Predicting production costs for advanced aerospace vehicles

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ABSTRACT

For early design concepts, the conventional approach to cost is normally some kind of parametric weight-based cost model. There is now ample evidence that this approach can be misleading and inaccurate. By the nature of its development, a parametric cost model requires historical data and is valid only if the new design is analogous to those for which the model was derived. Advanced aerospace vehicles have no historical production data and are nowhere near the vehicles of the past. Using an existing weight-based cost model would only lead to errors and distortions of the true production cost.

This paper outlines the development of a process-based cost model in which the physical elements of the vehicle are costed according to a first-order dynamics model. This theoretical cost model, first advocated by early work at MIT, has been expanded to cover the basic structures of an advanced aerospace vehicle. Elemental costs based on the geometry of the design can be summed up to provide an overall estimation of the total production cost for a design configuration. This capability to directly link any design configuration to realistic cost estimation is a key requirement for high payoff MDO problems.

Another important consideration in this paper is the handling of part or product complexity. Here the concept of cost modulus is introduced to take into account variability due to different materials, sizes, shapes, precision of fabrication, and equipment requirements. The most important implication of the development of the proposed process-based cost model is that different design configurations can now be quickly related to their cost estimates in a seamless calculation process easily implemented on any spreadsheet tool.

INTRODUCTION

The Multidisciplinary Optimization (MDO) Branch at NASA Langley Research Center has been a leader in developing methodologies for design and analysis of complex engineering systems that exploit the synergism of mutually interacting phenomena. (Giesing 98, Zang 99, Walsh 00) While fluid dynamics and structural design remain the major areas of emphasis, acquisition costs that include production and assembly have lately been receiving more and more attention from the MDO research engineers. The problem that these research engineers are facing is the same one that the aerospace industry, just like any commercial industry, is facing: how to consider acquisition cost in the design process so that cost can be truly claimed as having played a role in the multidisciplinary optimization solution. Acquisition cost has a pervasive influence over all design alternatives. Life cycle cost has, and should be considered as having, an even more influential impact on the design of a product, particularly in the current environment where societal pressures such as cultural, gender, and ecological issues are of utmost importance. Cost is a difficult quantity to derive unless all details of materials, processes, and human efforts associated with the production of a product are known. At the conceptual design level, the details of production indicated above are sparse and, quite often, just not available or even non-existing. Yet it has been factually recognized by the research community that almost 70% of the product life cycle cost is committed at the early design stage, and that preliminary design decisions affect cost the most. (Stewart 82) What are then the available options for research engineers to incorporate cost considerations into their preliminary designs? This paper attempts to suggest a viable solution for this problem after a brief review of cost modeling alternatives.

REVIEW OF COST MODELING

Cost is an important parameter in all design considerations. There are so many cost models discussed in the open literature that it is impractical to mention all of them in this paper. The interested readers are referred to the following texts for general purpose cost models: Oswald 92, Stewart 91, and Greer 90. The space Systems Cost Analysis Group maintains a web page where a list of cost estimating models for aerospace and advanced systems is provided. (Pine 99) Bao (Bao 00b) categorized cost models into three appropriate groups for each of the three phases in the life cycle of a product: conceptual, development, and production. Figure 1 summarizes the appropriate cost models for each of these three phases.

