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Unit Cost Estimation Methodology for Commercial Aircraft

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The development of a new flexible design-oriented, unit cost methodology for large commercial jet aircraft with a seating capacity of more than 100 passengers is presented. The method is based on actual technical and cost data and incorporates cost estimation relationships derived from a thorough statistical and regression analysis filtered according to established engineering criteria. The selected models are implemented into a computer program, which provides quick, flexible, and accurate cost estimations, sensitivity analysis, and cost comparisons. The methodology's validity is tested by applying it to new aircraft, which are not included in the initial sample. The quantitative approach is focused on by analyzing and comparing these results in detail.

Nomenclature

$A\!\!R$	=	wing aspect ratio
bwing	=	wing span, m
C_T-Tail	=	conventional or T-tail, option switch
DP	=	number of design parameters in each model
d	=	mean fuselage width at the horizontal stabilizer location, m
Engine_FUS	=	fuselage-mounted engine, option switch
Engine_VS	=	vertical stabilizer integrated engine, option switch
Fuel_Not	=	horizontal stabilizer fuel tank, option switch
Loverall	=	overall fuselage length, m
M_bHS	=	span of horizontal stabilizer, measured from blueprints, m
M_bVS	=	span of vertical stabilizer, measured from blueprints, m
Mcruise	=	cruise Mach number
M_SHS	=	total area of horizontal stabilizer, measured from blueprints, m^2
M_Srudder	=	total rudder area, measured from blueprints, m^2
M_SVS	=	total area of vertical stabilizer, measured from blueprints, m^2
Ncontrsurf	=	total number of wing control surfaces
Nengines	=	number of engines
NHScontrsurf	=	number of horizontal stabilizer 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 stabilizer control surfaces
Nwheels	=	total number of wheels
Nwpanels	=	number of wing panels (segments)
R^2	=	regression coefficient, (percentage)
S	=	standard error deviation in regression analysis
Sw	=	total wing area, m^2
Sweepback	=	wing sweepback at quarter chord, deg
T	=	total engine thrust, lb
WfusEXT	=	maximum external fuselage width, m
WfusINT	=	maximum internal fuselage width, m
winglets	=	winglet, option switch

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Introduction

BOTH aircraft manufacturers and operators are consistently faced with controversial decisions on how to maintain the best possible product or service while keeping cost to a minimum. In the years of globalization, technological developments in the aerospace industry, based on high-quality standards and the current engineering and manufacturing trends, are constrained by budgets and cost–time limitations. The viability of the world's airline industry strictly depends on operational profit margins and substantial economic savings, gained from advanced operating strategies, detailed and accurate life-cycle cost estimates, and, of course, low aircraft procurement costs.

Most of the existing aircraft cost estimation methodologies are either detailed cost accounting methods,[1] or parametric techniques optimized for minimum cost (especially direct operating cost).[2–7] The need for an accurate new methodology that is based on actual cost and technical data, which at the same time is suitable for use in the initial phase of the aircraft design process for providing early and reliable unit cost estimates, is highly desirable. The newly developed approach, presented in this paper, aims to study some aspects of the economics of commercial aircraft production and operation and to analyze the correlation between key aircraft design parameters and cost. The methodology does not focus on the traditional weight parameter to calculate cost,[8] or depend on fluctuating economic terms.[9]

Design criteria and cost prediction methods are extremely important during the life of an airplane project, bearing in mind its increasing complexity and vast capital investment. Aircraft designers should be able to adjust their design decisions according to cost information, or alternatively, to reduce cost after identifying the cost drivers throughout the design process. Given that over 70% of the life cycle cost of an aircraft is committed during the concept stage of development,[2,10] it is really crucial to calculate cost right from the outset of the design process. Some of the decisions involved in the early design phases could significantly affect the overall cost, whereas most of them are difficult or even impossible to change in the following phases.

The accuracy of the methods for aircraft cost estimation is an issue of increasing importance, both in terms of calculating and predicting cost. Because a good cost estimate must also include a good forecast of what the aircraft will be on delivery,[11] some cost analysts predict several key characteristics of the system, including weight and complexity growth, whereas others make decisions after analyzing risk and uncertainty of the alternatives. Accurate matching between the predicting and actual program cost is dictated by the need for the development of a precise cost prediction methodology.

Because of 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 that are referenced later in this paper. 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 that influence the manufacturing cost, either directly or indirectly. Hence, when it is assumed 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 among 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 new methodology is intended to provide flexibility in terms of choosing which and how many of the design properties to consider, depending on pertinent technical or economic needs throughout the design, production, or operation of the aircraft. It is based on the results of the regression analysis between recommended price data (dependent variable) and multiple metric, for example, wing area, and nonmetric, for example, type of material, design properties (independent variables). The most influential design parameters affecting cost are determined following a carefully established approach, which consists of simple linear regression and best subsets analysis. Nonlinear regression analysis subsequently provides the cost estimation relationships (CER) that will be implemented into a computer program.

The new methodology is directed to both engineering designers and airline operators, who could benefit from such a unit cost prediction tool. Based on a flexible architecture, this program can be used during the early steps of the initial design process for realistic cost estimations, depending on the availability of aircraft design properties values, at the feasibility level using several easily available parameters of the overall aircraft, at a conceptual level predicting cost from only a key design parameter, and at the preliminary level, where the methodology can provide models with more than one design parameter for each aircraft subassembly.

During the preliminary level, the methodology is obviously more sensitive to design changes because it incorporates more design parameters, whereas the estimated cost is more accurate because of the inclusion of more precisely defined cost drivers. At the first two levels, when the designer or the manufacturer has only a guess on approximated estimates of the basic parameters for the aircraft under development, the method would still provide reasonable cost values, the accuracy of which would of course depend on the quality of the inputs, although when used on a comparative basis the results should still be significantly more accurate.

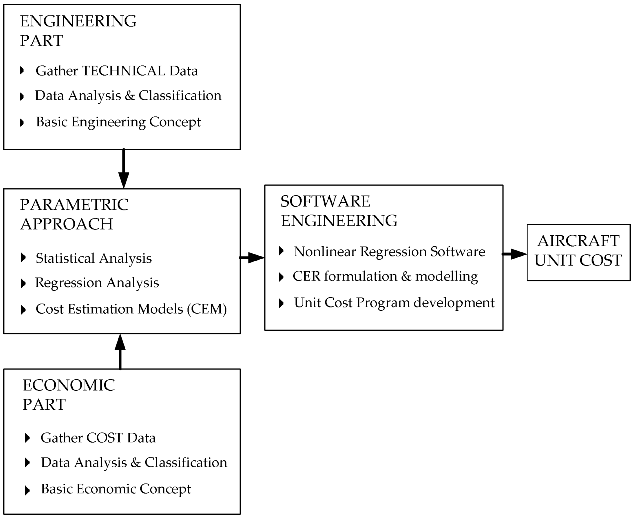


Fig. 1 Setting main concepts of unit cost methodology development.

