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A knowledge-based system integrated with numerical analysis tools for aircraft life-cycle design

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Abstract

An integrated design and manufacturing approach allows economic decisions to be made that reflect an entire system design as a whole. To achieve this objective, we have developed and utilized integrated cost and engineering models within a focused design perspective. A framework for the integrated design of an aircraft system with a combined performance and economic perspective is described in this article. This framework is based on the concept of *Design Justification* using a Design-for-Economics approach. We have developed a knowledge-based system that can be used to evaluate aircraft structural concept material and process selections. The framework consists of the knowledge-based system, integrated with numerical analysis tools including an aircraft performance/sizing code and a life-cycle cost analysis code. Production cost estimates are applied for evaluation of process trades at the subcomponent level of design. Life-cycle cost estimates are used for evaluation of process trades at the system level. Results of a case study are presented for several advanced wing structural concepts for a future supersonic commercial transport aircraft. Cost versus performance studies indicate that a high-speed civil transport aircraft with a hybrid wing structural concept, though more expensive to manufacture than some homogeneous concepts, can have lower direct operating costs due to a lower take-off gross weight and less mission fuel required.

Keywords: Aircraft Design; High-speed Civil Transport; Knowledge-based System; Life-cycle Cost

1. INTRODUCTION

Aircraft designs can be evaluated with several well-known and common metrics. Aircraft take-off gross weight, component weights, wing tip deflections, and flutter boundaries are common examples of product metrics used to evaluate alternative structural design concepts. Product metrics, in the aerospace industry, are often numerically defined as an "objective function" that is a weighted sum of several aircraft design variables (e.g., take-off gross weight, fuel weight, approach speed, take-off field length, etc.). The emerging field of multidisciplinary design optimization (MDO) is developing complex mathematical techniques for optimizing systems and subsystems using various formulations of such objective functions.

Process characteristics are not as easily quantified as typical aircraft product characteristics. Complex choice problems, such as the selection of a manufacturing process or a set of manufacturing processes for an aircraft component, are frequently not characterized by a unique, optimal solution that can be procedurally calculated. The utility of a solution and its consequences on subsequent decisions can be used as a process metric to evaluate complex choice problems. However, in the budget-constrained and affordability-oriented aerospace industry of today, the process metric of choice is "cost." The term "cost" implies many concepts, each of which may be best suited to evaluate a particular part of a production model. Hence, we will make the explicit assumption that, for the application described in this article, the utility function for process metrics is sufficiently represented by cost. Later, we will use a case study

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to show that our "cost" utility function is not *reduced* to a single-unit production cost, but actually *expanded* as life-cycle cost (LCC) to capture and quantify the effects of process and material selections on aircraft operating costs, a direct utility function of the airline operating the aircraft.

The integration of manufacturing considerations into the design process is a technical challenge that implicitly poses several questions:

1. What type of manufacturing knowledge can be processed during the aircraft conceptual and early preliminary design levels?
2. To what depth must the manufacturing knowledge extend to sufficiently reflect production cost differentials due to advanced material or processing alternatives?
3. What metrics are necessary to evaluate product designs in terms of their process characteristics?

In the past several years, knowledge-based systems (KBS) have been developed for specialized applications in the aerospace industry. However, the domains were limited in scope, often for evaluation of a particular part, such as an aircraft flap. The restricted scope of application for such KBS is a direct consequence of the fact that the knowledge required for these systems can be associated with what is typically referred to as the detailed design stage. Several disciplines in both the fields of design and manufacturing separately become involved with any integration development. Many knowledge-based techniques and systems have been developed for providing producibility guidance to the designer (Pecora et al., 1985; Zumsteg et al., 1985; Fisher, 1989; Rao et al., 1990; Messimer & Henshaw, 1994; Warburton & Glatfeltner, 1995), for determining the cost implications of structural design decisions earlier in the design process (Metschan et al., 1992; Mabson et al., 1994), and for design-to-cost applications (King, 1992; Meisl, 1992; Apgar, 1993; Lee, 1993). Current efforts of the Defense Manufacturing Council (DMC) are focusing on making cost an independent design variable in the design and optimization process itself.

No systems have been developed that can function with integrated engineering and cost models. None were meant to be utilized during the aircraft conceptual or early preliminary design stages to improve an aircraft *system's* economic viability. The use of cost models concurrently with design models creates many technical challenges, including the issues of data fidelity and the mapping between product and process design variables. Data fidelity, in this respect, is a concern because current cost models cannot sufficiently represent the use of advanced materials and processes such that the aircraft designer can determine production or life-cycle cost implications. Cost drivers have mainly been associated with *product* design features. This is primarily due to the fact that existing cost models are based only on *product* design variables. There is a definite need for higher fidelity cost models earlier in the design process.

Most aircraft designs of the past have been designed with performance as the main objective function; however, this is no longer possible in today's marketplace. The emphasis on lowering all aspects of LCC is leading to the development of new techniques to address LCC early in the design process. For example, a recent publication from the National Research Council (NRC, 1995) included a technology research agenda for Information Technology for Manufacturing. The agenda states that designers would greatly benefit from tools that would help them evaluate trade-offs (e.g., between cost and performances, between long-term operating and initial costs, etc.) in a rigorous and systematic manner. It is essential to develop tools that support analysis of the off-nominal behavior that results from manufacturing inaccuracies or deliberate variations introduced into a generic design. The integrated design system we have developed was structured to facilitate parallel trade-offs between cost and performance. This represents a significant step towards integrating aircraft design and manufacturing.

The fundamental difficulties involved in developing an integrated design system are related to knowledge content and process evaluation metrics. Knowledge acquisition is also an issue. Once the required knowledge was identified, its acquisition through research, company visits, and phone interviews was a time-intensive, yet required, development step. Most information and knowledge concerning the aircraft manufacturing process is informally, if at all, recorded, subjective, and partially judgmental. The largest obstacle for incorporating manufacturing technologies into the aircraft design process is devising a suitable reasoning/inferencing system to control the information flow between the various disciplines (Saggu, 1992).

The structural design of the High-Speed Civil Transport (HSCT) wing was chosen as the focus for this project. More opportunities for weight reduction exist in the wing than the fuselage of the HSCT (Velicki, 1995). Most of the weight savings will be incurred in the skin panels, since they comprise more than half of the primary wing structural weight. The wing planform is heavily constrained by the HSCT mission requirements, leading to little or no flexibility for weight reductions through wing size or shape changes. Therefore, the majority of the weight reductions will only be achieved through the use of advanced materials and processes. This scenario represents an ideal case study to show the advantages and disadvantages of material and processing alternatives through cost versus performance studies.

The purpose of our research is to provide a method for further understanding a particular element of the aerospace systems design space. The more the design space can be explored, interpreted, and comprehended, the more effectively a total aircraft development plan can be managed. The approach that we have taken to achieve this objective was not solely the improvement of the aircraft design process. We wanted to provide useable knowledge of the production functions to the designer for evaluation in conceptual and early preliminary design. For the case of integrating design

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and manufacturing, the most logical starting point is to select a certain body of knowledge, embody it in a functional design tool, and facilitate its use with other design tools.

2. APPROACH

Traditional design procedures often fail to capture the relevant information and factors necessary to justify investment in a particular technology for production. An approach, developed by Noble and Tanchoco (1993), proposes the consideration of the system justification concurrently with its design. With such a technique, it is possible to design a system and, from an economic standpoint, justify its development and implementation. The theory was originally proposed for the design of manufacturing systems, but we have tailored and applied it to the integrated design and manufacturing of an aircraft.

An integrated design and manufacturing approach should allow economic decisions to be made that can reflect the entire system design as a whole. To achieve this objective, integrated cost/engineering models must be developed and utilized within a focused design perspective. Our framework for the integrated product/process design of an aircraft system with a combined performance and economic perspective is described in this section. The framework is based on a Design-for-Economics approach. The existing Design-for-Economics approach, proposed by Noble and Tanchoco, was used as the governing framework. We have extended it to accommodate a specific application of Integrated Product/Process Development (IPPD).

2.1. Design for economics: A conceptual approach

The economic justification of a design is the determination of whether a particular action or decision is justifiable based upon its economic consequences. *Design Justification* is a term from Noble and Tanchoco (1990) used to describe a design process in which the economic ramifications of design decisions are considered concurrently with design development and are used to guide the design process to result in an economically feasible solution that meets the mission and performance requirements of the design. *Design Justification* is a central concept in our approach.

2.2. An IPPD approach for *design justification*

Figure 1 shows a traditional design and justification process while Figure 2 illustrates the *Design Justification* process. Typically, design economics are not evaluated until a design concept is relatively mature. At this point, most of the concept's incurred costs have been fixed. The *Design Justification* process, on the other hand, requires simultaneous performance and economic evaluations for the aircraft systems. While both design practices have similar constituents, there are three major differences in the underlying philosophies:

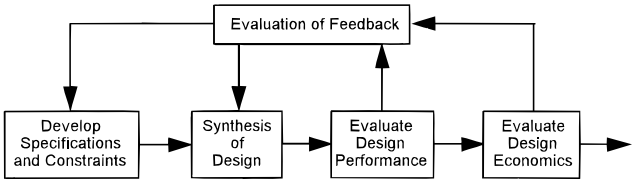


Fig. 1. Traditional design and justification process.

