



Open Archive Toulouse Archive Ouverte (OATAO)

OATAO is an open access repository that collects the work of some Toulouse researchers and makes it freely available over the web where possible.

This is an author's version published in: <https://oatao.univ-toulouse.fr/20042>

Official URL : <http://dx.doi.org/10.1177/1063293X05060698>

To cite this version :

Curran, Richard and Price, Mark and Raghunathan, Srinivasan and Bénard, Emmanuel and Crosby, S. and Castagne, Sylvie and Mawhinney, P. Integrating Aircraft Cost Modeling into Conceptual Design. (2005) Concurrent Engineering: Research and Applications, 13 (4). 321-330. ISSN 1063-293X

Any correspondence concerning this service should be sent to the repository administrator:

tech-oatao@listes-diff.inp-toulouse.fr

Integrating Aircraft Cost Modeling into Conceptual Design

R. Curran,* M. Price, S. Raghunathan, E. Benard, S. Crosby, S. Castagne and P. Mawhinney

*Centre of Excellence for Integrated Aircraft Technologies (CEIAT), School of Aeronautical Engineering
Queens University Belfast, BT9 5AG, NI, UK*

Abstract: The article presents cost modeling results from the application of the Genetic-Causal cost modeling principle. Industrial results from redesign are also presented to verify the opportunity for early concept cost optimization by using Genetic-Causal cost drivers to guide the conceptual design process for structural assemblies. The acquisition cost is considered through the modeling of the recurring unit cost and non-recurring design cost. The operational cost is modeled relative to acquisition cost and fuel burn for predominately metal or composites designs. The main contribution of this study is the application of the Genetic-Causal principle to the modeling of cost, helping to understand how conceptual design parameters impact on cost, and linking that to customer requirements and life cycle cost.

Key Words: cost modelling, concept design, aircraft design, life cycle cost, multidisciplinary engineering.

1. Introduction

The specification of aero-structural systems can be captured by utilizing systematic techniques such as quality function deployment (QFD) to define functionality and key quality requirements. This leads to informed decision making enabled through integrated product and process design (IPPD), but requires engineering tools and models to predict the impact on emergent attributes and behavior such as acquisition cost, time to market, and life cycle performance. At a more detailed level, these models can be based on design rules and principles that can be used within the context of design for manufacture and assembly (DFMA) [1] for more efficient conceptual design solutions. This is widely acknowledged through the need to reduce product complexity in the context of process and material capability, and robust design. This involves the early integration of knowledge and analysis within a concurrent engineering environment [2,3] as alternative design concepts are being considered [4]. Ullman [5] has highlighted the technical challenge in shaping materials by a process into a form in order to satisfy a functional requirement [6]. Typically, the graduation from conceptual design, through preliminary and detailed design to the critical design review (CDR), results in a struggle

to satisfy functional and through life customer requirements while maximizing profit for the airframer.

Currently within the aerospace industry, DFMA is an applied design methodology that is used to help multidisciplinary teams to achieve more efficient product definitions at the concept design stage [6]. Aero-structural systems are characterized as part intensive and difficult to fabricate and assemble, being a function of the conceptual material selection and associated processing capabilities. The focus is on achieving the simplest structural configuration that meets the system requirements, whether in terms of structural integrity, aerodynamic performance or additional functionality. However, cost modeling tools are required to guide cross-functional and multidisciplinary teams in decision making, although it is widely acknowledged that it is extremely difficult to obtain fast and accurate cost estimates [7]. Notwithstanding, parametric cost estimating relations [8,9] can be formulated from historical aerospace data and are well suited for deployment at the concept stage as they generate cost estimates in a simple and speedy fashion. Often, these are used in an analogous context where a baseline product is used as a reference cost breakdown structure. Cost estimating relationships are typically generated using linear regression to predict the statistical relation of parameters to their direct costs, being limited by the need for historical data and being subject to market forces and technology levels.

The work herein addresses the understanding and modeling required for the development of design tools

*Author to whom correspondence should be addressed.
E-mail: r.curran@qub.uk

that formalize the above best practice [10,11]. The key is to identify the engineering cost drivers that relate to the design and assembly of the structural configuration. In the context of life cycle analysis, the cost should include the non-recurring design cost, the recurring manufacturing costs (including amortized non-recurring elements), and the recurring operational costs. This will facilitate an early trade-off of engineering configurations to be performed in an informed and realistic manner in the design process when engineering detail is not yet fully defined. Consequently, one of the main contributions of the work is in identifying and modeling a number of key drivers that can be related to the costs of design, production, and operation. This is facilitated in the study by the application of the Genetic-Causal cost modeling principle that is utilized to identify and relate cost drivers in conceptual design.

2. Cost Estimating Technologies

Typically, the initial function of cost estimation is the provision of reliable capital and operating cost assessments that can be used for investment funding and project control decisions. At a lower level, it provides important information that is used in the development of the product through trending, documenting, and controlling costs. There are a number of alternative methods [12–18] which can be used that are considered now.

Bottom-up or detailed costing is the most obvious form of costing and is a very information-intensive approach that entails the gathering of all cost information that can be directly attributed to the cost of the final article. The cost is normally derived from the assessed hours associated with each element detailed in the work breakdown structure (WBS). The process is difficult to implement in practice as it requires very detailed inputs at every stage and for every new estimate. Fundamentally, it is posthumous and requires its output to be differentiated from any new design being considered. The latter aspect leads us to analogous costing and Case Based Reasoning (CBR), which principally rely on the similarity or differentiation of like-products to ensure that the cost estimate is comparative to a previous instance. In differentiation, the historical cost from the like-product should be refined or adjusted to account for the variation in product complexities, technical differences, and other such factors. This provides a very practical approach but is highly sensitive to change in design, material selection and process, and requirements. Modern forms of analogous-type costing exploit neural networks (NN) and fuzzy logic to teach a computer program to predict the outcome given certain product-related input attributes. Associated disadvantages are similar

to those of analogous technique but also include the need for a large population size that is split into input and test groups. Parametric estimating (PE) typically entails the linking of cost to high-level product parameters through statistical relations that establish estimating relations to be built into cost estimating models [19,20]. Finally, financial accounting techniques, such as activity based costing (ABC) or lean accounting, represent another grouping that map engineering effort and resource utilization.