Fundamental Principles

The theoretical framework of the unit cost analysis is based on the combined study of two different fields with 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 CER for modeling aircraft cost will be extracted. These models are in turn implemented into a software routine flexible enough to conduct cost analyses and comparisons among different aircraft types.

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. First, the aircraft is broken down into the following major subassemblies: horizontal stabilizer (HS), vertical stabilizer (VS), fuselage (FUS), engines (ENG), undercarriage (UND), and wing (W). In turn, five representative cost element categories are established to classify all parameters for the aircraft subassemblies: geometry, material, manufacturing, parts, and complexity. This selection was based on engineering criteria because the categories are primarily controlled by the design and not by financial fluctuations. Therefore, it has been attempted to include as many parameters as possible to represent the aircraft adequately and to enhance design sensitivity.

The strategy followed was 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. Following the rules of the regression analysis, simultaneous use of closely associated variables is not recommended to avoid the statistical correlation between them.

According to the preceding criteria, a fully detailed technical database was created containing a large number of aircraft design parameters that could influence cost (data from Ref. 12). A representative diagram is shown in Fig. 2, which contains the most suitable parameters for all aircraft subassemblies under different cost element categories. The parameters shown in cells with darker background were finally not adopted in the analysis, either because of missing or poorly correlated data during the initial analysis tests.

Approximately 60 commercial aircraft in total with a seating capacity of more than 100 passengers were considered and classified in accordance with the year of entering into service. This classification facilitated the normalization technique of dividing these aircraft into different generations. The developed unit cost methodology focuses on the study of the contemporary generations G2 and G3, as shown in Table 1. For the two generations (G3 and G2) collected cost data are based on two different years of reference (2000 and 1990, respectively, Refs. 13 and 14). This approach is adopted to exclude safely the effects of inflation, which could otherwise undermine the applicability of the results.

When the aircraft are classified into different generations, cost data are collected for each generation individually, and a separate unit cost analysis is conducted for each generation, the cost data are normalized. The classification in generations reflects the different technology levels, and hence, cost is more coherent within each generation. When two individual analyses with aircraft prices for different year of reference are conducted, cost is directly correlated

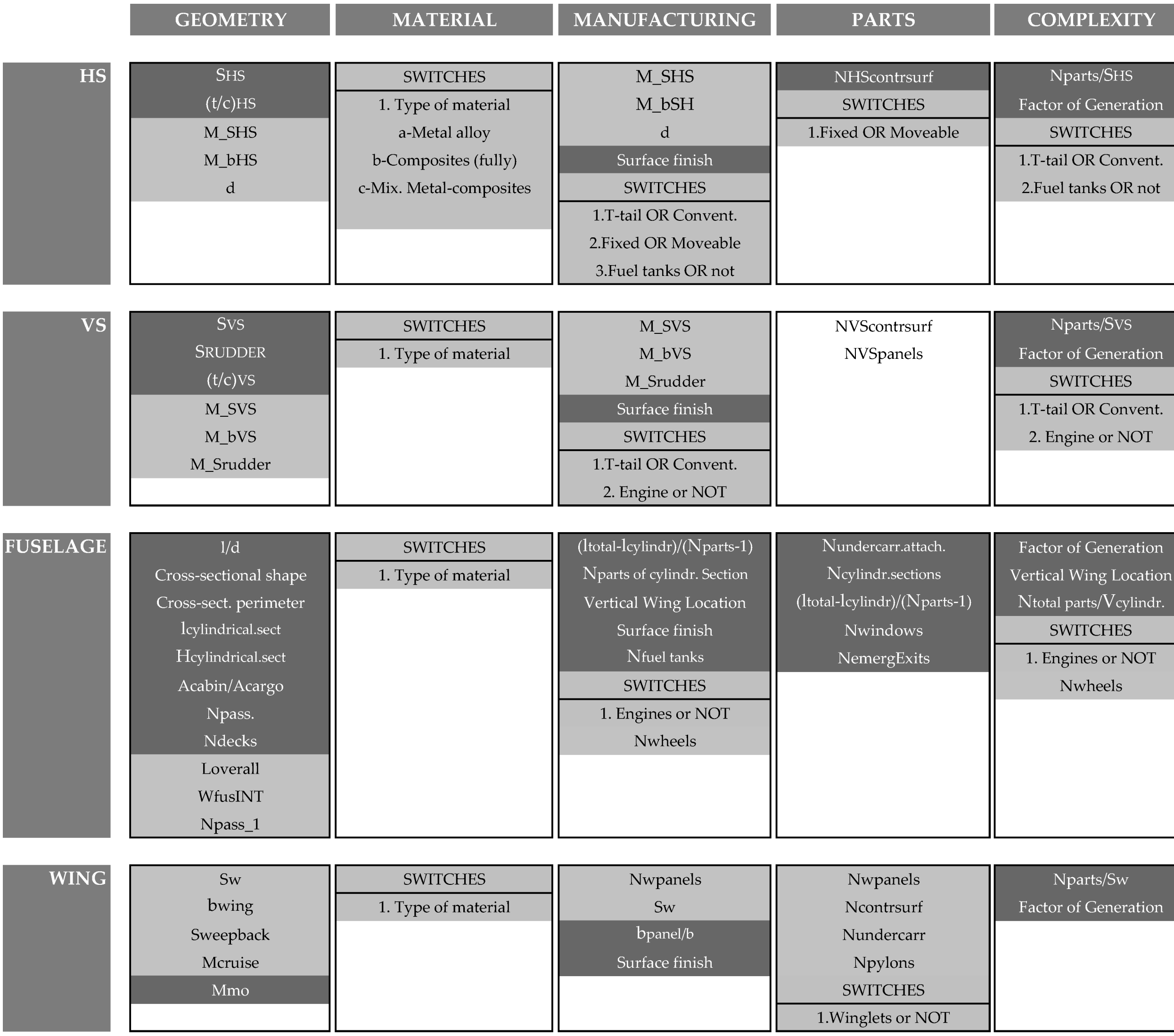


Fig. 2 Aircraft design properties under different cost element categories before filtering.