1. *Design Justification* includes a knowledge-guided design synthesis that is a combination of top–down and bottom–up design approaches. Traditional aircraft designs are synthesized using a top–down approach (algorithmic methods with simplifying assumptions), then evaluated using top–down cost models during conceptual design. However, the key to making process trades during conceptual and early preliminary design is to develop and link a bottom–up cost model into the evaluation procedure. No integrated cost/engineering models exist that make use of both cost model types. Our implementation of *Design Justification* required development of a combination top–down and bottom–up (i.e., a multilevel) LCC model (Marx et al., 1995).
2. The evaluation of performance and economics occur simultaneously in *Design Justification* to provide tradeoff studies that can quantify cost implications of design changes. Traditionally, the design and economic justification processes have been separated and sequential, allowing for a distortion in detail in the communication of results between analysis processes.
3. The information that is generated from the evaluation process should be strategically used to alter the design to meet the prespecified design objectives. Feedback information is commonly used to improve the performance characteristics of an aircraft, but is seldom used to improve the economic viability of the aircraft. Our method allows the designer to make changes in conceptual design based upon producibility constraints and estimated production and operational costs of the aircraft.

2.3. The elements of design justification

Design Justification is characterized by four main elements: it is simultaneous, goal-directed, decision-maker-

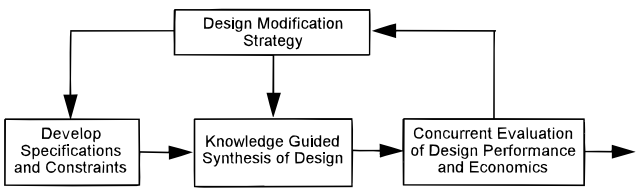


Fig. 2. Design justification process.

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centered, and knowledge-guided. These four concepts are discussed in the following sections.

2.3.1. Simultaneous design effort

Integrated engineering and cost models are required for *Design Justification*. The simultaneous consideration of the performance (i.e., product design) characteristics of a design and its associated cost (i.e., process design) characteristics allows *Design Justification* as the design matures. Detailed cost analyses conducted within the design process allow the major cost drivers to be identified and addressed before the design matures to a point beyond which redesign costs are too expensive to be implemented.

The simultaneous consideration of product and process design characteristics is the IPPD. As defined by the National Center for Advanced Technology (NCAT), IPPD is a management methodology that incorporates a systematic approach to the early integration and concurrent application of all the disciplines that play a part throughout a system's life cycle. Figure 3 shows a conceptual IPPD framework. Specifically, at phases during the design process, an analysis of the potential benefits from variables which could improve the aircraft's performance and economic characteristics must be conducted.

Figure 3 illustrates the decomposition activities from conceptual design (system level) to preliminary design (component level) to the detail design (part level) and manufacturing process level in a clockwise manner on the outer circle. Continuing clockwise leads to the re-composition activities, from part to component to system level. The inner loops on the top portion of the figure represent integrated product/process trades at the system level. The middle loop represents the same, except for component level product/process trades. Similarly, the lower loop corresponds to part level trades for products/processes. An iteration around the long outer loop represents what has typically been done in past sequential system design; redesign was often required due to product design incompatibilities with manufacturing processes. The attitude that process becomes important only as a product reaches maturity is not now and never was valid (Gaynor, 1993).

It is desired to have the ability to make *parallel* product and process design trades at the system, component, and part levels. It is also desirable to reach down to the part level trades for those product/process attributes deemed critical and bring those results to the component/system level during the preliminary/conceptual design phases. An integration of design and manufacturing cannot occur without

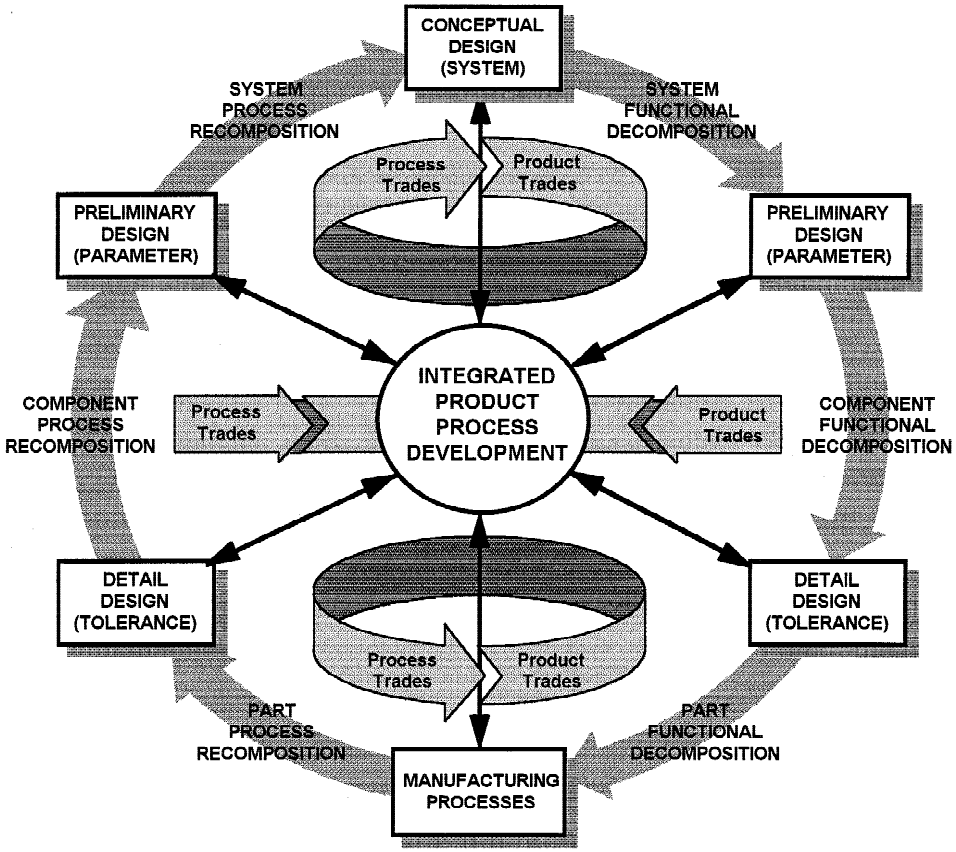


Fig. 3. Integrated product and process development.

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both product and process design trade iterations. Process trades are necessary for affordable systems design. The selection of manufacturing processes has traditionally been a costly bottleneck in the production phases in terms of both dollar and schedule overruns.

Addressing cost concurrently with the performance characteristics of the design can alleviate a common problem for economic justification. With our approach, the mapping of system cost variables to performance design variables is not done by a cost analyst after the design is completed. *Instead, the use of integrated engineering and cost models allows the cost data to be generated and analyzed as the physical system is being designed*. The mapping occurs during the analysis code integration.

2.3.2. Goal-directed design

A goal-directed design process is one in which the goals or objectives of the design are specified, and potentially modified, by the designer and are used during the design process to direct the analysis (Noble & Tanchoco, 1993). A branch-and-bound procedure is used to explore the design space as the design progresses. Branching allows exploration of the design space, while bounding permits calculation of metrics that can be used to evaluate the cost and performance of the design. Both branching and bounding occur during trade-off analyses for cost and performance. During the bounding phase, the designer evaluates metrics based on all design knowledge that has been accumulated up to that point. Interpolation and possible extrapolation of the metric allows reconsideration of the goals/objectives of the design and can guide further explorations of the design space.

Figure 3 also depicts the goal-directed aspect of *Design Justification*. The performance/economic aspects of the design are evaluated concurrently as different points of trade-off are encountered. Analyses within the bounding procedure are conducted at each level of the decomposition or recomposition. The design process continues until the requirements are met and/or the information needed to make a decision or selection is available.

With the use of integrated cost/engineering models, the information that is calculated during the design process will be characteristic of the actual source and nature of the costs, whether in terms of dollars or time. This information is directly related to the performance of the system and provides a mechanism for evaluating the economic implications of design decisions.

2.3.3. Decision-maker-centered design

The emphasis of the *Design Justification* procedure is *information processing and presentation in an appropriate manner to aid the designer* (Noble & Tanchoco, 1993). Figures 4 and 5 show a design-process-centered approach and a decision-maker-centered approach, respectively.

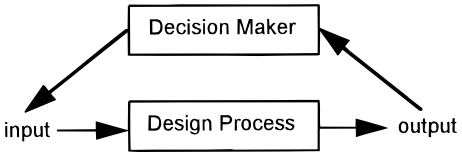


Fig. 4. Design-process-centered approach.

An analytic approach to design is a design-process-centered approach. A design is analyzed, resulting in a solution. Then the solution is interpreted by the designer. In contrast, *Design Justification* is a decision-maker-centered approach. The data generated during the design is received by the designer and processed with the designer's guidance. The designer is able to conduct sensitivity analyses to determine the advantages or disadvantages of allowing the design to progress in one direction over another.

2.3.4. Knowledge-guided design

As opposed to many current system design techniques, *Design Justification* is knowledge-guided. In the non-knowledge-guided approach (Figure 6), the conceptualization of the design is done strictly by the designer. A problem is modeled to a particular level of fidelity, then analyzed and interpreted. The designer can then modify the model until it meets the design objectives. While such a process is sufficient in many cases, design problems that require interpretation of heuristic knowledge cannot be handled.

The knowledge-guided design (Figure 7) has an additional component to handle heuristic problems: explicit knowledge. This approach allows the designer to model his system and guide the design process utilizing the knowledge component. This knowledge component could theoretically exist in many forms. The knowledge component of our design approach was a KBS, a design tool used concurrently with selected numerical analysis tools for production cost data manipulation and presentation to aid the designer.