It is now accepted that cost modeling is particularly useful during the early stages of development, when there is little product information available [15]. Systematic modern estimating models can reliably predict future project costs more efficiently than traditional estimating methods, although one must decide whether to formulate custom made relations or whether to calibrate a chosen commercial model. Commercial cost packages, such as PRICE-H and SEER-DFM, offer a facilitating environment and functionality that allows an organization to calibrate a cost framework with their own historical data in order to tailor the model to their specific financial needs and business environment. However, as well as historical data, the calibration process requires expert judgment, assumptions, and subjective opinion while the quality of data, information, and knowledge are all highly influential.

3. The Genetic-Causal Cost Modeling Principle

The work discussed herein is a part of larger body of work within the Integration and Cost Modeling research group at the Centre of Excellence for Integrated Aircraft Technologies (CEIAT) at Queens University Belfast. The group is developing an approach to engineering cost modeling that is conceptualized in the Genetic-Causal principle. This is illustrated in Figure 1, where the causal definition of the relation of cost to design driver is seen in the context of product and process families. The model adopts the scientific principle of categorization (Genetic) but also incorporates the rigor of requiring causality (Causal):

1. Genetic makeup: cost is inherited from the design definition and by product and process nature, is classified into certain groupings; shown in Figure 1 as the classification of families relating to some level in the hierarchical definition structure, from conceptual through to detailed definition.
2. Causality: all costs are an effect of causal drivers, which are only then influenced by environmental aspects; shown in the radial component of Figure 1 linking costs to engineering design parameters such as: weights, part counts, sizing, and material selection etc.

With regard to the first principle, industrial aircraft design tends to be derivative and incremental, and therefore, a type of cost blueprint can readily be seen in previous aircraft, hence the wide use of analogous costing. Engineering manufacturing costs can be classified according to materials, fabrication processes, and assembly, while additional cost is incurred through support, quality and inspection, and general factory overheads. It is also necessary to distinguish between recurring and non-recurring costs; the latter including equipment, such as jigs and tools, whereas machine costs are amortized over a recuperation period that is built into the process rate. However, broader life cycle analysis also considers the non-recurring cost of the design process plus additional company recurring overheads, all of which should be reflected in the unit cost. Typically, rather than an imposed percentage margin, the profit is given by the difference between airframer's

total cost and the maximum obtained market price, the latter being set by the price the airline is willing to pay for the business opportunity afforded by that aircraft. However, the airframer's costs can be said to be genetically inherited through the causal origination from engineering design definition, albeit then factored by financial and external factors such as material and labor rates, and supply chain management, etc. These factors can be assumed to be fixed at the product definition stage or can also be treated as having certain distributions and likelihood of occurrence, the aggregated cost variance being assessed through Monte Carlo analysis [21].

The cost modeling at QUB is being developed in order to manage cost in the context of systems design and integration. The general approach is illustrated through Figure 2, which shows cost being integrated into the engineering process as another design variable to be considered as the definition process converges towards an optimum. The model represents a highly concurrent conceptual design framework that will speed up the conceptual design process and facilitate systems integration for a more global optimum that better satisfies customer requirements. The framework is being developed to accommodate multi-fidelity models for each of the disciplines, which enables the automatic inclusion of local detail into the global analysis. The structure is recursive and additionally allows for error estimation to determine when local design changes invalidate the global analysis. In particular, Figure 2 illustrates how an initial specification (developed from customer

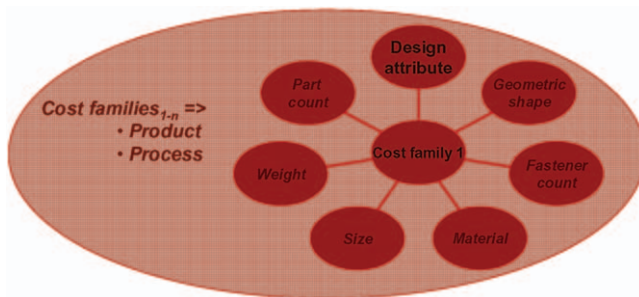


Figure 1. The Genetic-causal cost modeling principle.