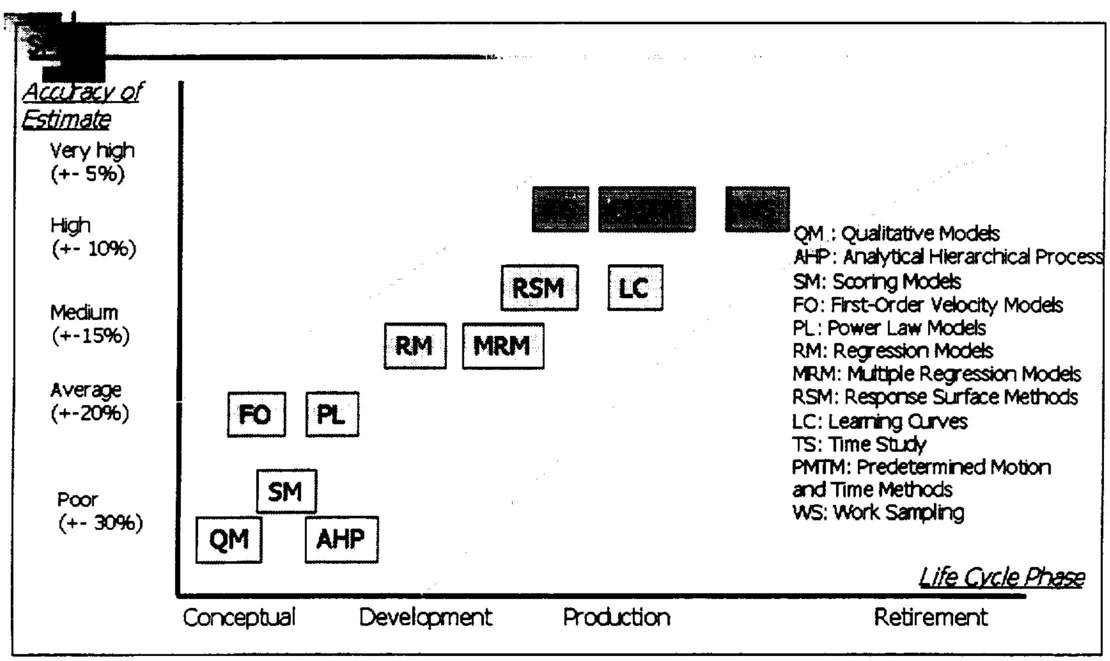

Figure 1. Cost models for various phases of life cycle (Bao 00b)

A number of cost models have been made a part of a global development system. For example, an integrated product development system has been proposed for the wing structural design of the high-speed civil transport. (Marx 94). Methodologies have been developed to integrate manufacturing costs with design. (Noton 91, Mabson 96, Clifton 98, DOD/NASA 83) Life cycle costing has been discussed at great length in many publications. (Apgar 93, Eberling 94, Dell'Isola 81)

For early design concepts, the conventional approach to cost is some kind of parametric weight-based cost model One of the most often quoted production cost trade-off equation comes from the Lockheed Martin PRICE H parametric cost model and is reproduced here. (Price H)

$$COST = (Weight^{a}.b) + \frac{Weight.c}{Q} \qquad \text{(eq.1)}$$

Where a is material cost; b is manufacturing complexity based on combination of material, processes, precision, and number of parts made; c is tooling cost based on material type and fabrication technique; and Q is the quantity of parts made.

There is now ample evidence that this approach can be misleading and inaccurate. By the nature of its development, a parametric cost model requires historical data and is valid only if the new design is analogous to those for which the model was derived. Advanced aerospace vehicles have no historical production data and are nowhere near the vehicles of the past. Using an existing weight-based cost model would only lead to errors and distortions of the true production cost. The need for a new type of cost model that is accurate as well as "sensible and intuitive" is therefore badly needed to help the design community to quickly, that is at minimum effort, derive cost based on design features. By "sensible" it is meant to indicate that, of all the processing steps involved in the production of a product, there must be one particular production step where most of the total cost comes from. For example, in the machining of a part the bulk of the cost is due to the machine operation itself. Therefore, if one knows the cost of that machining step, then one already should have a good estimate of the total cost of the operation. By "intuitive" it is meant to indicate that cost must be mostly related to some specific physical characteristic of the product. For example, the cost of painting must be more related to the painting surface than anything else. Therefore painting surface should be used as the independent parameter. For some other processes, it may be the length of the part. And for other products, it could be their volume. The concept of a new theoretical cost model based on features briefly explained above has been in the works at MIT for the last ten years or so. (Gutowski 91, Neoh 95, Hoult 96) This theoretical cost model known as *first order process velocity model* provides the foundation for the current effort at the MDO Branch at NASA Langley Research Center to establish a methodology to incorporate cost in the multidisciplinary optimization of advanced vehicle design. The development of a new concept – we call this concept *cost Modulus* - is also provided in this paper to address the issue of part complexity. Together with the process velocity model, cost modulus is expected to be a simple yet versatile tool to predict the production cost of any new space vehicle. In the rest of this paper, the first order process velocity model is first introduced then followed by a presentation of the cost modulus concept. Next, the two primary premises for cost prediction as advocated in this paper are brought together in a demonstration of the cost prediction for the rib of a concept vehicle known as the Blended Wing Body. The paper concludes with remarks regarding future work of the MDO Branch as far as cost optimization is concerned.