3. DEVELOPMENTS AND IMPLEMENTATION

The steps necessary to apply the *Design Justification* process theory to integrating design and manufacturing are described in the following sections.

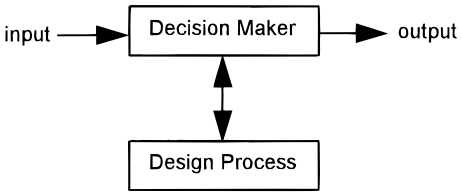


Fig. 5. Decision-maker-centered approach.

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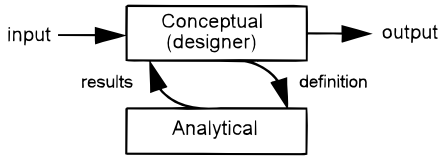


Fig. 6. Non-knowledge-guided approach.

3.1. KBS development

Feigenbaum (1980) defines knowledge engineering as the reduction of a large body of knowledge to a precise set of facts and rules. This task is a time-consuming deterrent to the widespread application of expert systems in new domains (Gaines, 1988). Manufacturing considerations are difficult to embody heuristically due to varying expert system user-preferences dependent upon the design goals (Thurston & Carnahan, 1993). This is due to the fact that, embedded in the rules themselves, are the programmer's assumptions regarding the values of the designer.

Expert systems are generally developed differently than conventional programs because the problems usually have no algorithmic solution and rely on inferences to achieve a reasonable solution (Giarratano & Riley, 1994). A reasonable solution, or possibly a set of reasonable solutions, may be what is most appropriate to expect if no algorithm exists to drive the design towards an optimal solution. Certain types of knowledge are more suitable for KBS applications than others. It is much easier to program expert systems with "shallow knowledge" based on heuristics (i.e., rules-of-thumb or general guidelines) than "deep knowledge" based on the basic structure, function, and behavior of objects (Giarratano & Riley, 1994). One particular type of shallow knowledge is "heuristic knowledge." Heuristics are not guaranteed to converge to a solution in the same way that a verified algorithm is guaranteed to solve a problem.

The selection of work materials and manufacturing processes impacts production costs considerably. The selection is committed almost entirely during the preliminary and detailed design stages of the product, and is usually based largely on product functionality, rather than manufacturing considerations. The method for selecting a set of manufacturing processes for a designed product involves the consideration of the product design attributes (i.e., material, size, shape, etc.) developed at each stage, and the creation of a set of manufacturing processes and associated materials which can be suitably processed. Once the set has been selected, it should then be ranked according to some type of cost criteria for the determination of the worth of each respective process and the materials associated with it (Gopalakrishnan & Pandiarajan, 1991). This is precisely the approach we have taken. During the conceptual or early preliminary design stage, the key design-related attributes should be compared to the process-related attributes using expert systems integrated with data bases to examine the suitability of the manufacturing process. Using a forward-chaining method of inference, the structural concept that provides the best balance between performance and affordability can be selected for the aircraft structural component.

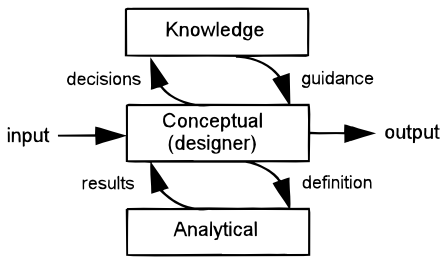


Fig. 7. Knowledge-guided approach.

The use of CLIPS (C Language Integrated Production System) as an explicit knowledge component (refer to Figure 7) required several separate developments. First, the types of knowledge that would be most functional for the designer had to be identified and acquired. Initially, we believed that the rules in CLIPS should be used to select a manufacturing process for a given structural member in the wing. However, the candidate processes for producing the major components of the wing structure are relatively limited. Most companies that are studying the HSCT airframe in depth have selected a single structural concept and its associated manufacturing processes. Industry research efforts are focusing more on improving performance through weight reduction or reducing cost through process improvement than alternative process selection. With the growing focus on improving aircraft affordability and predicting production costs based on the manufacturing processes used to fabricate, assemble, inspect, and tool the structure, we decided to populate our knowledge base with production cost rules.

The knowledge captured in our rule base was extracted from several previous supersonic transport studies (Jensen & Mijares, 1975; Sakata, 1975*a*,*b*; Wright & Ross, 1976; Sakata & Davis, 1977; NASA, 1989*a*,*b*; Bhatia & Wertheimer, 1993; Brunner & Velicki, 1993; Tzong et al., 1994; Röhl, 1995), as well as studies of candidate materials and processes to be used for the HSCT (Markus, 1991; Suarez & Dastin, 1991; Markus et al., 1992; Brunner & Velicki, 1993; Hatekeyama, 1995). Next, the structure for our rules was determined. We used the common "if-then" type logical construct. If the conditional checks on the left-hand-side (LHS) of a rule are met, the rule fires and completes the actions on the right-hand-side (RHS) of the rule. This construct allowed a simple, yet functional, embodiment of the production knowledge. Then, the rules were written. This was the most challenging and final development of our integrated design system. Inputs to our KBS are parameters that typically describe a wing structure during conceptual

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or early preliminary design. Weights, material usage, and structural concepts are inputs to the system. Hence, conditions related to product characteristics appear on the LHS of all rules. Since the information that characterizes wing concepts was always input in a consistent format, we input the facts to CLIPS using templates. Since it was desired that the output would be production cost data (labor hours and material costs), the rules relate product design variables to process costs.

KBS execution is commonly interactive. The system is invoked, then the user is prompted to answer questions. Automation of the data processing with CLIPS was done through execution in the batch mode. An input file contains all known facts to be asserted about the wing structure product data. A batch file is loaded into CLIPS, which loads templates, facts, and rules. A set-up file is then loaded to begin execution. After all matching rules have been fired and the agenda is cleared, CLIPS creates an output file (which is automatically parsed and appended to the LCC analysis code input file) and terminates.

All of the CLIPS developments for this project totaled approximately 4900 lines of code. Virtually no number-crunching is done in our implementation in CLIPS. The data that is output from CLIPS and subsequently input to the LCC analysis code is based on a production quantity of 100 units and a finished-material weight of 1000 pounds. All quantities are later numerically adjusted with learning curves and weight sizing factors using the detailed production cost model we have developed.

3.2. Production cost model formulation

It was necessary to formulate and implement a production cost model for the wing that captures the effects of alternative materials and manufacturing processes. The development of the model is contained in Marx et al. (1995) and Marx (1996). This also included development of suitable techniques to present the product and process trade results to the designer.

3.3. Tool integration

The process design tools (i.e., the rule-based manufacturing KBS and the cost models) were integrated with a product design tool (an aircraft sizing code, in this case) to form an integrated design system. The integration of the wing production cost model with a top–down LCC model can quantify where and how the processing costs produce significant effects and propagate through the aircraft's life cycle. The integration of the sizing code into the evaluation framework with automated data mapping and passing alleviates the distortion in data due to communication of results between analysis processes. Several preprocessors and post-processors and integration scripts were written to link the KBS with a top-level LCC model and an aircraft sizing code. FLOPS (Flight Optimization System; McCullers, 1994) was used to size the aircraft and the production cost model became a new module within ALCCA (Aircraft LCC Analysis; Bobick et al., 1979).

A classic paper by Dix and Riddell (1976) on cost-performance trades from the Institute for Defense Analysis (IDA) posed the following question: "For given performance requirements and a given state of technology, what would be the production cost of a proposed vehicle, and what would be the value of its performance?" It will be shown with our case study that our integrated design system can enable a designer to quantitatively answer this question.

4. SYSTEM AND MODEL VERIFICATION

The engineering economic analysis model and the KBS for structural concepts were verified with data from previous industry and NASA supersonic transport studies. Economic data for model verification is particularly scarce since most companies consider their data related to production costs highly competition sensitive. This section presents a summary of the detailed system and model verification that was completed before the HSCT case study was started.

4.1. Summary of the Lockheed SST evaluation process

Analytical design studies were performed by the Lockheed-California Company in the 1970s to assess the relative merits of several structural arrangements, concepts, and materials applicable to an arrow-wing Supersonic Transport (SST) configuration. The Lockheed SST concept carried 234 passengers, had a cruise Mach of 2.7, and a baseline wing area of 10,900 square feet. These SST studies resulted in a large amount of published data (Jensen & Mijares, 1975; Sakata, 1975*a*,*b*; Sakata & Davis, 1977; Wright & Ross, 1976). The published production cost data was the most complete non-proprietary set of data available for verification of the production and economic models.

An initial structural analysis screening was conducted by Lockheed on many potential wing structural concepts. These included chordwise stiffened, spanwise stiffened, and biaxially stiffened (monocoque) concepts. Unit weights were calculated for point design regions on the wing for each concept. There were three point design regions: the forward strake area, the inboard wing box, and the outboard wing box. By interpolating from the analysis point design regions, the unit weights derived during the initial screening were applied over all design regions to derive the total box structural weight for each prospective concept. Results of Lockheed's initial structural concept screening led to a more detailed analysis of five structural concepts: a chordwise-stiffened, convex-beaded concept; a spanwise, hat-stiffened concept; a mechanically fastened, biaxially stiffened, honeycomb con-

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cept; a welded, biaxially stiffened, honeycomb concept; and a boron-polyimide reinforced chordwise-stiffened concept.