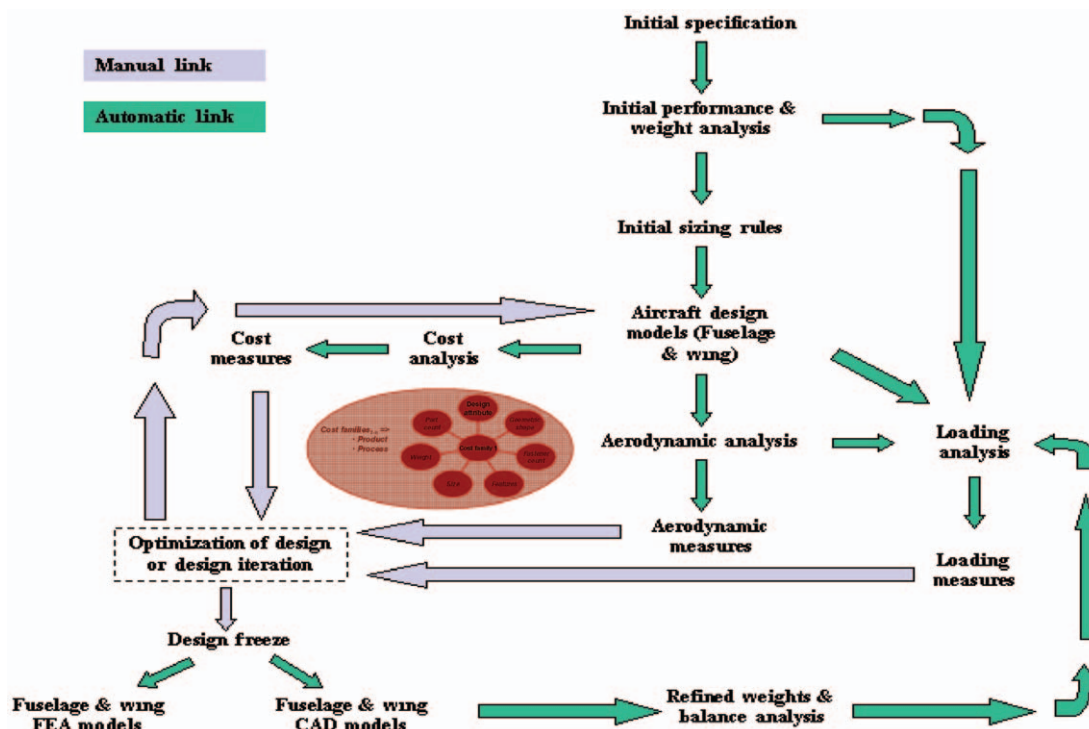


Figure 2. Integrating cost modeling into the conceptual design process.

and function requirements analysis) is first interpreted in terms of global performance, weights, and sizing. The next stage is to carry out a more detailed performance assessment of the subsystems, e.g., wing and fuselage, in order to integrate aerodynamic and loading analysis methods, etc. This results in a preliminary solution which can be costed so that iteration on the structural configuration and material selection can be performed. The optimal solution from a number of iterations then results in a 'design freeze' at a more global level, only then constraining the design space for optimization at a more detailed level. As shown, more detailed finite element analysis (FEA) can then be integrated into the process to further refine the design, thereby representing a more concurrent design process. Consequently, at least two levels of cost analysis are needed to facilitate (1) the global design process and (2) the lower level detailed optimization. It is the higher level cost modeling that is presented in this article, while the lower level modeling increases the fidelity of design definition and analysis while still being driven by life cycle requirements, being equally if not more true to the Genetic-Causal principle.

4. Manufacturing Cost Modeling

Figure 3 demonstrates the coupling between design for manufacture (DFM) and the minimization of manufacturing cost. The chart summarizes the results from a number of industrial redesign exercises. It can be concluded that better utilization of process capability can be implemented to produce more complex expensive parts. However, the reduced part count is seen to result in a reduction in unit cost, through reduced assembly cost. However, the redesign nature of the case studies may skew the potential benefits to be gained at concept design. It can be inferred that cost modeling needs to be used early in the design process in conjunction with DFM practice, whereas a lot of cost estimation is carried out only after much of the detailed design definition has been completed [14].

In order to understand fabrication and assembly costs, a research council (EPSRC) funded project was initiated that focused on the detailed investigation of two engine nacelle nose-cowls. This included the consideration of the various stages of assembly as sub-assemblies in their own right, and, at a lower level, part fabrication. The industrial data collected for the cost breakdown for the two engine nacelles chosen is illustrated in Figure 4 and includes: (1) part fabrication; (2) structural assembly; (3) raw materials; (4) purchased items; and (5) support. At 2005 prices, these aero-structures cost several tens of thousands of pounds, although in addition to the materials, fabrication and assembly costs, there is a significant portion

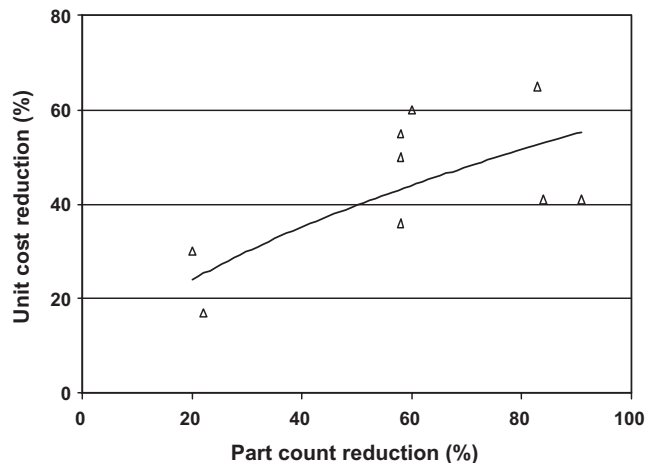
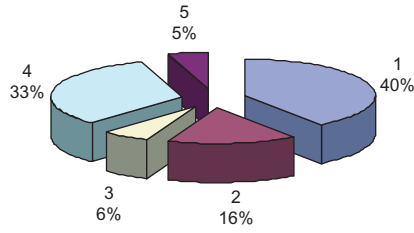


Figure 3. Cost reduction related to simple conceptual design parameters.

from: inspection, direct overheads, general and administrative costs (G&A), contingency, etc. In addition, cost definition is one of the most challenging aspects of cost modeling as data is not understood in terms of cause and effect, and is often rolled up. For example, material costs are often quoted within aerospace at 40% but this typically includes the cost of processed material, e.g., extruded stringer lengths, purchased items, and sub-contracted work. However, it is clear that in general, cost arises fundamentally from the part design and configuration definition (whether in-house or procured) and that either a reduction in the number of parts or in the average cost per part is pivotal. For the two nacelles presented, it should be noted that Nacelle B was manufactured with more advanced processes, such as auto-riveting, modular tooling, part to part assembly, etc., and that there is a decade between the development of the two designs. However, due to technology and process improvements, it will be seen that the manufacturing cost is of a similar magnitude, all the more surprising is that the nacelles are of a similar size but Nacelle B has a 40% higher thrust loading (stiffness requirements) and was subject to tighter certification standards. It is also evident from Figure 4 that there has been a shift to increased exploitation of outside production relative to in-house fabrication.