PROCESS VELOCITY MODEL

This cost model was first published in a paper by the research group at the Laboratory for Manufacturing and Productivity at MIT. (Gutowski 94) Details of this cost model were further elaborated in a Ph.D. thesis. (Neoh 95) It was born out of an observation that many human and machine activities can be represented by simple dynamic models indicated by the following equation:

$$V = V_0(1 - e^{\frac{-t}{\tau}}) \quad \text{(eq. 2)}$$

where V, the process velocity, has the dimension of λ/time with λ representing the appropriate variable for the process under consideration, and time t is the process time. V_0 is the steady-state process velocity, and τ is a time constant to capture the delay in attaining the full speed and should be related to the setup of that process. As indicated by Gutowski, λ could be a length, an area, or a volume, so long as it is the dominant parameter that affects process time.
The process velocity, V, can be equated to the time derivative of λ, i.e. V=dλ/dt. λ can therefore be obtained by integrating V over time, resulting in:

$$\lambda = V_0[t - \tau(1 - e^{\frac{-t}{\tau}})] \quad \text{(eq. 3)}$$

t is the quantity sought after. Unfortunately, equation 3 cannot be inverted explicitly for t. However two simple approximations are possible depending on the value of t relative to τ:

a. For t << τ : $t \cong \sqrt{(2\tau\lambda)/V_0}$

b. For t >> τ : $t \cong \tau + \dfrac{\lambda}{V_0}$

The above approximations could be combined into a single hyperbolic relation shown below, as suggested by Mabson (in reference Proctor 96):

$$t = \sqrt{(\lambda / V_0)^2 + (2\tau\lambda / V_0)} \quad \text{(eq.4)}$$

The implication of equation 4 is that process time t is simply related to λ, the dominant geometrical feature of the part, through two parameters V_0 and τ. The accuracy of this model has been validated in the MIT study (Gutowski 94) as well as for machining data at Boeing Corporation. (Metschan 00). It has also been pointed out that equation 4 is valid for a wide range of manufacturing processes from painting to carpet laying to hand layup of epoxy fiberglass composite. Thus such an expression for process time is universal and seemingly related to one of the physical features of a part. From an MDO standpoint it means that, at the conceptual design stage, that particular feature could be easily extracted from the CAD model of the product and the cost of production could be derived directly from the equation. Thus sensitivity studies could be made to determine the impact of design features on cost.

COST MODULUS

Cost modulus is a relative cost index to compare the cost of a design to some standard reference design for which cost is known. The use of this particular type of cost index is restricted to the methods of production that are intimately related to the design of the part as far as the choice of its material, size, shape, dimensional precision, and equipment requirements are concerned. Therefore cost modulus is to be considered as a design consequence, and it should be derived on the basis of engineering data known for the materials and processes. That way, cost modulus has a scientific basis and can be adopted universally since it is independent of "local" influences such as factory location and burden rates. The underlying work toward the formulation of a cost modulus for machined parts is contained in a Ph.D. thesis at Old Dominion University. (Kulkarni 01) For example, for a part submitted primarily to milling operations, its cost modulus involves the following coefficients:

C_v : Size coefficient
C_{pn}: Shape coefficient related to tool setting
C_{prt}: Tolerance coefficient related to Precision
C_{mtr}: Material coefficient related to rough cut
C_{mtt}: Tool material coefficient
C_{pv} : Shape coefficient affecting process velocity
C_{pw}: Shape coefficient related to work setting
C_{prs}: Tolerance Coefficient related to SF
C_{mtf}: Material coefficient related to finish cut
C_e: equipment coefficient