The structural mass of each aircraft configuration was estimated first based on the premise of a fixed vehicle size and taxi weight. This permits the determination of the allowable fuel for the aircraft, which ultimately yields the range capability. The costs were subsequently determined for each configuration. The disadvantage to using this approach was that, though the relative flyaway costs could be compared, the concepts could not be compared on an equivalent performance basis, since their respective mission capabilities (i.e., range, in this case) were different. This led to a resizing of all configurations for a constant payload/range requirement. The payload was held constant, the range was constrained, and the gross weight of the aircraft was allowed to vary to meet the desired range goal. Following the resizing, the concept evaluation could be performed on a minimum-total system cost (with regards to operating cost variations) for concepts that had the same mission capability.

A relatively detailed description of the production hours required for producing the wing structural concepts was documented by Sakata (1975*a*,*b*). The estimations included material dollars and fabrication (including subassembly) and assembly (including tank seal) hours. However, the bottom line of Lockheed's production cost analyses was a "value-per-pound" factor for each concept that was subsequently used for the economic evaluations. With the use of these "value-per-pound" factors, the economic subroutines within ASSET (Advanced System Synthesis and Evaluation Technique, a Lockheed sizing code from the 1970s) were used to estimate the flyaway costs for five aircraft, based on a total production of 300 units.

4.2. Production cost model verification

All cost calculations in ALCCA for this verification were based on a total production of 300 units. The costs for the SSTs were originally calculated using 1973 dollars; those calculated in ALCCA are in 1992 dollars. The results can be presented on an equivalent economic basis using either of two techniques. First, the flyaway costs estimated in 1973 dollars could be inflated to 1992 dollars, or *vice versa*. Second, the relative flyaway costs could be presented. Since the relative costs (both flyaway and operating), as functions of wing structural concepts, will be more useful for eventual HSCT cost/benefit studies, the relative SST costs will be discussed in the following sections for both the constant take-off gross weight (TOGW) and constant payload-range SSTs.

4.2.1. Constant TOGW SST

The system costs, normalized with respect to the composite-reinforced concept, as predicted with our integrated system, are given in Table 1 for the constant 750,000-pound TOGW aircraft. The relative differences of the predicted values, with respect to Lockheed's original estimates, are also included for comparative purposes.

All of the predicted trends are correct with respect to the composite-reinforced concept. The wing concepts with the highest areal weights (the chordwise and spanwise stiffened all titanium concepts) display flyaway costs lower than the composite-reinforced concept. However, their range capability was far below that of the boron/polyimide concept. The biaxially stiffened concepts had higher flyaway costs than the composite-reinforced concept, even though their range capabilities were less than that of the composite concept. This is due to the fact that significantly more production hours were required to fabricate the sandwich panels than the more conventionally stiffened panels. The composite reinforced concept was considered a higher technology concept than the biaxially stiffened concepts, but had a lower wing areal weight and, thus, a lower TOGW, tended to offset the costs incurred through an increase in technology level.

Table 1. *SST concept relative system costs for constant TOGW*

Structural Arrangement	Units	Chordwise (mechanical)	Spanwise (mechanical)	Monocoque (mechanical)	Monocoque (welded)	Chordwise (B/PI reinf.)
Lockheed						
Flyaway cost	$1973M	0.966	0.951	1.119	1.117	1.000
DOC	c/sm	1.010	1.000	1.057	1.063	1.000
IOC	c/sm	1.044	1.033	1.011	1.011	1.000
ALCCA						
Flyaway cost	$1992M	0.977	0.971	1.095	1.020	1.000
DOC	c/sm	1.025	1.023	1.041	1.018	1.000
IOC	c/sm	1.027	1.024	1.014	1.014	1.000
Relative differences						
Flyaway cost		1.12%	2.11%	−2.09%	−8.73%	0.00%
DOC		1.42%	2.31%	−1.52%	−4.17%	0.00%
IOC		−1.66%	−0.93%	0.24%	0.24%	0.00%

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Though the flyaway cost of the welded monocoque structure was correctly estimated to be greater than that of the composite-reinforced concept, the magnitude of the difference was not as great as that predicted with ASSET. This discrepancy, which is only evident for this particular concept, can be explained as follows. The "value-per-pound" factors used with ASSET in the Lockheed-California studies accounted for material cost, fabrication and assembly hours, and tooling hours. For the welded, biaxially stiffened concept, the material and tooling "value-per-pound" factors were not significantly different. However, their predicted production hours required for the mechanically fastened, monocoque concept were three times greater than what was predicted for the welded, monocoque concept. This does not correspond to the published values for the flyaway costs of these concepts being almost equal. ALCCA's predictions for the flyaway costs for the biaxially stiffened concepts were consistent with the number of hours required to produce the concepts, an advantage to using a model based on time (hours), as opposed to applying factors to weight-based algorithms only.

4.2.2. Constant payload-range SST

The relative system costs, as calculated with our integrated system, are given in Table 2 for the constant payload-range aircraft. These aircraft were all required to meet the 4200 nmi range requirement. Though the TOGWs were significantly different, the aircraft can better be compared on an equivalent economic basis since they all have the same mission capability. Again, the original estimates by Lockheed are included for comparison.

The flyaway costs for the constant payload-range concepts again all exhibit the same trends as those predicted by Lockheed. In this case, the composite-reinforced cocept is simply the lowest cost alternative. Though the noncomposite-reinforced, chordwise-stiffened concept and the spanwise, hat-stiffened concept had the lowest flyaway costs in the case for constant TOGW, their flyaway costs are now higher than that of the composite-reinforced concept. This is due to the fact that, during the resizing for constant payload range, their empty weights and TOGWs increased significantly, resulting in an increase in their flyaway costs. The monocoque, welded concept exhibited the same characteristics in this case as it did when constrained to a maximum TOGW of 750,000 pounds.

The results presented in this section display excellent correlation with the most comprehensive set of nonproprietary data available for SST model and system verification. All of the relevant trades, for both performance and economics, have been verified. With the use of a powerful LCC code like ALCCA, integrated with a production cost KBS and a sizing code, it is possible to show the effects of alternative structural concepts in cost/benefit studies. In addition, with automated data passing, file preparation, and preprocessing and postprocessing utilities, it is now possible to show the effects of alternative concepts or process implications on several constituents of the LCC at the desired level of fidelity.

An approach for integrating design and manufacturing has been described in this article. The design tools and system integration required to support this approach were also detailed. The integrated design system, comprised of an aircraft sizing code, a rule-based manufacturing KBS and a LCC code, was then validated against existing performance and cost data from previous supersonic transport studies. Extensions to the system for advanced HSCT wing materials and processes have been developed. With respect to the *Design Justification* approach, the notion of providing information to aid the designer can be exploited with our system.

Table 2. *SST concept relative system costs for constant payload range*

Structural Arrangement	Units	Chordwise (mechanical)	Spanwise (mechanical)	Monocoque (mechanical)	Monocoque (welded)	Chordwise (B/PI reinf.)
Constant payload range (Lockheed)						
Flyaway cost	$1973M	1.089	1.054	1.135	1.155	1.000
DOC	c/sm	1.109	1.083	1.067	1.093	1.000
IOC	c/sm	1.044	1.044	1.011	1.011	1.000
Constant payload range (ALCCA)						
Flyaway cost	$1992M	1.093	1.072	1.082	1.010	1.000
DOC	c/sm	1.115	1.097	1.048	1.033	1.000
IOC	c/sm	1.034	1.030	1.010	1.007	1.000
Relative differences						
Flyaway cost		0.38%	1.72%	−4.69%	−12.55%	0.00%
DOC		0.57%	1.31%	−1.84%	−5.52%	0.00%
IOC		−1.02%	−1.34%	−0.10%	−0.43%	0.00%

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5. CASE STUDY: THE HIGH-SPEED CIVIL TRANSPORT

The economic feasibility of the HSCT will ultimately be the deciding factor for starting production. Recent market surveys indicate a sufficient passenger demand will exist after the turn of the century for supporting a fleet of HSCT aircraft. However, no manufacturer would commit to the immense production investment without great confidence in making a reasonable profit on the venture. In turn, the airlines would not purchase the aircraft unless they too are assured of making a profit by operating the aircraft. This is a highly coupled problem. Often, an alternative that is beneficial to the manufacturer has adverse effects on the productivity/profitability for the airline. Similarly, an alternative that has lower operating costs and higher reliability is more expensive to manufacture.

The well-known relationship between acquisition cost, operating cost, and LCC is shown in Figure 8. The figure illustrates that lower operating costs can be achieved with higher reliability, but at an increased acquisition cost (point A). The lowest acquisition cost does not always signify the lowest LCC. Reduced acquisition costs may imply lower reliability, which translates to increased operating costs (point B). The "bucket" in the LCC curve indicates that there may theoretically be some feasible alternatives for which a higher acquisition cost can be offset or justified with reduced operating costs (point C) to result in a concept that may be the best alternative for both the manufacturer and the airlines. An example of this was encountered in our performance and economic evaluations of HSCTs with the three alternate wing concepts selected for this case study. For these reasons, the overall Design-for-Economics approach we have taken makes the HSCT an excellent case study example to demonstrate the applicability of our integrated design system for quantifying production cost implications of alternate wing structural concepts, for conducting system cost/performance trades, and for performing IPPD studies.