Each of the manufacturability drivers identified were tested relative to either part fabrication cost or assembly cost in order to identify which drivers correlated best to either cost. Weight and part count were found to correlate best to fabrication cost while part count and fastener count were best for assembly cost. This is a reasonable outcome given the linkage between the logistics of manufacturing a certain number of parts of a certain size, and of assembling those parts with a given number of fasteners. Regression analysis was performed to quantify the degree of correlation in each case,

Summary of manufacturing cost Nacelle A



Summary of manufacturing cost Nacelle B

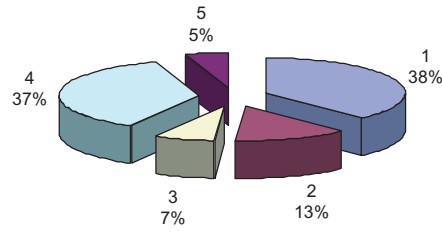


Figure 4. Typical cost breakdown for engine nacelles; for: (1) part fabrication; (2) assembly; (3) raw materials; (4) purchased items; and (5) support.

the trending helping to identify which parameters were likely to be the true causal drivers.

Fabrication and assembly coefficients were developed from the identified cost drivers for either process. In addition, due to the procurement of purchased items, the part-fabrication cost relation also utilized the part count and weight of bought-out items. This helps to factor in the cost effectiveness in off-loading the most inefficiently manufactured parts to outside suppliers, who are either more specialized in the associated manufacturing processes or who benefit from more favorable labor and overhead rates. In formulating the fabrication and assembly coefficients, the main aims were to (1) maximize accuracy through the utilization of the most relevant cost drivers and (2) to have a definition that was simple and readily usable at the early conceptual design stage. The definitions of fabrication coefficient (ϕ), bought-out coefficient (β) and assembly coefficient (α) are shown below in Equations (1)–(3), respectively.

$$\phi = \beta \left(W_{Tot} + \left(\frac{PC_{Tot}}{W_{Tot}} \right) \right) \quad (1)$$

$$\beta = \left(1 - \left(\frac{W_{B-Out}}{W_{Tot}} \right) \left(\frac{PC_{B-Out}}{PC_{Tot}} \right) \right) \quad (2)$$

$$\alpha = PC_{Tot} + \frac{FC_{Tot}}{PC_{Tot}} \quad (3)$$

It should be noted that all of the input variables utilized are either known at the concept stage or could be easily estimated. Total weight (W_{Tot}) and part count (PC_{Tot}) would be known early while an estimated value of the number of fasteners necessary per unique part (FC_{Tot}/PC_{Tot}) is often used in companies based on previous contracts; similarly, for the weight of bought-out parts (W_{B-Out}/W_{Tot}). Incidentally, in addition to facilitating assembly, it should be noted that fasteners also play an important structural role in providing the stiffness to withstand buckling (stiffened skins), and even the rivet spacing is subject to inter-rivet buckling considerations. Consequently, the higher thrust rating of Nacelle B requires a higher rivet count

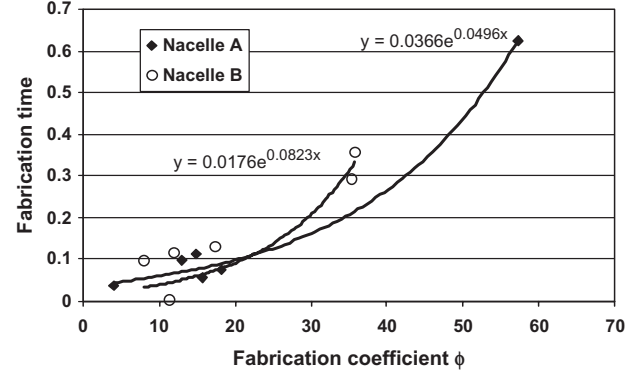


Figure 5. Correlation of fabrication coefficient to time.

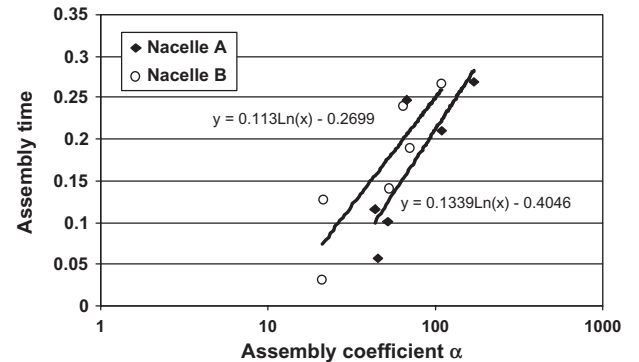


Figure 6. Correlation of assembly coefficient to time.

for structural reasons rather than only for manufacturing assembly.

