designed to conduct nonlinear regression analysis between one dependent and several independent variables, by exploiting the Marquardt-Levenberg algorithm provided from Gnuplot's code. The interaction between the program modules and Gnuplot is depicted in Fig. 15, showing also the main features at each level. The Graphical User Interface (GUI) of the main form is shown in Fig. 16.

4.1 AUCER advanced features

The user is entitled to select which type of equation to fit, from a range of four categories. This classification is made according to the number of the included regression variables (*a*, *b*, *c* and *d*). Regression analysis can be conducted in two levels. The second level of regression is accomplished by assigning two already fitted models from the first regression level, as independent variables in a new equation. The newly composed equation can, therefore, contain either alternative forms of the same variable or up to four different independent variables. In other words, aircraft cost can be predicted from a single equation containing up to four different aircraft design properties.

The Marquardt-Levenberg algorithm used by Gnuplot for the nonlinear curve fitting can be controlled by modifying its fundamental parameters (maximum number of iterations, converging limit value, step change, etc.) from the AUCER's user interface.

5.0 DEVELOPMENT OF UNIT COST MODELS

Table 7 illustrates the most applicable equation forms, selected after a thorough analysis of a wide range of alternative relationships. *X1* and *X2* in these equations are alternative design parameters from the list in Table 6, under the different aircraft sub-assembly categories.

Some of these equations are shown in Fig. 17 for a program run, which in fact comprises a filtered equation table containing selected cost models, according to the criteria established to control the development of the new unit cost methodology.

The CERs derived from the thorough statistical and regression analysis were used to model the aircraft cost in this new unit cost methodology, which is based on the overall adopted approach and its results as presented in this paper.

The total number of the cost estimation models (CEMs) finally incorporated into the unit cost methodology consists of up to 90 equations, distributed under the different aircraft sub-assembly

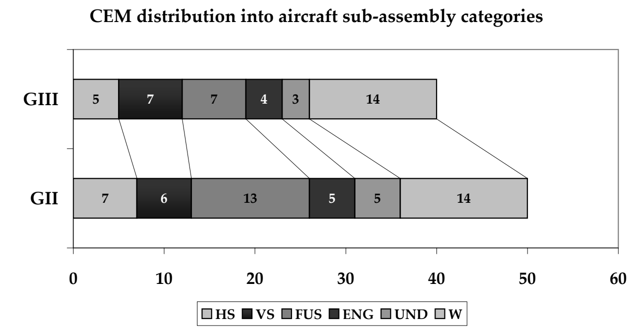
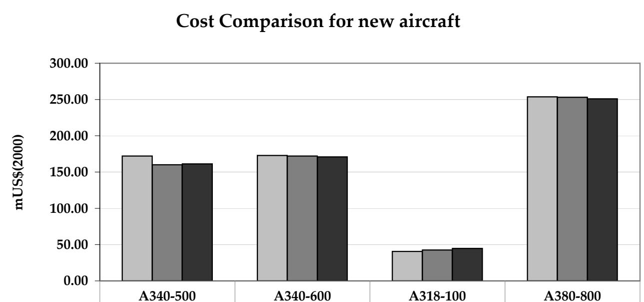
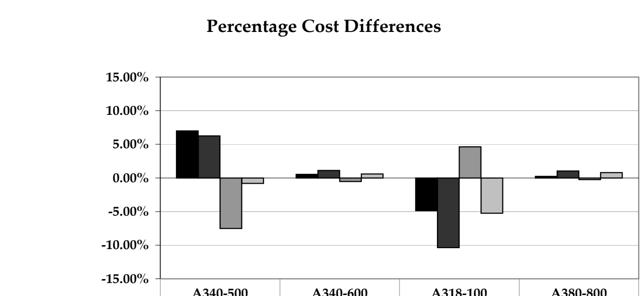


Figure 18. Distribution of CEM under each category for both generations.



	A340-500	A340-600	A318-100	A380-800
Janes	172.04	172.92	40.53	253.61
Lloyds	160.00	172.00	42.50	253.00
UC	161.29	170.98	44.73	250.97

Figure 19. Comparison between the predicted unit cost from the new methodology and existing values in literature.



	A340-500	A340-600	A318-100	A380-800
Lloyds from JANES	7.00%	0.53%	-4.86%	0.24%
UC from JANES	6.25%	1.12%	-10.36%	1.04%
Janes from LLOYDS	-7.53%	-0.53%	4.64%	-0.24%
UC from LLOYDS	-0.81%	0.59%	-5.25%	0.80%

Figure 20. Percentage difference between predicted and recorded in literature aircraft cost values.

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categories as illustrated in Fig. 18. These CEMs are integrated into a new software, which allows the analyst to test the developed regression equations from a rather user friendly interface and decide whether or not to include them into the unit cost estimation process. Furthermore, it provides the user with the ability to test the sensitivity of the selected models on changes in design properties within reasonable extrapolation limits.

5.1 Validation

The chosen equations comprise a well balanced set of CEMs, which make the methodology easily applicable for either small (such as the A318) or big (A380) aircraft. The validity of the methodology and its accuracy were tested, by applying it for the estimation of the unit cost of newly developed aircraft. The results are summarised in Fig. 19.

Applying the methodology to calculate the cost of the A340-500 and -600 was rather straightforward, provided that those aircraft are well adjusted to the sample of GIII. The high accuracy levels depicted by the small percentage differences between the predicted cost from this methodology and the recorded values (Fig. 20) are interpreted as a successful cost estimation.

Unlike the A340s, the A318 case has some peculiarities, which however didn't prevent the process for a successful cost estimation. A318 is an aircraft which falls close to the predefined lower applicability limit of ≅ 100 passengers, and therefore the divergence percentages between estimated and recorded cost values vary between 5% and 10%. These values are justified by considering the fact that the size of the specific aircraft is distinctively small.

The analysis of the A380 case set new standards in applying the unit cost methodology. The successful cost estimation based on specific criteria in terms of handling the exceptionally greater design properties of the A380 compared with other GIII aircraft (approximately 40%), has shown that the method can be used effectively in estimating the cost of future and relatively unconventional aircraft types.

6.0 CONCLUSIONS

Aircraft unit cost estimation processes are traditionally based on detailed cost accounting or weight-based parametric techniques. The need for the development of a new design-oriented unit cost methodology for large commercial jet aircraft, demanded the prior setup of a robust and effective methodology for the identification and assessment of the most significant design and technology based, unit cost drivers. The new assessment methodology, presented in this paper, clearly defines the fundamental steps involved for data collection, classification, qualitative examination and detailed quantitative statistical analysis. It establishes the rules and criteria for selecting and filtering the best and most technically relevant subsets, which could be reliably used as sensitive building blocks for the development of the new aircraft unit cost methodology. The quantified approach clearly identified the most important unit cost drivers and proved that, changes in design parameters, which represent aircraft geometry, manufacturing and complexity, affect the unit cost of the aircraft in a distinctive way.

Although the basic principles of the methodology could be applied for the cost estimation of several systems in various scientific fields, the selection of these specific models was driven by the qualitative association between the design parameters and their influence on aircraft unit cost.

The same methodology principles were applied on two different cost samples for two different predefined aircraft generations. The results were very coherent in both cases in all levels during the analysis, and that strengthens the validity of the new methodology.

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