Extensions of the rule bases developed for the SST were the only addition to the integrated design system required to broaden its domain of applicability to include additional aircraft. Rule bases developed for the candidate advanced materials and processes for the HSCT wing allow our integrated design system to be used for a more complete system performance and LCC analysis than is possible with any other existing methods or systems.

The modern HSCT concept is a 300-passenger aircraft with a design range of 5000 nautical miles. Its cruise speed is Mach 2.4. Weight estimates range from an optimistic 750,000 pounds to over 900,000 pounds, depending on the specific configuration. The HSCT was modeled in FLOPS with relevant geometry, mission parameters, aerodynamic data, and propulsion data. The baseline HSCT modeled in FLOPS had the characteristics defined in Table 3.

Off-the-shelf aerodynamic design codes (Harris, 1964; Middleton et al., 1980*a*,*b*; Middleton & Lundry, 1980*a*,*b*; Carlson & Walkley, 1984; McCullers, 1992) were used to generate the user-defined induced drag coefficients for FLOPS. The optimum twist and camber distribution for the wing and the area-ruled fuselage were used in generating

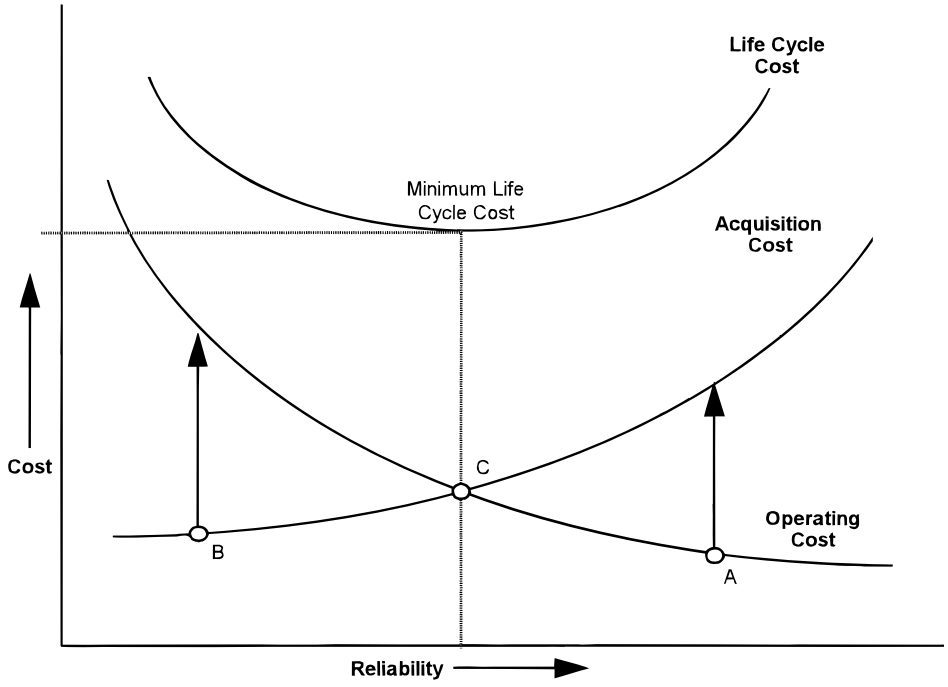


Fig. 8. Trade-off between acquisition and operating costs.

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Table 3. *HSCT configuration description*

Range	5000 nmi
TOGW	825,000 lbs
Number of passengers	300
Cruise ceiling	70,000 ft
Approach speed	155 knots
Fuselage length	330 ft
Wing area	9,000 ft^2
Wing span	130 ft
Horizontal tail area	1000 ft^2
Vertical tail area	600 ft^2
Horizontal tail sweep angle	35°
Vertical tail sweep angle	41°

the drag polars that were input into FLOPS. A fixed cycle for a mixed-flow turbofan engine was selected from the FLOPS-supplied engine cycles. The mission used for sizing the aircraft in FLOPS was a nominal 85% supersonic and 15% subsonic (by distance) mission. Both the subsonic and supersonic cruise segments were flown at a fixed Mach number, with the optimum altitude for specific range calculated by FLOPS.

5.1. Wing region descriptions

The wing was divided into three main design regions: the forward strake, the inboard (or main) wing box, and the wing tip box (Figure 9).

The baseline wing concept is representative of current concepts under study by industry. Composite honeycomb skin panels and superplastically formed/diffusion bonded (SPF/DB) titanium skin panels are viable candidates for HSCT wing structure (Brunner & Velicki, 1993). Three potential HSCT wing structural concepts are evaluated in this article using the approach and implementation described previously. These substantially different concepts were chosen to show a variety of trends in cost and performance. The three concepts are shown in Figures 10–12.

Concept one has SPF/DB titanium skin panels and titanium substructure in all three wing design regions. Concept 2 has Z-stiffened polymer matrix composite (PMC) skin panels and PMC substructure in all wing regions. Concept 3 has a hybrid wing structure similar to that in Brunner and Velicki (1993). While the structural product and process characteristics of the concepts were different, the platform shape and size remained constant.

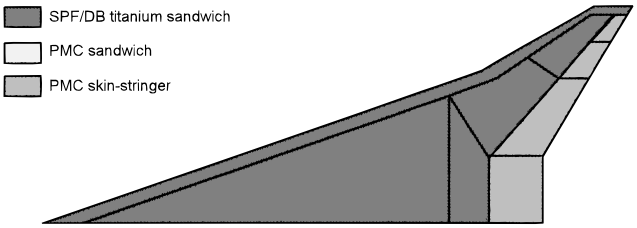


Fig. 10. HSCT wing Concept 1: Metallic homogeneous concept.

The product and process characteristics of the individual design regions were identified. The product characteristics are similar for all three concepts, but the processing characteristics are quite different. Table 4 shows the product and process characteristics for the Concept 3.

5.2. Relative concept costs

McDonnell Douglas provided the relative data given in Table 5. The objective of the study was to determine the effects of alternative structural concepts on the manufacturing (fabrication and assembly labor) hours and tooling costs for each of three design regions of the wing. The process characteristics given in Table 4 were used to generate the relative numbers given in Table 5. The causes of the high and low numbers due to the specific process characteristics of the design region and/or the structural concept are noted below the table.

Concept 1 is represented by the titanium SPF/DB column in the table. Concept 2 data is the PMC Z column in the table. The baseline hybrid concept data is marked. The knowledge contained in Tables 4 and 5 was embodied in the rule bases in CLIPS. It was used to adjust the production cost estimates for the specific materials and processes used to manufacture the structure in each section of the wing. This way, the cost estimates generated are representative of the actual production processes and materials used to manufacture the wing structure.

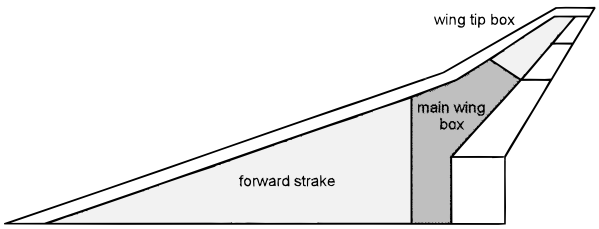


Fig. 9. HSCT wing design regions.

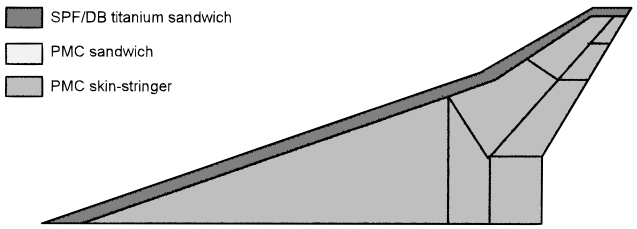


Fig. 11. HSCT wing Concept 2: Composite homogeneous concept.

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Table 4. *Wing region product and process characteristics for concept 3*

Wing Region	Product Characteristics	Process Characteristics
Forward Strake	The forward strake region experiences light or moderate biaxial loads with respect to wing bending. Much of the forward strake is designed to meet minimum gage requirements.	The loft-to-loft distance is large in this section; access for automation is possible up to a depth of about 24 inches (the length of a human arm). As opposed to the conventional birdcage assembly approach, in which the internal structure is assembled first and then the skin panels are subsequently attached, this section of the wing will be assembled in reverse order. First the lower skin will be placed in its respective tool, the spar caps will then be (automatically) fastened to it. The spar webs will be fastened next, followed by the top spar caps. The upper panel, which is tool coordinated, is then placed and fastened. With this sequence of assembly steps, the *substructure* will be floated, as opposed to the wing panels being floated. The loft dimensions are very critical on this type of a wing. Therefore, the tools will be made for the skin panels to achieve the necessary tolerances. At depths of more than 24 inches from the skin panel, assembly will be manual (which increases the fastening cycle time). It is assumed that the spar caps and spar webs were cocured, requiring no additional stitching.
Main Wing Box	The major load path of the wing is in the inboard wing box. This section experiences high spanwise load intensities due to wing bending, and variable chordwise load intensities due to bending and torsional effects. This section has the highest average areal weights. The engine pylons are attached to the rear spar of this section. The inboard flap and spoiler will also be attached to the rear spar of this section.	A four-sheet SPF/DB titanium skin panel is used in this highly loaded section of the wing. The substructure is also all titanium, with extruded spar caps and sheet metal webs. The two inner sheets are first intermittently roll-seam welded with a cross pattern while the two outer sheets are periphery welded. The four sheets are heated to the processing temperature, and put in the SPF/DB press. Gas is injected to inflate/form the sheets; the temperature is held for diffusion bonding, followed by a cooling and unloading period. Then the panel is trimmed. No jig is needed for this procedure, since there are no stringers. The panels are integrally stiffened, hence there is a reduced fastener count. There is also no spring-back of the structure. A disadvantage in using this process is the high tooling cost for the individual dies.
Wing Tip Box	The wing tip box is the most stiffness-critical design region of the wing. This section experiences high load intensities, and is driven by stiffness constraints to prevent flutter and to ensure aileron control effectiveness. An outboard flap and spoiler, flaperon, and aileron will be attached to the rear spar of the wing top box.	A conventional assembly approach will be used for this section of the wing. The substructure will be assembled first, followed by the skin panels. One of the panels will be put on first, then drilled and removed. The other skin will be placed on the substructure and fully fastened. The first skin panel will then be tacked in place and mechanically fastened. Blind fasteners will be used on parts of the wing tip structure since the tip is relatively thin (approximately 6 inches loft-to-loft distance).