Table 1 Commercial aircraft classification into generations

G1, 1980	G2, 1990	G3, 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

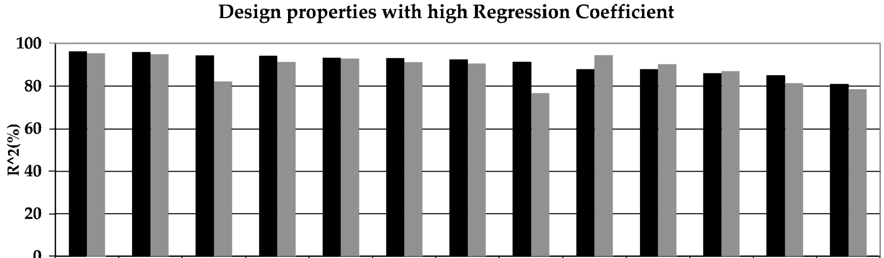
with aircraft design properties and remains unaffected by economic factors.

Initial Analysis

A simple linear regression approach was first implemented in this part of the analysis to point out the most highly correlated parameters against cost. Figure 3 shows the aircraft design properties with regression coefficient R^2 greater than 80% for the aircraft in both generations.

Having $R^2 < 80\%$ is not a restrictive criterion for not incorporating some of the parameters in the final cost models, but, surely, the highly correlated parameters must be included in the analysis. Parameters with regression coefficients of less than 30% apparently do not strongly affect cost. The best subsets analysis, conducted at the early stages of the analysis, proved that neither their combination with the highly correlated parameters offers exceptionally good fitted models.

On the other hand, several alternative combinations of the most highly correlated design properties can give regression equations with exceptionally high goodness of fit. The fitted equation has normally better regression coefficient, when incorporating more variables in a model, 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.



	Sw	Npass_1	Wfus-INT	bwing	M_SHS	Nwheels	M_bHS	Loverall	M_SVS	M_Srud-der	Sweep-back	Mcruise	M_bVS
■ G3	96.3	96	94.4	94.1	93.3	93.1	92.4	91.2	87.9	87.8	85.9	84.9	80.9
■ G2	95.4	94.9	82.1	91.2	92.8	91.1	90.5	76.7	94.5	90.3	86.9	81.3	78.4

Fig. 3 Most highly correlated parameters against cost after individual analysis.

Table 2 Aircraft properties finally selected for 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

This initial analysis revealed the set of parameters, including engine bypass ratio (BPR), with the biggest influence on aircraft unit cost, as summarized in Table 2.

Nonlinear Regression

The CER implemented into the unit cost methodology are derived from a nonlinear regression fitting process, followed by a thorough filtering procedure based on several established engineering criteria, presented in the following section.

The nonlinear regression approach followed in the developed methodology is based on the Marquardt–Levenberg (see Ref. 15) technique, implemented into a computer program that automatically retrieves, analyzes, and stores the produced cost estimation models (CEM). This aircraft unit cost estimation relationships software, AUCER, provides the ability to conduct basic statistical calculations, nonlinear regression, and curve fitting in both two-dimensional and three-dimensional systems. It incorporates a wide range of built-in equations specifically selected to cover the needs of the aircraft unit cost analysis. Therefore, the analysis can be fully adjusted to include from simple to more complicated models, in one or more program runs. Regression analysis can be conducted in two levels. The second level is accomplished by denominating 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 (maximum of two independent variables in models of each regression level, to be able to plot them in three-dimensional diagrams). In other words, aircraft cost can be predicted from a single equation containing up to four different aircraft design properties.

CEM Selection Criteria

CEM resulting from nonlinear regression were filtered according to specific engineering criteria. First, simple equation forms that ensure easy implementation in the developed methodology are preferable to the inconvenient complex models. An adequate range of parameters enhances the method's applicability and flexibility, in accordance with the designer's needs.

For the sake of simplicity but also to avoid collinearity between the regression parameters, polynomial models of second or higher order (and cross products) are excluded. These types of equations can only be substantiated when the sample is big and there is a justification for the local peaks and troughs that they exhibit. Furthermore, adding more polynomial terms in an equation is an indirect way of forcing the curve fitting and achieving better regression coefficient, but this does not necessarily reflect the actual correlation between cost and the independent variables.

Individual characteristics of the selected aircraft design properties should be taken into account, to improve the methodology's accuracy. For example, the method has to be able to give a nonzero value for aircraft cost, in the case where parameters such as *d*, *Sweepback*, and *Npylons* have values equal to zero. At the same time, equations with constant terms are avoided because those kinds of parameters can be mistakenly interpreted as fixed costs. For similar reasons, logarithmic and rational forms for both dependent and independent variables are eliminated.

Equations with positive coefficients are preferred, especially when this affects the trend of cost variation by changing the values of the design properties. Following the results from scatter plots analysis, a positive increment in the value of a design property normally causes a positive increment in cost. No conflict should exist between this interaction and the model's graphical shape.

Although the individual models are not meant to be used for calculating the aircraft cost as stand-alone relationships, a basic sensitivity analysis test has to accompany the selection process to avoid extreme cases. For instance, there is no obvious reason to accept a model that implies that extending the HS span by 1 m would double the overall aircraft cost.

When all of the preceding criteria are fulfilled, the selection of the equations can be further decided by the maximum value of the nonlinear regression coefficient. The strategy adopted for CER formulation and the criteria to apply are obviously the same for the aircraft in both generations. The equations, however, will not necessarily have the same form for G3 and G2, under each aircraft subassembly category.

CEM Methodology

The aircraft design properties identified as prominent unit cost drivers (Table 2) are normally incorporated into the CEM in pairs, by considering the initial goal of this approach, which was to develop practical and easily implemented models. Having a greater variety of compact equations to choose from is deemed more beneficial than having fewer equations with more parameters, or even one equation with all possible variables. In the latter case, it would be more difficult to study the effect of each parameter individually. On the contrary, the chosen approach provides the designer with the ability to select equations based on the appropriate type and number of aircraft design properties for each case.