The characteristics for the above-mentioned coefficients are presented in Figures 5 and 6 for fabrication time, and assembly time, respectively. The associated costs are calculated with appropriate manufacturing cost rates and the fabrication cost also incorporates the bought-out coefficient to include procured items. It can be seen from Figure 5 that the relation of fabrication coefficient to fabrication cost was characterized by exponential functions. With reference to Equations (1) and (2), it can be inferred that the weight of parts is associated with increased part count and higher fabrication costs. Some of the deviation is explained by the simplicity of the analysis not incorporating process type. This is being investigated to increase the fidelity of the model. It can be seen from Figure 6 that

the relation of assembly coefficient to assembly cost was characterized linearly in a logarithmic form. Work is currently ongoing to improve the correlation by distinguishing between subassembly work and final assembly. This will aid in helping to incorporate the influence of the different build sequences employed.

However, another important aspect that is difficult to model is the impact of part to part, modular tooling and jigless assembly philosophies. This is relevant, as Nacelle A is manufactured using a more traditional serial approach whereas Nacelle B exploits the more advanced techniques mentioned. It is believed that the variation between the two nacelles, evident in the fabrication and assembly modeling, is due to improvements in manufacturing capability. Nacelle B took half the time to assemble that Nacelle A did while the latter had a lower specification and was slightly smaller in diameter. However, Nacelle B was designed in a design for Six Sigma environment utilizing DFMA principles. Consequently, one can conclude that this approach has reduced part count at the expense of the fabrication cost per part and assembly time per part. This is reasonable if one accepts that the complexity of each part for Nacelle B must have increased as the assembled system still provides the same geometric form requirement, and also meets higher structural performance specifications. The results support the principle that there is a trade-off between the part count of assemblies, and the complexity of the individual parts. This is important to remember when implementing DFMA, which can now be optimized by using the trend characteristics found in Figures 5 and 6, rather than simply reducing part count without informed thought to complexity and process capability issues.

The modeling was used to estimate the fabrication and assembly costs and in addition, multiple linear regression analysis was also performed as a benchmarking exercise, using the variables utilized in the creation of the fabrication and assembly coefficients. For the multiple regression analysis (MRA), the fabrication cost as the dependant variable was related to total part count and weight, as well as the bought-out part count and weight as the independent variables. For assembly cost as the dependent variable, the relation was modeled to part count and fastener count as the independent variables. Both sets of results are compared with the original costs in Table 1. Also, the error is given for the percentage difference from the actuals. It can be seen that the error for each of the combined assembly stages is improved by approximately 25%, using the causal definitions of assembly coefficients, with an even higher improvement for fabrication cost. Therefore, the Genetic-Causal principle has been used to good effect in guiding the modeling process through data classification into families and by imposing causal requirements on the identification of cost drivers.

Table 1. Results of predictions for assembly time and fabrication time.

Stage	Nacelle A				Nacelle B			
	Pred	Error	MRA	Error	Pred	Error	MRA	Error
	Assembly							
1	0.96	0.00	1.44	0.02	0.67	-0.04	1.26	0.03
2	0.45	-0.06	0.27	-0.08	0.85	-0.02	0.29	-0.09
3	0.70	-0.01	-0.16	-0.04	21.9	0.07	33.2	0.11
4	1.04	0.03	0.87	-0.08	0.94	-0.02	1.30	0.11
5	0.84	-0.01	1.81	0.06	1.10	0.03	1.55	0.16
6	0.46	-0.05	0.78	-0.02	0.63	-0.04	0.51	-0.05
TOT	0.89	-0.11	0.86	-0.14	0.99	-0.01	1.27	0.27
	Fabrication							
1	1.28	0.03	1.16	0.02	1.59	0.02	1.71	0.02
2	2.05	0.06	1.72	0.04	1.35	0.05	1.36	0.05
3	0.95	-0.01	0.68	-0.04	1.22	0.04	1.20	0.04
4	0.93	-0.02	0.92	-0.02	0.92	-0.02	0.94	-0.01
5	0.98	0.00	1.07	0.01	1.11	0.03	1.11	0.03
6	0.63	-0.09	0.78	-0.05	0.42	-0.07	0.50	-0.06
TOT	0.97	-0.03	0.96	-0.04	1.05	0.05	1.06	0.06

5. Life Cycle Cost Modeling

It has been established that part count and weight are primary drivers of manufacturing cost; evident through their causal impact on fabrication and assembly cost, and material cost. However, it is likely that weight is not causally linked in terms of material but rather in terms of larger items utilizing more resource, within each product family. These relationships are also found to be true for non-recurring design cost. Just as manufacturing cost is driven by the number and total weight of the parts, these are also drivers of design effort and cost. In concurrence, one of the most commonly used parametric relation in the industry is the relation of design drawings to the cost of the design process. The implication is that more the unique parts, the costlier the design process will be. However, this principle only remains true for a significant amount of commonality within the product family.

Figure 7 illustrates some limited industrial data on the relationship between design cost and the weight and part count of airframe fuselages. Although the population size is small, it can be seen that there is strong evidence of a relation between design cost and the weight and/or part count. There is a slight improvement in the statistical significance between cost and weight, and the correlation testifies that an increase in part count is synonymous with an increase in weight. The statistical relation with either parameter was tested through regression trending, while multiple linear regression was used to improve the R^2 value by 1%, thereby also providing a third relation for a three point estimate. It is reasonable to propose that all costs arise as a result of engineering definition and that these

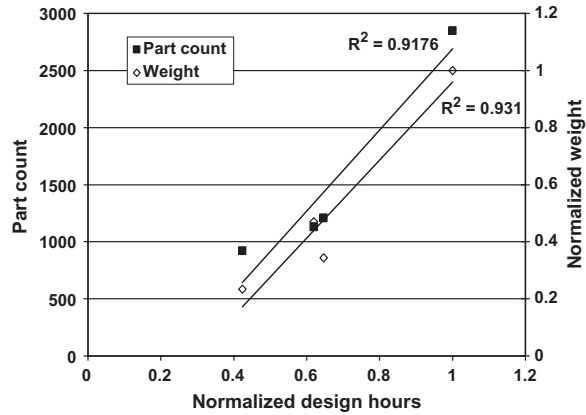


Figure 7. Design cost modeling relative to part count and weight.

are a further function of environmental and market factors. It is also noted that the complexity and originality of parts has a significant bearing on the costs. For example, a more complex and innovative part design may cost 100 h of design time while a derivative part may cost a quarter of that.