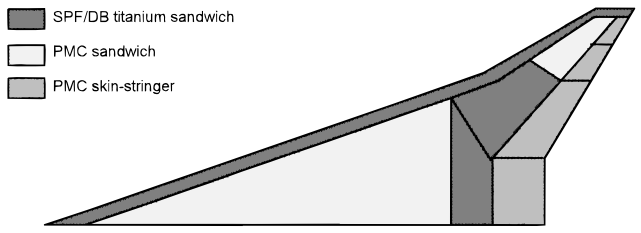


Fig. 12. HSCT wing Concept 3: Hybrid metallic and composite concept.

5.3. Results

The results presented in this section are based on several assumptions:

1. The process-dependent parameters in the model are for the wing only.
2. The manufacturer's module in the LCC code is not a factory simulation model, but a model of the produc-

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Table 5. *Relative concept costs*

Design Region	Aluminum Z	Titanium SPF/DB	Titanium H/C	PMC H/C	PMC Z
Forward Strake				*Baseline*	
Fabrication labor hours	1.0	0.67[h]	0.81	0.97	1.13[b]
Fabrication tooling cost	1.0	1.22[d]	0.30[f]	0.36[g]	0.34[c]
Assembly labor hours	1.0	0.86	0.86	0.86	1.00
Assembly tooling cost	1.0	0.95	0.95	0.95	0.97
Tip Box				*Baseline*	
Fabrication labor hours	1.0	0.65[h]	0.87	1.13	1.46[b]
Fabrication tooling cost	1.0	1.80[d]	0.53[f]	0.61[g]	0.61[c]
Assembly labor hours	1.0	0.95	0.95	0.95	1.07
Assembly tooling cost	1.0	0.92	0.92	0.92	0.94
Inboard Wing Box		*Baseline*			
Fabrication labor hours	1.0	0.77[h]	0.86	0.94	1.15[b]
Fabrication tooling cost	1.0	0.98[e]	0.33[f]	0.35[g]	0.38[c]
Assembly labor hours	1.0	1.24[a]	1.24[a]	1.24[a]	1.32[a]
Assembly tooling cost	1.0	0.95	0.95	0.95	0.97

[a]Relatively high number of fasteners needed.
[b]Includes stitching zee's onto the panel.
[c]Stitched/RFI is a low-cost tooling approach.
[d]High cost of tooling (die) for the SPF/DB panels.
[e]The die/jig cost is nearly that of aluminum, due to high compound curvature in this region.
[f]No stretch form of skin required.
[g]One-sided tooling.
[h]Not a time-intensive process step.

tion of a single aircraft. The delivery schedule is assumed to be equivalent to the production schedule, and the order schedule preceeds the delivery schedule by the number of months in the Research, Development, Test, and Evaluation (RDT&E) phase.

3. Distribution of the RDT&E costs, the manufacturing and sustaining costs, and revenue (income) are as outlined by Marx et al. (1995).
4. All estimates are based on a production of 600 units, unless indicated otherwise.
5. The airline module in ALCCA provides an analysis of the costs and revenues an airline will experience in purchasing and operating one aircraft. Schedules for financing, depreciation, interest, tax, and cash flow are also found in Marx et al. (1995).
6. Fuel costs were assumed to be $0.61 per gallon. The economic mission was 3800 nmi and aircraft utilization was 5000 h per year. The load factor was 0.65. The aircraft was assumed to be financed at an interest rate of 8% over a 20-yr economic lifetime for the aircraft.
7. All cost estimates are in 1992 dollars.
8. Propulsion costs are not eroded with a learning curve. They were considered a fixed cost from the airframer's perspective.
9. The effects of the structural concept and process alternatives on the maintenance of the aircraft were not considered. Hence, variations in direct operating cost for the concepts are due only to differentials in financing, interest, depreciation, and insurance costs for the aircraft.

Figures 13 and 14 show the implementation of the new wing labor and material learning curves in ALCCA. The figures give the unit cost at T1 and any unit beyond, but unit costs, especially at T1, are not the best indicator of profitability to the manufacturer. A better indicator of profitability for the manufacturer is the discounted rate of return.

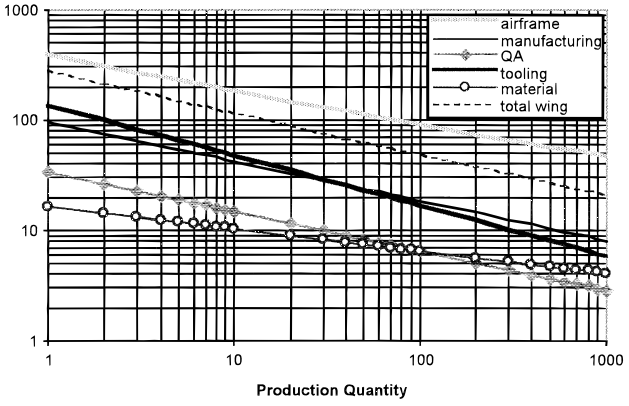


Fig. 13. Wing Concept 3 component costs versus production quantity.

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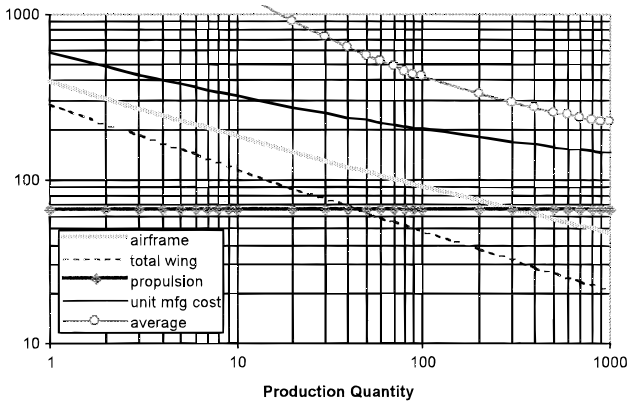


Fig. 14. Aircraft (wing Concept 3) group costs versus production quantity.

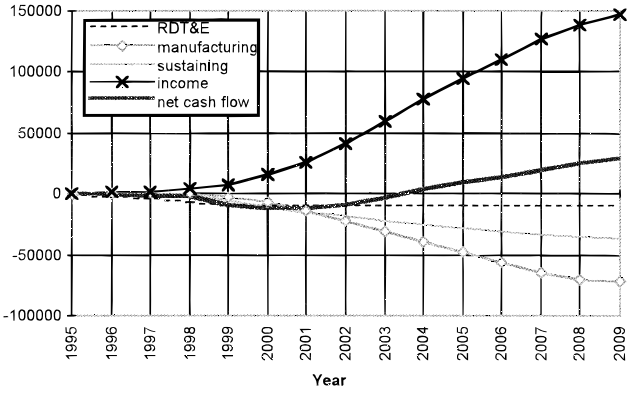


Fig. 16. Cumulative manufacturer cash flow for baseline concept.

5.3.2. Manufacturer's return on investment versus aircraft price

Figures 15 and 16 show the annual and cumulative manufacturer cash flow distributions for HSCT production with wing Concept 3. Figure 15 shows the annual cash flows over the 60 month pre-production period and 10-yr production period. RDT&E costs are distributed over the first 72 months of the program. The plot of the income clearly shows the order payments and delivery payments corresponding to the delivery schedule. The annual net cash flow is negative for the first 6 years of the program, but is positive for the remaining 9 years of the program.

The cumulative annual cash flows are shown in Figure 16. The most interesting line on the plot is the cumulative net cash flow. For a 600-unit production run, with the aircraft selling at a price that corresponds to a 12% Return on Investment (ROI) for the manufacturer, the break-even point is approximately $9\frac{1}{2}$ years into the production; the break-even unit is 365 aircraft.

As stated earlier, the comparisons of discounted ROI versus price provide information that may be most useful to a designer or manager during the aircraft conceptual design phase. The cash flows must be calculated to determine the internal rate of return. Figure 17 shows a plot of manufacturer's internal rate of return versus the selling price of the aircraft for the three aircraft sized with the three different wing concepts.

The horizontal line in Figure 17 is placed at 12% ROI for the manufacturer. As shown, the price of the aircraft with the hybrid wing concept is slightly higher than that of the aircraft with the all SPF/DB wing concept. The price for the aircraft with the Z-stiffened PMC wing must be set more than 10% higher than that of the aircraft with the hybrid wing concept to yield the same ROI for the manufacturer. Later, it will be shown that higher acquisition costs can be offset enough by lower operating costs to justify investment in an advanced production alternative for some specific cases.