The underlying principle for selecting the pairs is the connection among the parameters in terms of aircraft design relevance. The small difference in the regression coefficient percentages between alternative variable subsets allows the unrestricted selection of any combination, with minor effect on the overall accuracy. For the HS, VS, UND, and ENG categories, it is easy to form the most suitable pairs because the parameters involved are only up to three in total. A more subjective selection is required for the FUS and W categories,

Table 3 CEM describing wing for G3 aircraft

DP	Steps	Equation	R^2, %	Identification
2	A1	$C = 0.004602273243 \cdot Sweepback^{2.702149936} + 1610.45379 \cdot Mcruise^{15.27849295}$	88.76	G3–W-1
	A2	$C = 2.559346792 \cdot 1.090139659^{Sweepback} + 1696.277677 \cdot Mcruise^{14.88869113}$	87.83	G3–W-2
	A3	$C = 1.11171978^{Sweepback} + 1522.058233 \cdot Mcruise^{13.77752361}$	87.69	G3–W-3
2	B1	$C = 1.080339337^{bwing} + 45.12755164 \cdot 1.001^{Npylons}$	89.99	G3–W-4
	B2	$C = 1.080229491^{bwing} + 44.63732986 \cdot 1.010009647^{Npylons}$	90.0	G3–W-5
1	B3	$C = 0.1295248338 \cdot bwing^{1.726801305}$	93.71	G3–W-6
2	C1	$C = 1.027093152 \cdot Sw^{0.8292651922} \cdot 1.001^{Ncontrsurf}$	96.49	G3–W-7
	C2	$C = 0.3484699051 \cdot Sw + 0.3999480786 \cdot Ncontrsurf$	95.47	G3–W-8
	C3	$C = 1.673597895 \cdot Sw^{0.6868602576} \cdot 1.01^{Ncontrsurf}$	91.59	G3–W-9
1	D1	$C = 15.84131301 \cdot Nwpanels^{2.050297286}$	78.14	G3–W-10
3	A1 and D1	$C = 0.8752779965 \cdot A1^{0.9601933876} + 0.009687576148 \cdot D1^{1.699191428}$	94.14	G3–W-11
4	B1 and C1	$C = 0.2714130315 \cdot B1^{1.095625135} + 22.87861626 \cdot 1.0084771336^{C1}$	92.03	G3–W-12
7	A1, D1, B1, C1	$Cost = 159.234075 + 0.2895834801 \cdot (A1 \text{ and } D1) - 7308.656444/(B1 \text{ and } C1)$	96.34	G3–W-13
	or	$Cost = 1.006345249 \cdot (A1 \text{ and } D1)^{0.9960044553} + 0.02229397403 \cdot (B1 \text{ and } C1)^{0.8929108893}$	94.14	G3–W-14

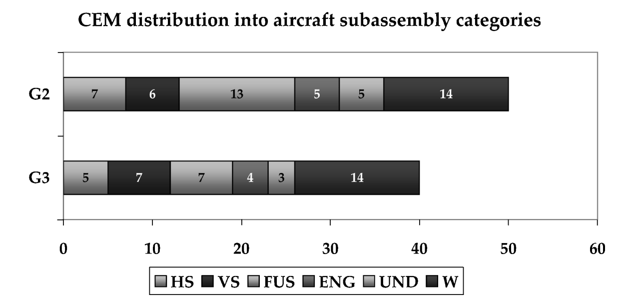


Fig. 4 Distribution of CEM under each category for both generations: ▪, HS; ▪, VS; ▪, FUS; ▪, ENG; ▪, UND; and ▪, W.

which contain more than three design properties each. The details follow.

Details

In the FUS category, *Loverall* and *WfusINT* combined together provide a good representation for the fuselage shape and size. By the use of both these parameters in a single cost model, the designer can distinguish between wide- and narrow-body aircraft types. For the aircraft in the sample, *Npass_1* is highly correlated with both *Loverall* and *WfusINT*. Another good combination is identified in the pair of *Npass_1* and *Nwheels*, which also expresses an obvious association between the potential maximum seating capacity (payload) of the aircraft and its pavement (footprint) area. The results have shown that different combinations of the fuselage parameters may give similar regression coefficients, and consequently, the final pair selection should be made on the merits of technical relevance.

Under W category, the combination of *Sweepback* and *Mcruise* is highly endorsed by their association within the context of wing aerodynamics. The pairs of *Sw–Ncontrsurf* and *bwing–Npylons* are also well justified, as expressing wing design complexity and weight. In that sense, their combination represents the wing's contribution within the complexity and manufacturing element categories. The *Nwpanels* parameter is justifiably considered as an individual parameter that contributes to aircraft cost within the manufacturing category.

Results

The total number of the CEMs finally incorporated into the unit cost methodology consists of up to 90 equations, distributed under the different aircraft subassembly categories as shown in Fig. 4.

For the aircraft in generation G3, Table 3 lists the whole range of the selected CEMs under the W subassembly category, which were finally incorporated into the unit cost methodology. The most suitable equations of all pairs (A1, B1, C1, and D1) with the highest R^2 were then analyzed once again to determine the new best subsets, which led to relationships G3–W-11 and G3–W-12. Finally, the combined models G3–W-13 and G3–W-14 contain all seven wing design properties.

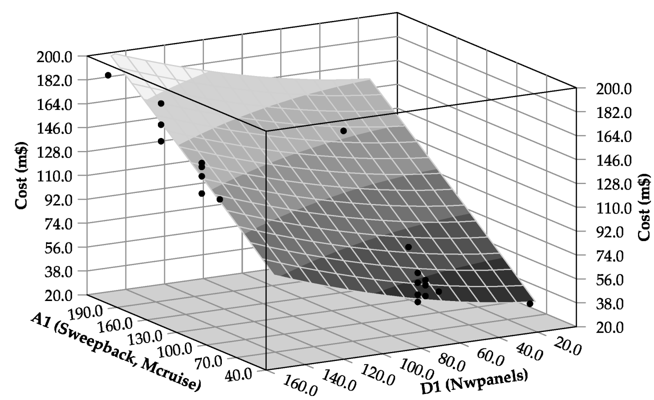


Fig. 5 Three-dimensional view of G3–W-11 model, cost = *f*(*Sweepback*, *Mcruise*, *Nwpanels*).

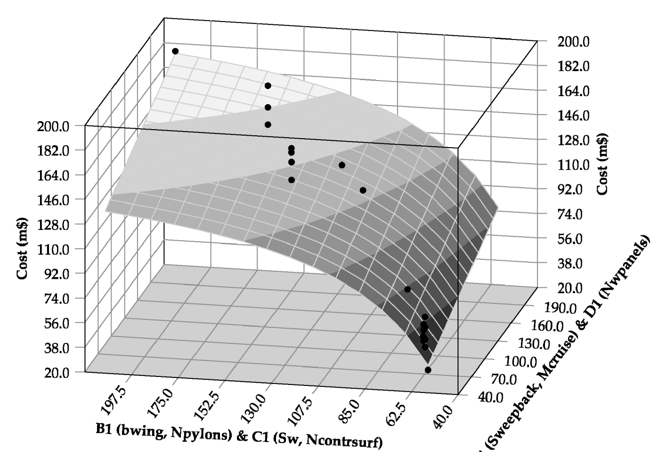


Fig. 6 Three-dimensional plot of G3–W-13 model, cost = *f*(*Sweepback*, *Mcruise*, *Nwpanels*, *bwing*, *Npylons*, *Sw*, *Ncontrsurf*).