Even prior to part design, material selection is an obvious design/cost driver that impacts on manufacturability. Within aerospace, the selection of a material other than aluminum is often driven by a performance consideration such as weight reduction (composites), fire resistance (titanium) or strength (steel). Beyond process capability, the overriding limitations are material and processing costs, closely followed by manufacturing tolerances and finish, and operational life cycle performance. Therefore, it is necessary to investigate the trade-off between the cost impacts from one material over another, remembering that there may be certain additional design constraints that require the more expensive option.

Figure 8 illustrates the typical impact of material selection on the unit cost of an engine nacelle. A number of industrial examples for either metal or composite are presented along with a trend line plotting the statistical relation across the range of non-dimensional weights. In keeping with the earlier work within the article, it is again seen that weight is an indicator of manufacturing unit cost, as is part count. It is evident that unit cost is more similar for the nacelles at the lower range, towards 1 m diameter, but that the metal structures seem to be clearly less expensive for larger nacelles (toward 2 m in diameter).

One basic aim of the work is to help understand and model the impact of engineering design definition on cost. This can be related to design value, which includes both functional performance and cost, where performance has a quantitative cost impact. The direct operating cost (DOC) breakdown is presented in Figure 9 for a regional commercial jet, where the cost of ownership is triple that of the fuel burn. The significance of this is that the traditional approach of maximizing lift

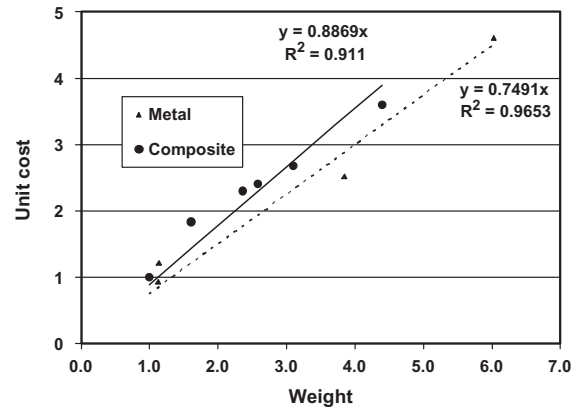


Figure 8. Unit cost relative to weight and material type.

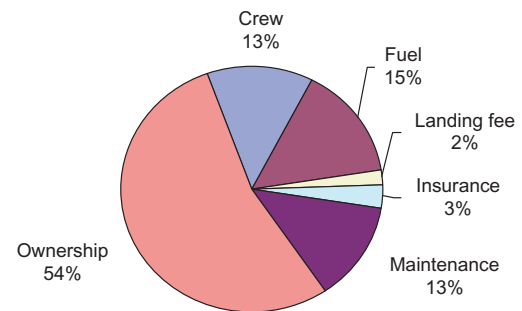


Figure 9. Direct operating cost (DOC) breakdown for a regional jet.

to drag (aerodynamics) and maximizing strength to weight (structures) is now in the context of a design specification with a cost dimension. Therefore, relative to customer requirements, it is three times more important to reduce the cost of ownership than the cost of fuel burn on its own, although that will certainly contribute to the DOC reduction.

In terms of structural design, it is inferred that a reduction in manufacturing cost will have three times the impact that a reduction in weight will. This seems an ideal analysis to apply to an engine nacelle as the challenge is whether to choose the more expensive to produce and maintain composite design or the cheaper but heavier metal design. Figure 10 incorporates the influence of material on the operational performance through a simple consideration of the impact of weight on fuel burn. The analysis simplifies fuel burn as a function of weight and consequently, there is no attempt to consider any change to the aircraft utilization or mission profile, i.e., exchanging airframe weight for passengers or fuel/distance. However, the analysis is important in providing a method of assessing design choices in terms of the operational cost impact. It is evident that there is an increasing penalty on the metal design as the diameter (size) of the fan increases. This is reasonable if one considers that a larger nacelle can better exploit the manufacturing process of composite lay-up, requiring the same cure time, etc. However, Figure 10 makes it clear that there are definite lifecycle (performance) aspects to

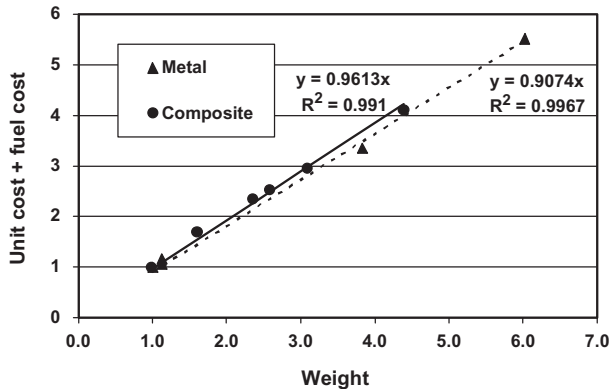


Figure 10. Relationship between life cycle cost and material type relative to weight.

be exploited as the size increases. Again, the Genetic-Causal principle has been applied to categorize into groupings and in identifying key causal drivers.