5.3.3. Operating costs versus stage length

The price that corresponds to a specific manufacturer ROI is used as the acquisition cost to the airline to ensure continuity between the manufacturer and air carrier economic analyses. Changes in wing labor or material costs due to structural concept selection that affect system cost, manufacturer cash flows and ultimately, acquisition cost, are felt

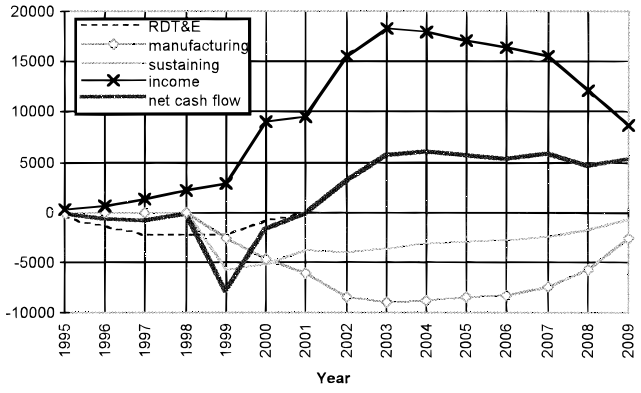


Fig. 15. Annual manufacturer cash flow for baseline concept.

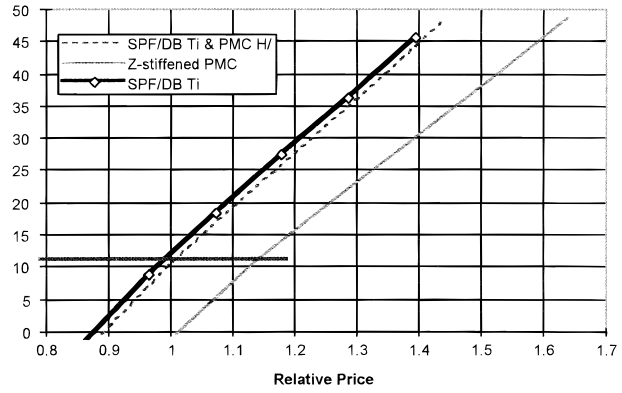


Fig. 17. Manufacturer ROI versus price.

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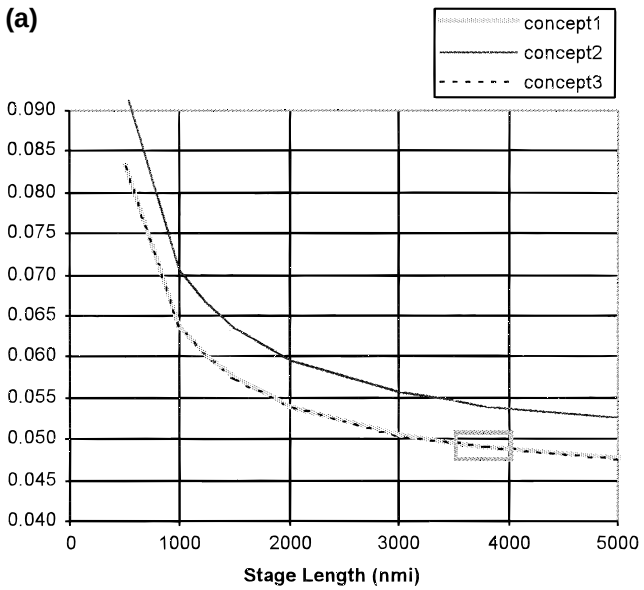


Fig. 18a. Aircraft DOC versus stage length.

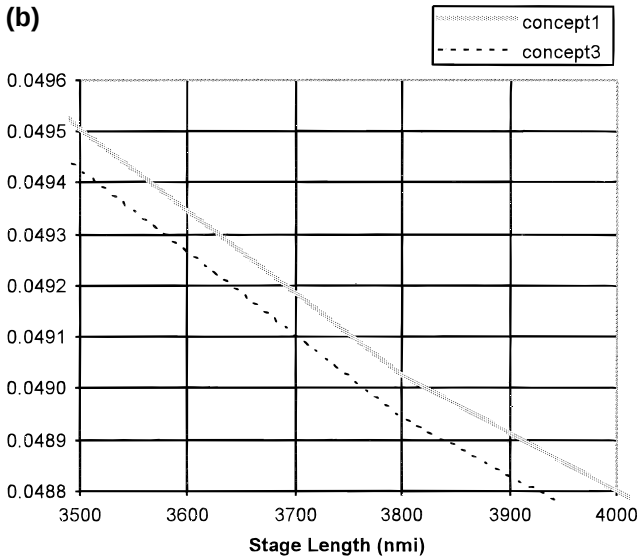


Fig. 18b. Aircraft DOC versus stage length (detail).

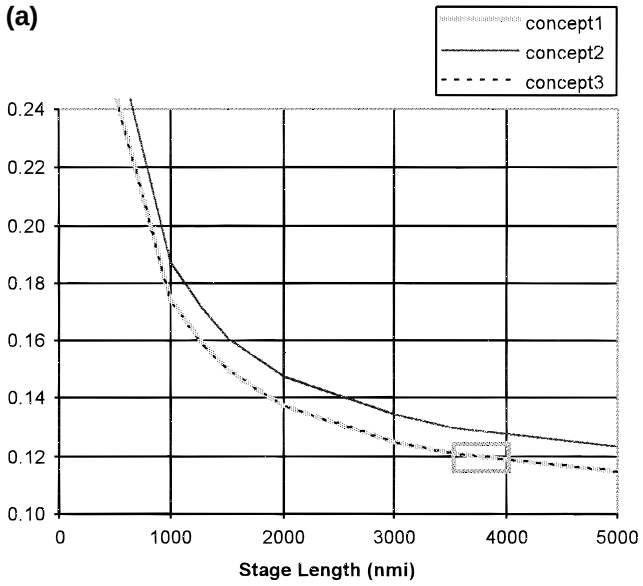


Fig. 19a. Aircraft required revenue versus stage length.

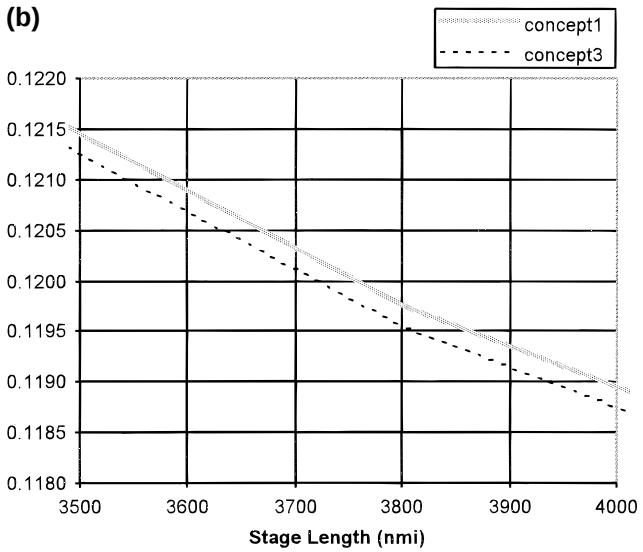


Fig. 19b. Aircraft required revenue versus stage length (detail).

in a ripple effect in the airline cost analysis through increased or decreased ownership DOC.

Figures 18a and 18b show the DOC for the aircraft with the three wing concepts versus stage length. Figure 18a shows that the aircraft with the all PMC Z-stiffened wing has higher operating costs at any stage length than the other two concept alternatives. This is because the sized aircraft is substantially heavier and has a higher price tag associated with a 12% ROI for the manufacturer. This translates to higher cash and ownership DOC for this concept. The higher cash DOC is due to the increase in mission fuel required over the other two concepts. The higher ownership DOC results from the higher selling price of the aircraft to give the manufacturer the prespecified 12% ROI. Concepts 1 and 3 have nearly identical direct operating costs; detail is provided in Figure 18b. Upon closer inspection, it is evident that the aircraft with the hybrid wing concept has slightly lower DOC than the aircraft with the all SPF/DB titanium wing. The consequences of this are discussed further in the next section.

Figures 19a and 19b show the required revenue (in \$/RPM, or dollars per revenue passenger mile) for aircraft

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sized with the three wing concepts. The trends exhibited for the required revenue are the same as those for the DOC.

5.3.4. *Cost versus performance*

The recent emphasis in the aerospace design community on providing greater system affordability mandates quantitative evaluations of the "cost of performance" for feasible alternatives. The capability to do cost versus performance trades during conceptual design *based on manufacturing considerations* allows the evaluation of alternatives and concept down selection to occur before the design may progress too far in one direction and lose its targeted cost-effectiveness.

Figures 20–23 show a series of comparisons of product and process metrics for the wing, the aircraft, and the operating costs. The plots are normalized with respect to the aircraft with wing Concept 1.