The three-dimensional plots of the G3–W-11 and G3–W-13 models are in Figs. 5 and 6, respectively. Figures 5 and 6 graphs simply facilitate the graphical representation of all of the parameters included in the models (all costs in U.S. dollars).

CER Modeling

Unit Cost Program Architecture

The CERs discussed in the preceding section are integrated in a user friendly interface, which allows the analyst to test the developed

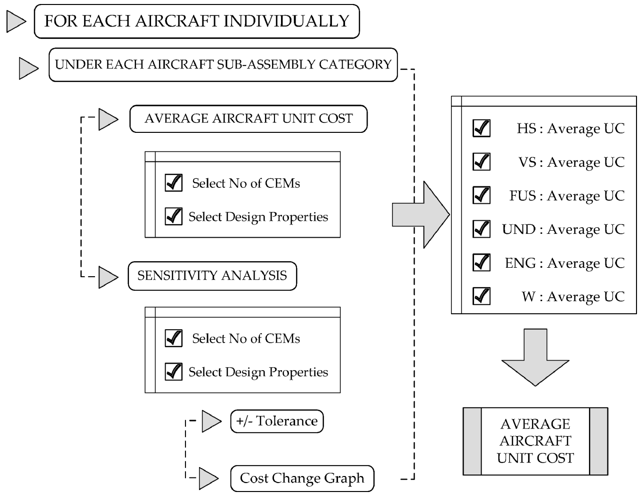


Fig. 7 Unit cost program architecture.

regression equations and decide whether or not to include them into the unit cost estimation process.

For each aircraft generation, six separate forms, similar in appearance, contain the models for the established aircraft subassembly categories. Under each category, the user can test any of the developed equations by comparing among them the estimated unit cost they provide. At the same time, their sensitivity to variable changes may be analyzed. The selected models give an average unit cost under each category. From these average values, the user can then again choose which ones will be included in the calculation of the new average unit cost value for the overall aircraft under study (Fig. 7).

By default, costs for G3 and G2 aircraft are shown in 2000 and 1990 millions of dollars, respectively. These costs can be adjusted to another year with the use of the inflation calculator on the same form. This calculator uses the consumer price index (CPI) inflation indices, as cited in Ref. 16. Note that the calculator does not interact with the methodology. By the conversion of the final average cost values from the year of reference to an equivalent amount of another year, only the results are interpreted differently. The calculator's primary use is mainly the comparative analysis between generations or different years of reference in general.

Sensitivity Analysis

The allowable maximum limit for changing the values of the aircraft design properties is controlled by a user-defined tolerance percentage. When the limitations of regression analysis are considered in conjunction with aircraft design principles, it is reasonable to set a default value of 20% for that change. In general, accuracy of regression is not degraded as long as the margins for the independent variable values are small. Changing the value of an independent variable by this tolerance percentage practically means "moving" the observation from its original place with respect to the fitted model. For a change greater than 20%, the fitted model may no longer provide accurate results.

When changing the minimum or maximum observation value, that change can be interpreted as an extrapolation of the model, and additional considerations must be taken into account. Again a 20% extrapolation margin is considered acceptable for accurate results, depending on the specific fitted model. For linear models, or models constantly increasing or decreasing (without peaks and troughs), it might be safe to extend even by 50% the "length" of the model line, provided that the accumulation of values along this line is more dense and uniformly spread and the sample is big. In our case, the fact that the polynomial models of second or higher order are excluded is helpful in successfully extending this margin and applying the methodology for bigger aircraft such as the A380, as shown in a following section.

Nevertheless, before specifying the tolerance, the designer has to take into account the effect of the changes of each aircraft property on the overall design process. It is highly likely that significant changes in one design parameter will cause variations in other properties. For example, it is not recommended to investigate the unit cost variation by significantly altering the wing's Sw alone because the aircraft design problem to be solved in this case is in fact multidisciplinary. Aerodynamics, structure, weight, performance, and cost issues should also be addressed before using the new Sw value in the unit cost methodology. In accordance with aircraft design process, more multidisciplinary properties need to be considered and their effect on cost included.

Results on Aircraft in the Sample

Before the methodology is applied to new aircraft cost estimation, it is useful to investigate the differences in actual and estimated unit costs for the aircraft in the initial sample. All CEM under all categories are used to calculate the costs for all aircraft in each generation. This approach should not be confused with the comparison between actual and predicted value of the dependent variable that is normally conducted for every fitted model to evaluate its goodness of fit. The latter regression analysis technique uses the model under investigation to compare the actual and the estimated value of the dependent variable for all observations and calculates the residual values and creates their plots. What is conducted in this step of the unit cost approach is the comparison between the actual value and the average estimated cost obtained from all models in the methodology. What is meant to be assessed is the coherence of the selected equations that form the methodology.

In addition, the analysis of the predicted cost from the entire collection of models will provide an indication for the scale of the method's error. The comparison between the actual and estimated cost will suggest a reasonable value for the acceptable error.

The percentage differences for the aircraft in G3 (Fig. 8) are fairly small in most cases. The estimated cost for the majority of these aircraft, obtained from the average unit cost of all models, is not significantly different from their actual cost. The only exceptions are the 717-200, 737-600, and the 737-700. This anomaly is understandable because the development of these aircraft is based on an old airframe structure with revamped technology, such as new lightweight materials and more sophisticated systems. Therefore, their higher actual cost compared to the predicted one might be better attributed to the step introduction of several technological advances.

However, the overall deviation between predicted and actual costs is still small because the average of these differences just exceeds 5%. The same value when excluding the cited three aircraft is merely 0.17%. The results for the more coherent G2 are unbiased, and the overall deviation is calculated at 2.67% (Fig. 9). In addition, but supporting the validity of the methodology, the whole set of equations estimates the cost of the 747-300 with a divergence of only 1.17% from its actual value. The observed differences may be attributed to the emphasis placed on selecting models containing variables based strictly on design criteria.