6. Discussion and Conclusion

The article presents the results of cost modeling that uses the Genetic-Causal principle to understand and develop manufacturing and life cycle models. Various elements of life cycle cost are considered according to the principle and are shown to be highly relevant to the early conceptual design process. This approach is generic in dealing with a wide range of cost elements and incorporates design definition as well as performance. The genetic aspect identified weight, part count, and fastener count as significant identifiers of cost. The analysis of the manufacturing cost breakdown showed cost to be classified according to material, part fabrication, and assembly; but also that procurement is a key driver. These engineering design parameters were then used to investigate the modeling of fabrication cost and assembly cost; material costs being modeled as a function of material cost per unit weight. However, the Causal aspect has been considered in verifying the scientific basis of the Generic relations. This has validated the use of part and fastener counts in terms of assembly but is less conclusive regarding the use of weight in part fabrication and procured items, although strongly significant in the statistical testing. However, it is believed that weight is causal in being related to the amount of manufacturing effort and resource that is expended in processing larger parts, rather than being driven by the material cost. The Causal aspect of the Genetic-Causal principle is therefore presented as one of the main contributions to cost modeling discipline, requiring the practitioner to incorporate an understanding of the true drivers, rather than simply accepting statistical and implied relations. However, this then feeds back into the genetic aspect in being able to code cost correctly into the product and process definition, underlining the scientific approach to

the cost modeling. It is concluded that process and material selection, and the resultant structural configuration design, is highly significant in determining the causal life cycle cost; through both the manufacturing cost and the operational cost. However, further research will incorporate maintenance cost as an element that will affect the analysis, currently tending to favor metals over composites.

References

1. Boothroyd, G., Dewhurst, P. and Knight, W. (1994). *Product Design for Manufacture and Assembly*, New York: Marcel Dekker Inc.
2. Prasad, B. (1996). *Concurrent Engineering Fundamentals, Volume I: Integrated Product and Process Organization*, Upper Saddle River, New Jersey: PTR Prentice Hall.
3. Prasad, B. (1997). *Concurrent Engineering Fundamentals, Volume II: Integrated Product Development*, Upper Saddle River, New Jersey: PTR Prentice Hall.
4. Curran, R., Kundu, A., Raghunathan, S. and Eakin, D. (2002). Costing Tools for Decision Making within Integrated Aerospace Design, *Journal of Concurrent Engineering Research*, 9(4): 327–338.
5. Ullman, D.G. (1992). *The Mechanical Design Process*, New York: McGraw-Hill.
6. Kundu, A.K., Raghunathan, S. and Cooper, R.K. (2000). Effect of Aircraft Surface Smoothness Requirements on Cost, *The Aeronautical Journal*, RAeS, 415–420.
7. Bashir, H.A. and Thomson, V. (1999). Metrics for Design Projects: A Review, *Design Studies*, 20(3): 263–277.
8. Ostwald, P.F. (1992). *Engineering Cost Estimating*, Prentice Hall, ISBN 0-13-276627-2, p. 576.
9. Department of Defense (1999). *Parametric Estimating Handbook*, 2nd edn, DoD.
10. Fan, I.S. (1997). Concurrent Engineering in Aerospace Extended enterprises, In: *Proceedings of the International Conference on Concurrent Enterprising*, Nottingham, pp. 307–314.
11. Porter, M.E. (1985). *Competitive Advantage: Creating and Sustaining Superior Performance*, New York: Free Press; London: Collier Macmillan, ISBN: 0029250900.
12. Gauthier, B., Dewhurst, P. and Japikse, D. (2000). Application of Design For Manufacture and Assembly Methodologies to Complex Aerospace Products, In: *Proceedings of 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*.
13. Curran, R., Raghunathan, S. and Price, M. (2004). A Review of Aircraft Cost Modelling and Genetic Causal Approach, *Progress in Aerospace Sciences Journal*, 40(8): 487–534.
14. Curran, R., Kundu, A.K., Raghunathan, S. and McFadden, R. (2003). Influence of Manufacturing Tolerance on Aircraft Direct Operating Cost (DOC), *Journal of Materials Processing Technology*, 239–247.
15. Mileham, A.R., Currie, G.C., Miles, A.W. and Bradford, D.T. (1993). A Parametric Approach to Cost Estimating at the Conceptual Stage of Design, *Journal of Engineering Design*, 4(2): 117.
16. Pugh, P. (1992). Working Top-Down: Cost Estimating Before Development Begins, *Journal of Aerospace Engineering*, 206: 143–151.

17. Herrera, A. (1998). Design for Manufacture and Assembly, a Cost Effective Tool Supporting Lean Design Initiatives, In: *Proceedings of International Forum on DFMA*.
18. Rush, C. and Roy, R. (2000). Analysis of Cost Estimating Processes used within a Concurrent Engineering Environment Throughout a Product Life Cycle, *CE2000*, Lyon, France: Technomic Publishing Co. Inc., pp. 58–67.
19. Arrow, K.J. and Arrow, S.S. (1950). *Methodology Problems in Airframe Cost-Performance Studies*, Rand Corporation Document No: RM-456-PR, p. 33.
20. Levenson, G.S. and Barro, S.M. (1966). *Cost-Estimating Relationships for Aircraft Airframes*, Rand Corporation Document No: RM-4845-PR, p. 99.
21. Curran, R., Castagne, S., Rothwell, A., Price, M. and Murphy, A. (2005). Integrating Manufacturing Cost and Structural Requirements in a Systems Engineering Approach to Aircraft Design, In: *Proceedings of the 46th AIAA Structures, Structural Dynamics and Materials Conference*, Houston, USA, Paper AIAA-2005.