Derivation of each of the above coefficients is available in Kulkarni 01. Together with known percentages (P_s, P_t, P_f, and P_n) from the detailed process plan of the reference object, the final formulation of the cost modulus for a part machined by milling is given as:

$$C_m = \frac{C_{act}}{C_0} = \left[\frac{\left(\left(\frac{C_v}{C_{pv} C_{mtr}} + \frac{P_f P_s}{C_{mtf}} \right) C_{prs} + (1+P_f)(P_{nt} C_{pn} + P_{nw} C_{pw}) \right)(1 + P_t C_{mtt}) C_e C_{prt}}{(1+P_f)(1+P_n)(1+P_t)} \right]$$

(eq.5)

where C_m is the cost modulus of the part, and C_0 is the cost of the reference object. P_s, P_t, P_f, and P_n are respectively the area to be machined as a percentage of the area to be machined in the reference object, the tooling cost as a percentage of the machining cost, the finishing machining time as a percentage of the rough machining time, and the non-productive time as a percentage of the total rough machining time. P_n is further decomposed into P_{nt} and P_{nw} respectively for non-productive time due to tool and due to work piece. It should be indicated that these percentages P, except for P_s, are all about the reference object, and they should be well defined by now, being known quantities in the process plan of the latter. Equation 5 is essentially a close loop equation that translates design specifications into a single 'cost' related parameter. If the absolute cost of the reference object is known, then the cost of the designed object can be determined by multiplying its cost modulus by the reference object's cost. While this equation has been derived strictly for a machining operation, it also provides a general framework to tackle the cost estimation of any kind of object. In that sense, cost modulus is a truly universal concept of cost estimation based on the operations of manufacturing. Finally, while equation 5 may look complicated, all of its elements, i.e. the C's and the P's, should be readily recognized by people who are knowledgeable in machining technology. In the simplest application, for example when the designed part is no different than the reference object, then all the C terms become equal to 1 and, with P_s also equal to 1, equation 5 boils down to C_m equal 1, as expected. In the case of a design still in its conceptual phase, many of the manufacturing decisions are not known yet, but equation 5 can still be useful simply by giving a value of 1 to any of the coefficients that are still in doubt. Later on, when details are available, these coefficients could be specified in greater accuracy. In other words, a close loop cost estimation equation like equation 5 can be used in multiple phases of the product. Thus it is truly a flexible and universal tool for cost estimation. Cost prediction will be more accurate as more details of manufacturing are available.

CASE STUDY

The Blended Wing Body (BWB) is a revolutionary aircraft concept being explored by NASA as a future configuration for passenger and airfreight transportation. It has a hybrid shape resembling a flying wing, with passengers and cargo located within the center body of the aircraft. Because of its unique configuration, the BWB offers high lift and minimum drag, highlighting its potential for improved fuel economy of up to 20% compared to current jet liners with similar passenger and cargo capacity. It is designed to take off and land at existing commercial runways. Figure 2 shows the functional arrangement of the BWB.