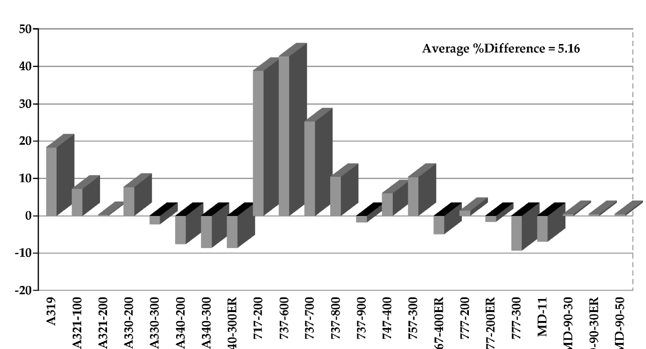


Fig. 8 Percentage difference between actual and average predicted cost from all models under G3.

Validation

The validity of the derived CER is tested by applying the methodology in estimating the unit cost of aircraft that were not included in the sample. Cost analyses for A340-500, A340-600, A318-100, and A380 were conducted with the aid of the unit cost program, aiming to predict their values and compare them with their recorded prices in the literature.

Apart from the sensitivity analysis tool, the user is provided with another option while running the program, which can be used to choose the models to be included in each case study. The predicted cost value from each model is compared to its category's average that is calculated from all available models in the category. From the wide range of available models, only those that are not significantly different from the average category cost are then selected for use in the final estimation of the aircraft unit cost.

A340-500

The results for the A340-500 are summarized in Fig. 10, from which the predicted unit cost value is calculated to be \$161.29 million in 2000 dollars. None of the models had to be excluded based on the 20% difference criterion. The aircraft under study is well adjusted to the sample of G3 because it is a derivative of the existing A340s. Hence, it is justified to incorporate the effect of all models in the developed methodology. Its behavior in that case is quite normal as expected.

The distinctive powerplant of the A340-500 justifies the drastically different value of the average cost retrieved from the ENG category, in comparison with the other categories. According to its description, the Trent 500 series has a considerably higher BPR than any other engine in its thrust class, to offer improvements in fuel efficiency and lower noise. Furthermore, the thrust of the Trent 553 (53,000 lb) used for the A340-500 is significantly greater than the thrust of the CFM56-5C2 (31,200 lb) used on the smaller A340-200 and -300 of our sample.

When the strict criterion of excluding all models with greater than 10 and 5% difference from the category average is applied, the new estimated costs become \$162.15 and \$161.57 million (2000), respectively, which practically do not differ much from the initial prediction. When the results from the three cases are compared, the confidence for the validity of the estimated cost is strengthened (Fig. 11).

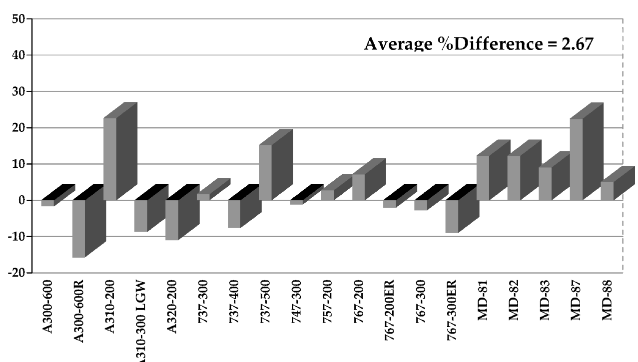


Fig. 9 Percentage difference between actual and average predicted cost from all models under G2.

A340-600

The A340-600 is a stretched version of the A340-500, with a fuselage length of 74.96 m to accommodate a maximum of 485 passengers (*Npass*_1). Its powerplant consists of four Trent 556 (56,000 lb), instead of the Trent 553 for the -500 series. Other than that, the two aircraft have exactly the same design properties.

As expected, the cost analysis of the A340-600 shows very similar behavior and results with the A340-500. Only one of the models representing the ENG category differs most within its category, whereas the engine-based average aircraft cost is significantly higher than the corresponding averages of the other categories due to the reasons explained in the A340-500 section.

The differences in predicted unit costs from the unit cost methodology and the alternative data sources are rather small. Whether the predicted \$170.98 million (2000) is compared to the estimated value from Lloyd's (Ref. 13), or the reported one from Jane's (Ref. 12)

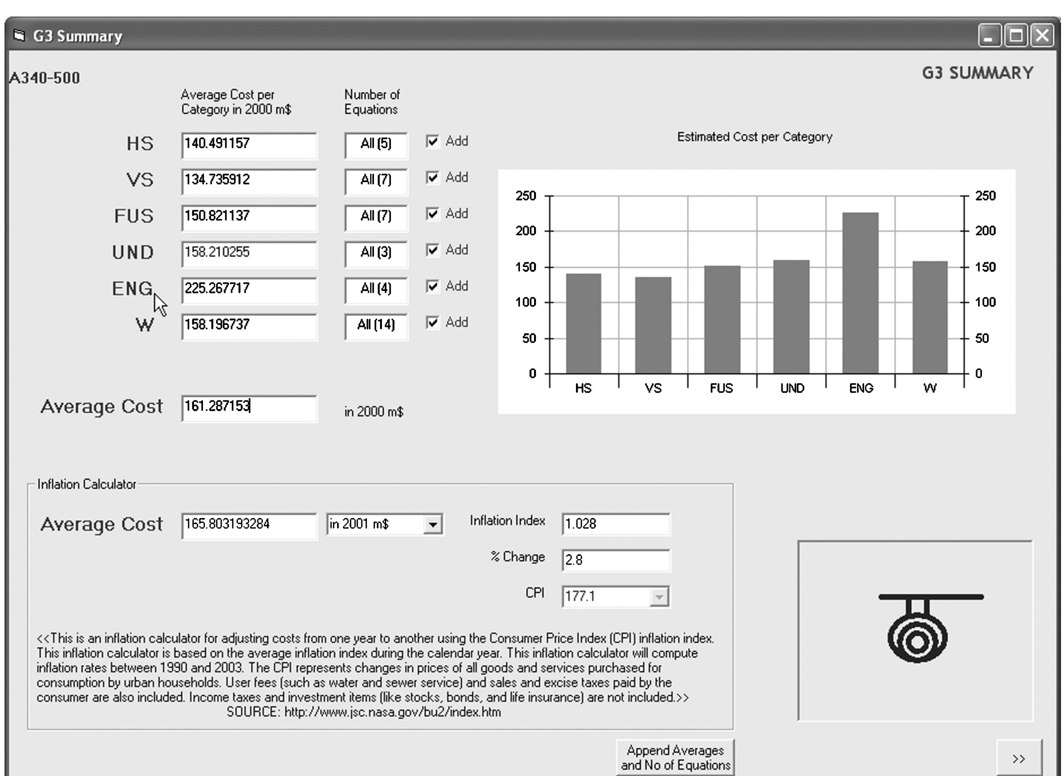


Fig. 10 A340-500 cost analysis: unit cost program form for average estimated cost of all categories.