Dr Richard Curran



Dr Richard Curran is a Senior Lecturer in the School of Mechanical and Aerospace Engineering at Queen's University Belfast. He teaches Aeronautical Engineering 1, Aircraft Systems Engineering 2, Design for Manufacture (DFM) 4, and Structural Optimisation 4. His research interests are focused on

Engineering Cost Modelling; Digital Manufacture and DFM, and Product Life Management (PLM). He has published over 70 internationally refereed articles. He is a member of the Economics Technical Committee of the American Institute of Aeronautics and Astronautics (AIAA). He is the General Secretary and an Executive Committee member of the International Society for Productivity Enhancement (ISPE); and is a member of the Technical Committee of the International Society of Offshore and Polar Engineering (ISOPE). He is a rolling Conference Committee Member for ISPE, ISOPE and the International Conference on Innovation and Integration in Aerospace Sciences, Belfast.

Dr Mark Price



Mark graduated with a BEng in Aeronautical Engineering from Queen's University Belfast in 1987, and an MSc in Engineering Computation in 1988. After a period as a stress engineer in Short Brothers (now Bombardier Belfast) he

returned to Queen's to undertake a PhD which he successfully completed in 1993. After a further spell of industry working on projects for Computer Aided Engineering and a brief sojourn in the financial industry he returned to Queen's to lecture in Aeronautical Engineering again in 1998. Since then he has published widely in aircraft structures, computer aided design methods and systems engineering. He is a member of the Centre of Excellence for Integrated Aircraft Technologies (CEIAT) at Queen's and his current research focus is on design integration within systems engineering.

Professor S. Raghunathan



Professor Raghunathan received his PhD from Indian Institute of Technology, Bombay in 1970, was a Postdoctoral Fellow at Loughborough University during 1970–74, was appointed as a Lecturer in Aeronautical Engineering at Queens

University, Belfast in 1974. He was promoted as a senior lecturer in 1983, Reader in 1986, Head of the School and Professor in 1995. He was appointed as Bombardier Aerospace – Royal Academy Chair in 2001. He received his DSc from Queens University in 1991.

His research interests include Transonic Aerodynamics, Wave Energy and Integrated Aircraft Technologies. His research activity on transonic flows has led to the prediction of buffet due to transonic shock oscillations on aerofoils. His original designs of self-starting and high solidity wells turbine, biplane/ contra rotating are currently in use for wave power generation, worldwide. His current research activities include nacelle and wing Aerodynamics, buffet, flow control and integrated aircraft technologies. He has been the principal investigator of over 40 research projects, supported by, EPSRC, DEL/CAST, IRTU/ InvestNI, Teaching Company, EU, Bombardier Aerospace, Tales Defence Ltd., BAE Systems and FG Wilson, has supervised over 30 PhDs and published over 250 technical papers including 100 in journals.

Professor Raghunathan has also been recognized with numerous awards and honours from organizations around the world. He has been a Fellow of the Royal Aeronautical Society since 1986. He is a Honorary Member of the American-Romanian Science and Arts Academy. He was awarded the prestigious Royal Society – ESSO Gold Medal for his research on wave energy. He was a member of Group on UK Science Mission to Japan, was a recipient of Japanese Promotion of Science Visiting

Fellowship; Royal Society, Indian Science Academy Visiting Fellowship; and a Hertz Foundation Fellowship and Northern Ireland Industrial Federation trophy. He holds a patent on Transonic Flow Control.

Dr Emmanuel Benard



Emmanuel graduated with a BSc in Theoretical and Applied Mechanics from University of Lille I (France) in 1990, and a MSc in Fluid Mechanics in 1991. He moved to University of Poitiers (France) to undertake a PhD in Experimental Hypersonics which he completed in 1998. After a year in Trinity College Dublin, he joined

Queen's University Belfast as a lecturer in Aeronautical Engineering. He is a contributor to the Centre of Excellence for Integrated Aircraft Technologies (CEIAT) at Queen's and his current research focus is on aerodynamics and heat transfer but also on some aspects of design integration.

S. Crosby



S. Crosby is currently a Research Associate in CEIAT at the School of Aeronautical and Mechanical Engineering Queen's University, Belfast for the past 4 years. He has 18 years experience as a Manufacturing Engineer – 14 years at Bombardier, Belfast (including 2 years secondment in West Virginia), 2 years at Boeing, Seattle, and

2 years at BAE Systems, Warton England. He received his MSc in Manufacturing: Management & Technology through the Open University, UK. He is pursuing his part-time PhD in the aerospace application of virtual manufacturing technology creating a fully integrated digital solution for manufacturing and production functions through the use of scheme models.

Sylvie Castagne



Sylvie Castagne obtained her masters in Applied Physics Engineering (Ingénieur Civil Physicien) from the University of Liège (Belgium) in 1998. From 1998 to 2003 she was a researcher at the Department of Mechanics of Solids and Materials at the University of Liège where she completed a DEA (Diploma of Advanced

Studies) in Applied Sciences in 2001. Her research field was the modelling of metal forming processes and the development of finite element models for the analysis of damage and crack propagation in metals at high temperature.

Since October 2003 Sylvie is a research fellow at the Centre of Excellence for Integrated Aircraft Technologies at the Queens University Belfast where her present interests focus on systems engineering and cost modelling.

Dr Paul Mawhinney



Dr Paul Mawhinney is a research fellow at the Centre of Excellence for Integrated Aircraft Technology in Queen's University Belfast. He graduated with a BEng (Hons) degree in 2001 in Aeronautical Engineering from Queen's University Belfast and has since obtained a PhD in 2005. His doctorate was on the integration of

CAE methods for the aircraft design process in particular the aspects involved in the airframe design process. He specializes in the development of automated analysis driven design tools and approaches allowing CAE integration. He is currently working on methods to allow the integration of geometry based analysis methods into multi-disciplinary design frameworks.