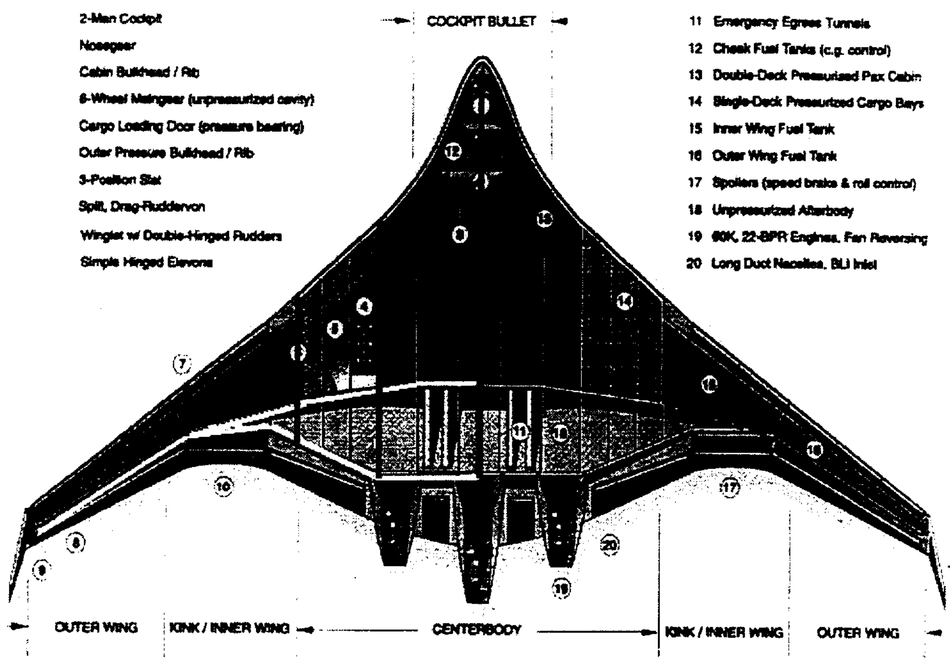

Figure 2. Functional arrangement of BWB

The estimation of the total cost of such an aircraft is a daunting task and, at the present time, we are nowhere near its resolution. What is currently available is a shell of the aircraft, and the focus is on an assessment of the aerodynamic properties of the external shape of the BWB. No detail of the internal structure is known yet. Nevertheless, a preliminary study is going on at NASA LaRC to begin a process of cost estimation for at least the principal structural elements of the aircraft such as front spars, rear spars, skins, etc... The methodology that has been adopted is explained in figure 3 below.

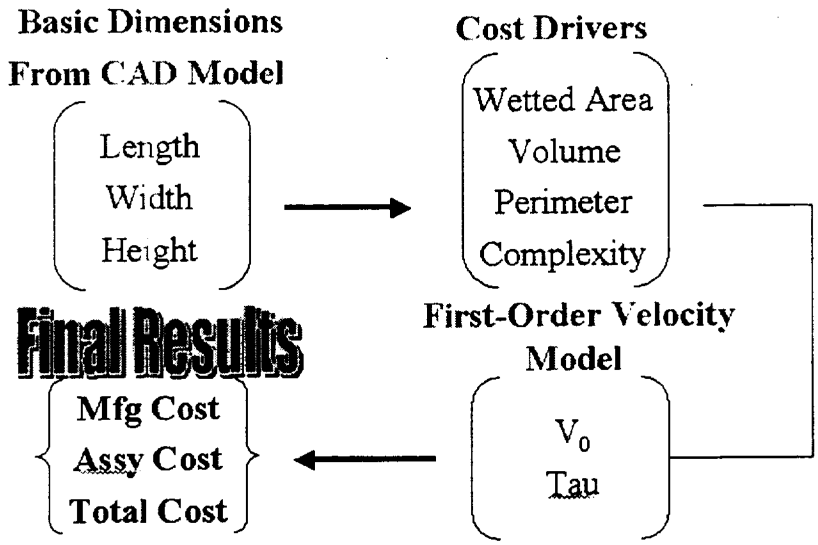

Figure 3. Overview of process-based cost modeling

The CAD model of the BWB is first exported as an IGES file. The IGES file is next imported into Solidworks™, a solid modeling tool with capability for writing macros in visual basic. Essentially these macros create imaginary surfaces at set distances from the centerline of the BWB, and then set out to determine the intersections between these surfaces and the shell of the BWB. The surfaces are selected to coincide with the junctions between the various sections of the BWB, notably passenger compartment, cargo compartment, inner wing, and outer wing. Another visual basic program creates the intersection points between the different contours of the intersections with vertical lines where the spars are supposed to be. Finally a last program transfers the coordinates of the intersection points to a spreadsheet where the following calculations are made: 1- Areas and perimeters of front spars, front rears, aft rears, and skins, and 2- Areas and perimeters of ribs. Based on values of V_0 and Tau derived previously (Bao 00a) the manufacturing cost and the assembly cost of each structural element can be determined through the process velocity cost model. The cost of the BWB limited to only spars, ribs and skins can be determined by summing up the cost of each structural elements. The process described above is summarized in figure 4.