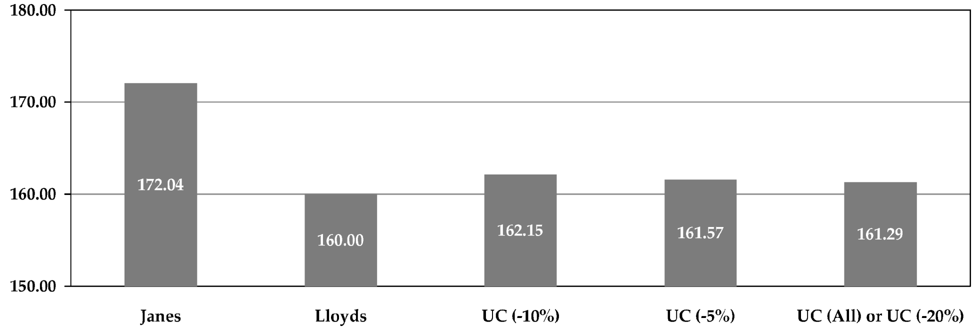


Fig. 11 A340-500 values comparison diagram in millions of dollars (2000).

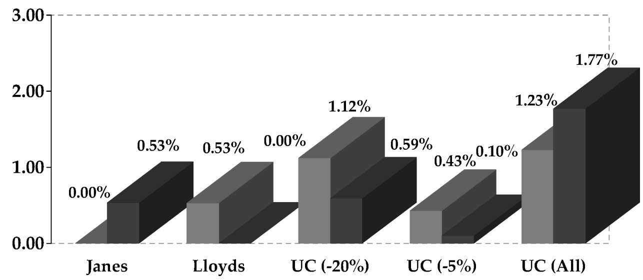


Fig. 12 A340-600 values comparison diagram based on millions of dollars (2000): ▨, % difference from Jane's (absolute values) and ■, % difference from Lloyd's (absolute values).

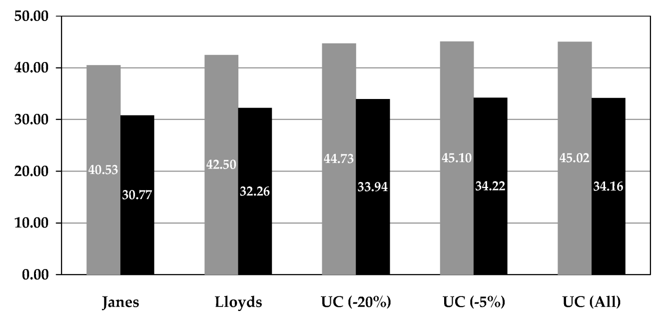


Fig. 13 A318-100 values comparison: ▨, cost in millions of dollars (2000), CPI adjusted, and ■, cost in millions of dollars (1990), from G2 models.

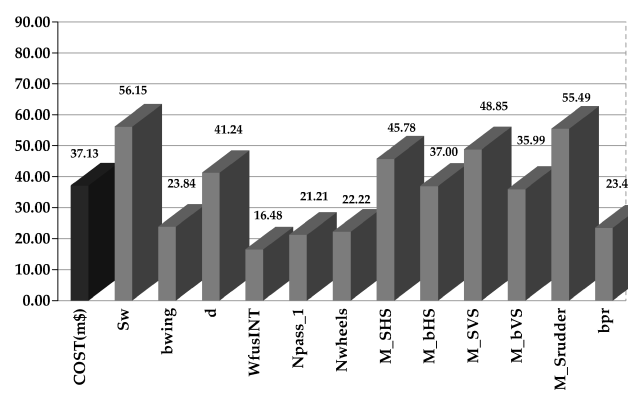


Fig. 14 A380-800 cost analysis: design properties comparison with maximum values from G3; indicated cost price of $265 million (2000).

($172 and $172.92 million (2000), respectively), the percentage difference does not exceed the 2% error margin (Fig. 12).

A318-100

The A318-100 is a derivative airplane from the A320 family. It is a short-bodied version with the smallest fuselage length of its family (*Loverall* = 31.45 m), capable of accommodating 117 passengers in a single-class configuration (*Npass_1*). Its engines have slightly smaller thrust (23,000 lb), and its fin has a tip extension, and so it is slightly bigger in size. Jane's (Ref. 12) states literally that the A318-100 has 95% commonality with other A320 family members.

When the biased character of the G3 because of the bigger and more expensive aircraft it contains is kept in mind, it is deemed as more appropriate to use the G2 set of equations to estimate the unit cost of the A318-100. Because of its distinctively small size, and its technology/design commonality with the A320, the A318-100 fits more appropriately in the G2 category but treated as a future aircraft. For comparison, the finally estimated cost in millions of dollars (1990) will then be converted in millions of dollars (2000) with the use of the inflation calculator.

The analytical implementation of the methodology shows several CEM with significant difference (>20%) from their category average, especially under the FUS category. Although these relationships are not very sensitive to parameter changes, their predicted costs differ significantly from the corresponding average values.

The summarized results for all models with less than 20% difference revealed that its concise fuselage (*Loverall* and *Npass_1*) has the smallest average of the category. The unit cost is estimated at $33.94 million (1990) or $44.73 million (2000) adjusted for inflation, which is not considerably different from the $42.5 million (2000) predicted from Lloyd's (Ref. 13) (approximately 5% difference) (Fig. 13).

A380

The exceptionally greater magnitude of the design properties of the A380-800 compared to the other G3 aircraft provides a challenge for the unit cost methodology, considering that it is not normally safe to extrapolate extensively regression models considerably beyond the maximum values of the independent variables. Figure 14 shows the design properties for which the A380's values are greater than the maximum recorded from other G3 aircraft. At the same time, Fig. 14 shows the magnitude of that difference in a percentage scale. The predicted cost of $265 million (2000) for the A380-800 is 37.13% larger than the $184.5 million (2000) for the 747-400 (maximum in our database). The approximately 40% difference in the dependent variable could be used to suggest that the A380 analysis extends the sample of aircraft covered by the methodology by almost half its original range.