Figure 20 shows several standard product evaluation metrics that are used to evaluate concepts during conceptual design. The three wing concepts show the intuitive trend: the concept with the lowest weight (Concept 3) corresponded to the aircraft with the lightest operating weight empty (OWE), least mission fuel required for the design range, and lightest TOGW. The heaviest wing concept (Concept 2) resulted in the heaviest OWE, most mission fuel, and heaviest aircraft TOGW. One might expect the composite wing concept to weigh less than the titanium concept. However, the previously defined product characteristics stated that much of the HSCT wing structure experiences light to heavy bidirectional loads. The discretely stiffened PMC concept is consequently substantially heavier due to its inability to resist the biaxial loads as well as the SPF/DB panels or the PMC honeycomb panels in wing Concepts 1 and 3, respectively.

Figure 21 shows that the hybrid concept, which had the lowest wing weight, has a wing theoretical first unit cost (TFUC) approximately 40% higher than the slightly heavier SPF/DB concept. The Z-stiffened PMC concept is substantially higher than both of the other concepts. The airframe and aircraft TFUCs exhibit the same trends, but with smaller relative magnitudes. However, when the various manufacturing costs, tooling costs, material costs, and learning curves are all considered simultaneously, the *prices* required for the manufacturer to make a 12% ROI on the production investment for 600 units are much closer in magnitude. The Z-stiffened PMC concept price is about 15% more than the SPF/DB concept. The price for the hybrid concept was slightly higher than that of the SPF/DB concept, even though it weighed less.

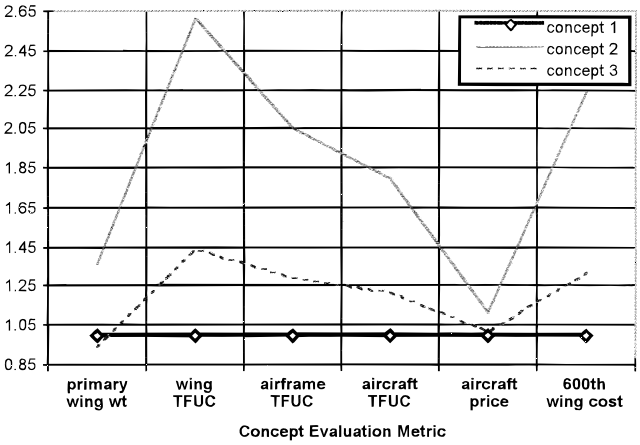


Fig. 21. Component and system costs.

The TFUCs for the wing labor and materials are shown in Figure 22. The relative magnitude of the TFU tooling costs for the concepts is quantified in the figure. The TFU tooling costs for the heavy PMC Z-stiffened concept are extremely high, with respect to the other concepts.

The interesting effect of the differences in price between wing Concept 1 and wing Concept 3 is evident in Figure 23. Recall that the price of the lighter aircraft with the hybrid wing structure was higher than that of the aircraft with the all SPF/DB titanium structure. One might expect that, ac-

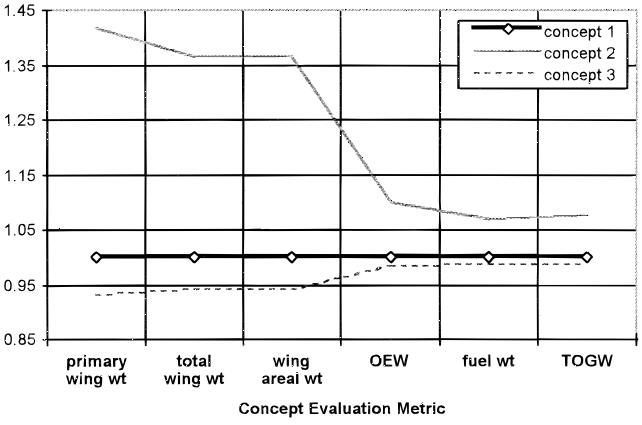


Fig. 20. Component and system weights.

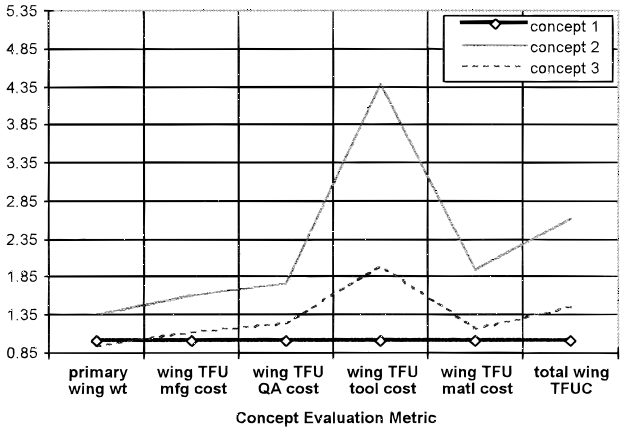


Fig. 22. Subcomponent and component first unit costs.

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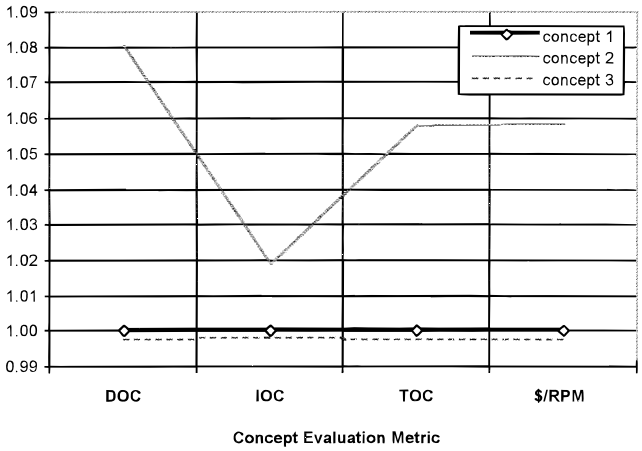


Fig. 23. Operating costs.

cording to Assumption 9, the operating costs for the hybrid aircraft would be more than that for the other. As shown in Figure 20, the mission fuel required by the aircraft with the hybrid wing was less than that for the aircraft with the all SPF/DB wing. The higher price of the hybrid concept was more than offset by the lower fuel cost to fly the mission. Hence, the DOC of the aircraft with the hybrid wing structure is less than that of the aircraft with the all SPF/DB titanium wing. This type of result is precisely that which can be used for the economic justification of a major design decision. This result illustrates the cost trade-off between production costs and operational and support (O&S) costs for a commercial aircraft system, represented in Figure 8.

6. SUMMARY AND CONCLUSIONS

In terms of both the product and process trades, the Z-stiffened PMC wing concept is not a viable structural concept. Its inability to support the bidirectional load distribution resulted in it having the highest wing weight, OWE, TOGW, and mission fuel. Its large weight and relatively expensive production costs yield an aircraft with the highest selling price and operating cost of the three concepts.

Comparing and contrasting the remaining two concepts is not as simple. While the hybrid wing concept weighed less than the all SPF/DB titanium wing, all components of its total wing production costs were somewhat higher. However, when all RDT&E, manufacturing, and sustaining costs are amortized over the production of the aircraft, the resulting cash flows result in relatively similar selling prices for the aircraft to achieve a prespecified ROI for the manufacturer. Though the aircraft with the hybrid wing had a higher selling price, its lower weight and required mission fuel reduce its direct operating costs to be slightly lower than those of the aircraft with the all SPF/DB titanium wing. This is an excellent example of a cost versus performance trade study result showing the balance between acquisition (production) costs and operational costs.

In terms of the functionality of our approach and its implementation, our system was able to accurately reproduce the published performance and economic (including manufacturer and air carrier) results for the SST studies conducted by the Lockheed-California Company in the 1970s. The values predicted for HSCT operating costs and required revenue are consistent with the limited published HSCT economics data.

Our prototype system, tested and validated for the SST, was extended for HSCT candidate advanced materials and processes with the development of new rule bases. The performance and economic characteristics of HSCT aircraft with three different wing structural concepts, two homogeneous and one hybrid, were evaluated. The aircraft had the same missions and identical wing planforms and sizes. The differences were in the materials and processes used to manufacture each concept. The method developed and demonstrated in this article allows the simultaneous evaluation of concept performance and economic metrics, including manufacturing considerations.

The case study for the three alternative wing concepts was a combined performance and economic evaluation. It was found that, using a bottom–up cost estimate for the wing in the LCC analysis, the lowest weight concept is not always the lowest cost concept. This is well known, but cannot be quantified with existing weight-based models. The balance between acquisition and support costs was also shown with an example for which the higher acquisition costs of one concept were more than offset by its reduced operating costs.

We assert the following deductions with respect to the three questions stated in the beginning of the article:

1. The *first* concerned the type of manufacturing knowledge that can be processed during the aircraft conceptual design phase. We have shown that it is possible to incorporate manufacturing considerations into the aircraft design process through concept evaluation based on production costs. Rules that contain parameters for estimating labor and material costs based on materials and structural concept for given regions of the wing are contained in the knowledge base.

2. The *second* question was related to the depth to which the manufacturing knowledge must extend to provide useful information to the designer, yet not confuse the solution strategy or designer with unnecessary information. Production cost data for the major wing structural components, grouped by design region of the wing, can be used to effectively differentiate concepts based on combined performance and economic evaluation metrics at several levels in the LCC hierarchy. While more detailed data exists for wing component costs, most of it is highly proprietary and is better suited for giving producibility guidance to a designer during detailed part design stages. The processing of the detailed design-level producibility knowledge related to

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specific, individual parts would make the design and evaluation cycle time prohibitively time consuming.

3. The *third* question addressed the metrics that can be used to evaluate product designs in terms of their process characteristics. Several cost versus performance trades were conducted at the system and major component level to demonstrate alternative process evaluation metrics.

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