COMBINING PROCESS VELOCITY MODEL WITH COST MODULUS

As indicated above, the V_o and Tau values used so far to determine the cost of each structural element were based on current manufacturing data for these components. For a new structure, it is conceivable - in fact expected - that the V_o and Tau for it would be different from values for previous structures. There are two ways to deal with the problem: a- Start from scratch and, through experimentation, determine the new and appropriate V_0 and Tau; or b- Use the same V_0 and Tau to arrive at a baseline cost for that structure first, then use the cost modulus concept to modify its value. It is quite obvious that the first option is really not viable due to too much human effort and time required to conduct the experiment. The cost modulus approach is therefore the only option left. As indicated previously, equation 5 provides a framework to determine the cost modulus of any structural component submitted to machining. There are five factors that affect the cost modulus: predominant variable or size, shape, precision, material, and equipment. Each of these five factors

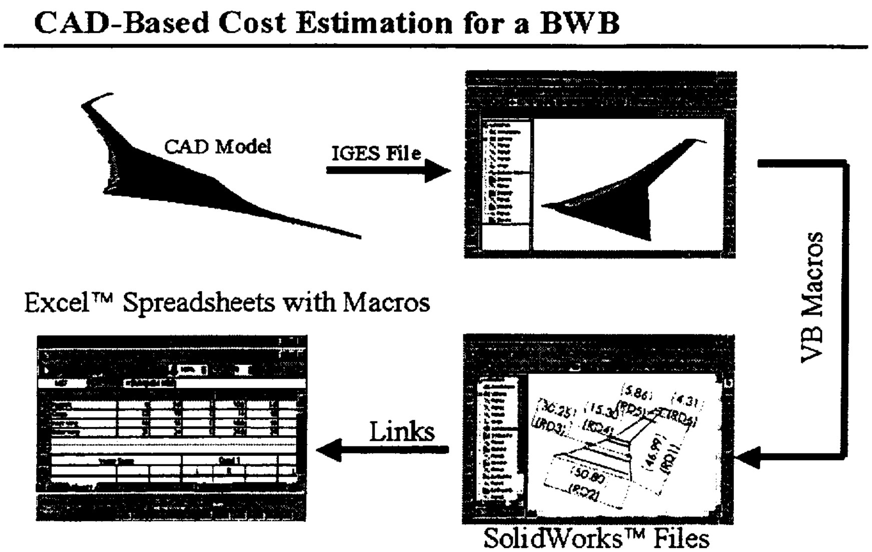

Figure 4. Interfacing a CAD file with Solidworks™ and a spreadsheet

results in a series of coefficients labeled as C coefficients in equation 5. Table 1 below summarizes the impacts of these C coefficients.

Table 1a. Impact of design specification on machining process

No	Description	Notation	Related Design Specification	Process Impact	Cost Effect Variable
1	Predominant Variable OR Size Coefficient	C_v	Change in Volume	Machined Volume	Productive Process Time - Roughing
2	Cost Coefficient - Shape, Process Velocity	C_{P_v}	Shape	Process Velocity	Productive Process Time - Roughing
3	Cost Coefficient – Shape. Tool Settings	C_{P_n}	Shape - Number of Features	Tool Setting Time	Non-Productive Time
4	Cost Coefficient – Shape. Work Settings	C_{P_w}	Shape - Faces to be Machined	Work Setting Time	Non-Productive Time
5	Cost Coefficient – Precision. Tolerance	C_{Rt}	Precision – Dimensional Tolerance	Processing Time. and Equipment Cost	Total Cost before tolerance correction

Table 1b. Impact of design specification on machining process (Continuation)

5	Cost Coefficient – Precision, Tolerance	C_{pr_t}	Precision – Dimensional Tolerance	Processing Time, and Equipment Cost	Total Cost before tolerance correction
6	Cost Coefficient – Precision, Surface Finish	C_{pr_s}	Precision – Surface Finish	Process velocity – Finish Cut	Productive Process Time - Finishing
7	Cost Coefficient – Material, Rough Cutting	$C_{mt_{rv}}$	Material	Process Velocity – Rough Cut	Productive Process Time Roughing
8	Cost Coefficient – Material, Finish cutting	$C_{mt_{fv}}$	Material	Process Velocity – Finish Cut	Productive Process Time - Finishing
9	Cost Coefficient – Material, Tool Cost	C_{mt_t}	Material	Tool Replacement	Tooling Cost
10	Cost Coefficient – Equipment Factor	C_e	Physical Size	Equipment Size	Equipment Setup Cost