It is obvious from Fig. 14 that the models including most of these parameters cannot be incorporated into the methodology to estimate the A380's cost accurately. Cost estimation relationships should be accordingly filtered to comply with regression principles. The 40% margin described sets the new criterion for that choice.

In detail, none of the models under HS and VS categories can be used because the *M_SHS*, *d*, *M_SVS*, and *M_Srudder* values are significantly bigger than the corresponding maximum values in the sample. Alternatively, no obvious reason exists to prevent the use of all models under the FUS, UND, and ENG categories. More analytically, 1) the values of the design properties under these categories are not excessively bigger, 2) the estimated cost of all

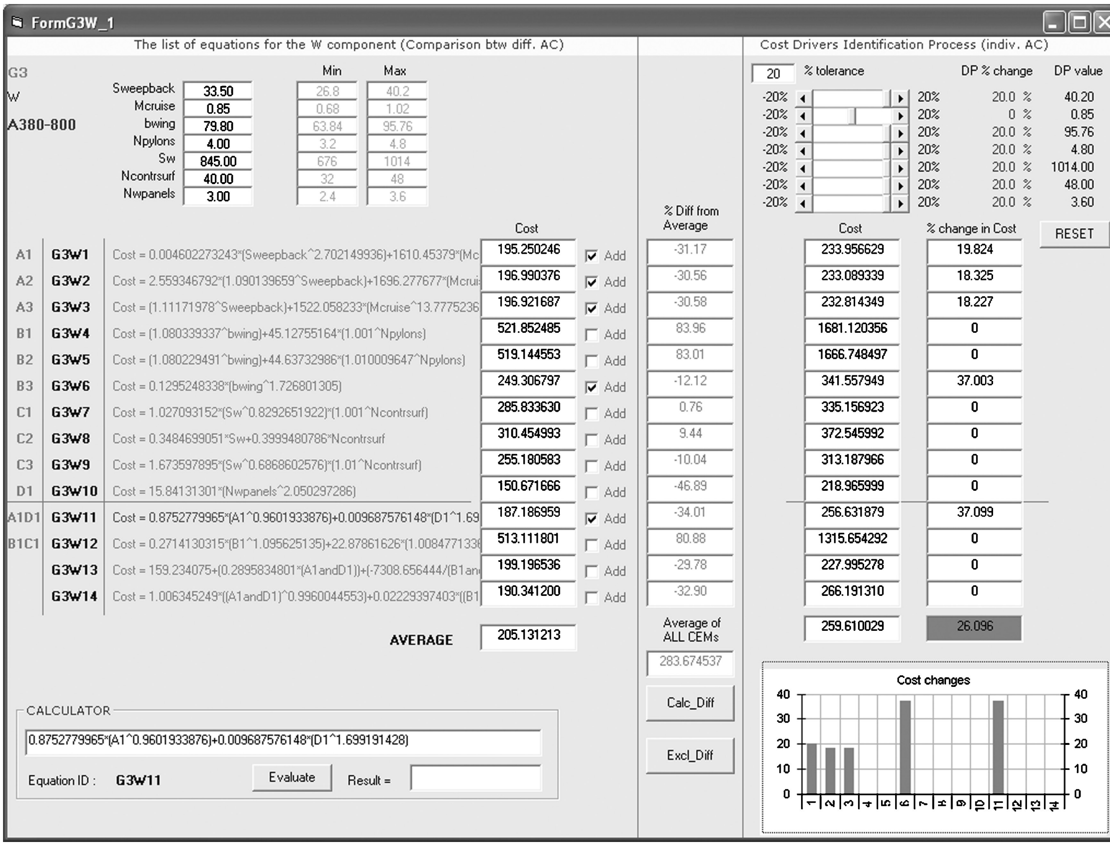


Fig. 15 A380-800 cost analysis: unit cost program form for W category.

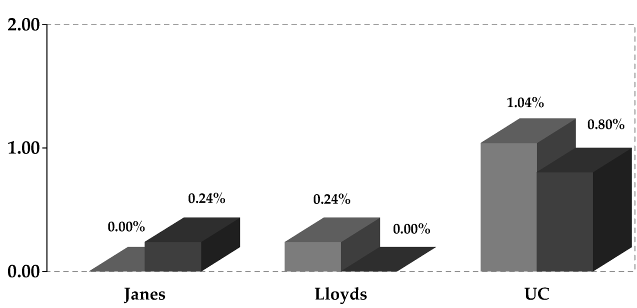


Fig. 16 A380-800 values comparison diagram based on millions of dollars (2000): ■, % difference from Jane's (absolute values) and ■, % difference from Lloyd's (absolute values).

models does not exceed the 20% of the average cost of their category, and 3) the sensitivity analysis of all equations shows an intuitively reasonable variation in cost changes with design property changes.

Under the W category, the G3W7–G3W9 and G3W12–G3W14 models are also excluded because they incorporate Sw with 56.15% difference. In addition, the G3W4, G3W5, and G3W10 cannot be used, given that their predicted cost is much greater than the category average. The rest of the models respond normally in sensitivity analysis tests and can be included without hesitation for the unit cost analysis (Fig. 15).

With the filtered model, the methodology estimates the average unit cost of the A380-800 to be $250.97 million (2000). According to Jane's (Ref. 12), the projected unit cost at launch was $217 million, whereas the revised average unit cost by mid-2002 was $265 million. The latter figure is converted to roughly $253.61 million (2000) and is almost identical with the predicted cost from Lloyd's (Ref. 13) at $253 million (2000). The comparison between the program's and the reported values is impressive (Fig. 16).

Conclusions

The new methodology proposed here can effectively be used to predict with reasonable accuracy the unit cost of large commercial jet transports with a minimum seating capacity of 100 passengers. The chosen equations comprise a well-balanced set of CEM, which make the methodology easily applicable for either small (such as the A318) or big (A380) aircraft within this category. It is a unique and flexible tool for the aircraft designer that can analyze the unit cost for future and relatively unconventional aircraft types such as the A380.

The method is well balanced to provide reasonable estimates for the unit cost of all types of future or existing aircraft within the specified category. The models reflect the effect of the design changes on cost. For similar aircraft to those in the sample, the methodology can estimate the unit cost quite accurately, even without filtering the model set.

It is not intended to be used as a fully automated tool for predicting unit cost, although the results in that mode so far have been shown to be quite acceptable. The designer can adjust the methodology with confidence based on the defined criteria to provide realistic unit cost predictions that reflect the design, technology, complexity, and size of the aircraft analyzed.

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