To provide a simple illustration, let's consider a rib, say the one between the inner and outer wing. From the CAD model, its area and perimeter are respectively 52.78 ft^2 and 20.89 ft. Assuming the material is conventional 7000 series aircraft aluminum and other data available in (Bao 00a), the process time using equation 4 comes out to be 17,872 min. Suppose for the new design that the only thing changed is a different type of material, say aluminum lithium, presumably to increase stiffness and decrease weight a little bit. Then, according to table 1, the C parameters affected would be C_{mtrv}, C_{mtfv}, and C_{mtt}. C_{mtrv} is the ratio of specific cutting power of the reference object over that of the design object. Using standard machinability handbooks, it could be determined to be about 0.90. C_{mtfv} is the ratio of material removal rate of the design object over that of the reference object. It could be determined to be 0.95. C_{mtt} is related to the tool life of the tool. It is equal to the ratio of the product of speed, feed, and depth of cut of the design object over the product of speed, feed, and depth of cut of the reference object. Practically it is the same as C_{mtfv}. Hence its value is also 0.95. The values of C_{mtrv}, C_{mtfv}, and C_{mtt} can be fed into equation 5 to determine the cost modulus. Finally, assuming the same proportions of P_f, P_t, and P_n of respective values of 0.2, 0.3, and 0.1, the final value of C_m turns out to be 1.08. Practically, it means that the rib made out of aluminum lithium would cost 1.08 times the cost of an equivalent rib made out of conventional aluminum. This example is simple, but it demonstrates a viable approach to assess cost directly based on the design requirements and the extensive manufacturing database of currently known processes.

CONCLUSION

In this paper, two new concepts have been put forward: Process velocity and cost modulus. The process velocity model initiated by work at MIT through a NASA contract (NASA 89) advocates the use of simple first-order dynamic models for the most influential process steps in the sequence of production. The MDO Branch at NASA LaRC has adopted this model as a basis for cost modeling of advanced vehicles. Current work involves the expansion of this basic model to production activities beyond machining. The second concept is cost modulus. Essentially it is an index of the cost of a design compared to some reference design for which production and cost data are known. The reader might think that cost modulus is simply a substitute for the manufacturing complexity index, the so-called MCPLXS index in the PRICE H system often quoted in papers related to process costing. Ultimately, both cost modulus and MCPLXS serve the same purpose, which is to provide a means of capturing the manufacturing complexity of a design. But the big difference comes from the way each of these indices were derived. In the case of MCPLXS, the index was based on very general notions of precision of fabrication, machinability of material, difficulty of assembly, number of parts and specification profile. On the other hand, cost modulus is much more specific and directly related to the design features such as size, shape, precision, material and equipment needs. Another important aspect of cost modulus is the fact that it can be used for all phases of the design from conceptual to development to production. The more details one has, the more accurate the cost modulus index can be. From an MDO standpoint, the development of a process-based cost model plus the availability of the cost modulus formulation means that there is now a capability to carry out sensitivity analyses using cost as an objective function. Much more work remains to be done as we have barely scratched the surface with this type of approach.

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REFERENCES

(Apgar 93) "Design-To-Life-Cycle-Cost", Apgar, H., AIAA/AHS/ASEE Aerospace Design Conference, Feb 1993, Irvine, CA.

(Bao 00a) "Affordable Design: a Methodology to Implement Process-Based Manufacturing Cost Models into the traditional Performance-Focused Multidisciplinary Design Optimization", Bao, H.P., and Samareh, J.A., 8th AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Long Beach, CA, September 2000.

(Bao 00b) "In-Depth Survey of Cost/Time Estimating Models", Bao, H., Seminar at MDO Branch, NASA LaRC, July 17, 2000.

(Clifton 98) "Inputs for Successful Target Costing", Clifton, B. and Townsend, W., DE-Vol.99/MED-Vol. 7, Applications of Design for Manufacturing, ASME 1998, pp.21-27

(Dell'Isola 81) Life Cycle Costing for Design Professionals, Dell'Isola, A.J. and Kirk, S.J., McGraw-Hill Pub. 1981.

(DOD/NASA 83) DOD/NASA Advanced Composite Design Guide 1983

(Ebeling 94) "Operations and Support Cost Modeling of Conceptual Space Vehicles", Ebeling C., NASA Research Grant NAG-1-1327, Annual Report 1994.

(Greer 90) Cost Analysis and Estimating, Greer Jr., W. R. and Nussbaum, D. A., Editors, Spring-Verlag Pub.1990.

(Giesing 98) "Summary of Industry MDO Applications and Needs," Giesing, J., and Barthelemy, J.-F. M., AIAA Paper 98-4737, 7th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, St. Louis, MO, Sep. 1 – 4, 1998. (Available electronically at http://techreports.larc.nasa.gov/ltrs/ltrs.html)

(Gutowski 94) "Development of a Theoretical Cost Model for Advanced Composite Fabrication", Gutowski, T., Hoult, D., Dillon, G., Neoh, E-T, Muter, S., Kim, E., and Tse, M., Composite Manufacturing, Vol. 5, No. 4, 1994, pp. 231-239.

(Kulkarni 01) "Generic Cost Estimation Framework for Design and Manufacturing Evaluation", Kulkarni, U.A., Ph.D. Thesis, Department of Mechanical Engineering, Old Dominion University, Fall 2001.

(Marx 94) "Integrated Product Development for the Wing Structural Design of the High Speed Civil Transport", Marx, W.J., Mavris, D.N., and Schrage, D.P., 5th AIAA/USAF/NASA/ OAI Symposium on Multidisciplinary Analysis and Optimization, Florida, 1994.

(Mabson 96) "Cost Optimization Software for Transport Aircraft Design Evaluation (COSTADE)", Mabson, G.E., Ilcewicz, L.B., Graesser, D.L., Metschan, S.L., Proctor, M.R., Tervo, D.K., Tutle, M.E., and Zabinsky, Z.B., NASA Contractor Report 4736, 1996

(Metschan 00) "Validated Feasibility Study of Integrally Stiffened Metallic Fuselage Panels for reducing Manuacturing Costs", Metschan, S., NASA/Cr-2000-209343 Report.

(NASA 89) Advanced Composite Technology Program, Contract C NAS1-18889

(Neoh 95) "Framework for Estimating Fabrication Time of Advanced COmposites Manufacturing Processes", Neoh, E.T., Gutowski, T., and Dillon, G., Proceedings of 40th International SAMPE Symposium and Exhibition, Anaheim, CA, 1995.

(Noton 91) "Manufacturing Cost/Design Trade-Off Methodology", Noton, B.R., Proceedings of Japan-U.S. Composite Materials Conference, Tokyo, 1981.

(Pine 99) "Abstracts of Cost Estimating Models", Space Systems Cost Analysis Group, web page: http://www.sscag.saic.com

(Price H) The PRICE Hardware Estimating Model, a Lockheed Martin Product.

(Proctor 96) "Cost Optimization Software for Transport Aircraft Design Evaluation (COSTADE): Process Cost Analysis Database (PCAD), Proctor, M.R., Metschan, S.L., and Klein, H.S., NASA Contractor report 4739, 1996.

(Oswald 92) Engineering Cost Estimating, Prentice-Hall Pub. 1992

(Stewart 91) Cost Estimating, 2nd Edition, John Wiley & Sons, Inc., New York, 1991.

(Walsh 00) "Multidisciplinary High-Fidelity Analysis and Optimization of Aerospace Vehicles, Part 1: Formulation," Walsh, J. L., Townsend, J. C., Salas, A. O., Samareh, J. A., Mukhopadhyay, V. and Barthelemy, J.-F.,AIAA Paper 2000-0418, 38th AIAA Aerospace Sciences Meeting & Exhibit, Reno, NV, Jan. 10-13, 2000.(Available electronically at http://techreports.larc.nasa.gov/ltrs/ltrs.html)