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Validated Feasibility Study of Integrally Stiffened Metallic Fuselage Panels for Reducing Manufacturing Costs

Cost Assessment of Manufacturing/Design Concepts

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February 2000

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1 Summary

1.1 Deliverable

Cost methods and analysis tools to support a technology assessment and down selection of candidate manufacturing processes/design concepts for integrally stiffened fuselage panels, and an evaluation of selected hardware fabrication. The cost analysis approach is capable of discriminating between different design/manufacturing configurations, including such factors as high-speed machining and extrusions.

1.2 Purpose

The purpose of the cost analysis was to provide information about the concepts that were down selected, in order to evaluate the potential of these concepts to meet or exceed IAS program cost reduction goals.

1.3 Summary of Results

The hybrid design, which will be described in greater detail below, is the best overall approach from an absolute cost perspective. This design is made from high-speed machined extruded frames that are mechanically fastened to high-speed machined plate skin/stringer panels.

Recurring labor and material costs of the hybrid design are 61% less than the current technology baseline. This would correspond to a total cost reduction of $1.7 million per ship set for a 777-sized airplane. However, there are important considerations (discussed in Section 4 Outstanding Issues) that should be addressed before this conclusion can be accepted and development work can move forward.

2 Method

2.1 Scope

The two design concepts that are the focus of this cost study are shown in Figure 1. The baseline configuration is built-up aluminum structure using current machining technology and assembly processes. The two IAS design concepts are various monolithic and semi-monolithic structures that utilize different raw material forms, in this case plate and extrusion, to achieve a baseline structural equivalent. All three design concepts will be analyzed and cost results provided for conventional and high-speed machining technologies.

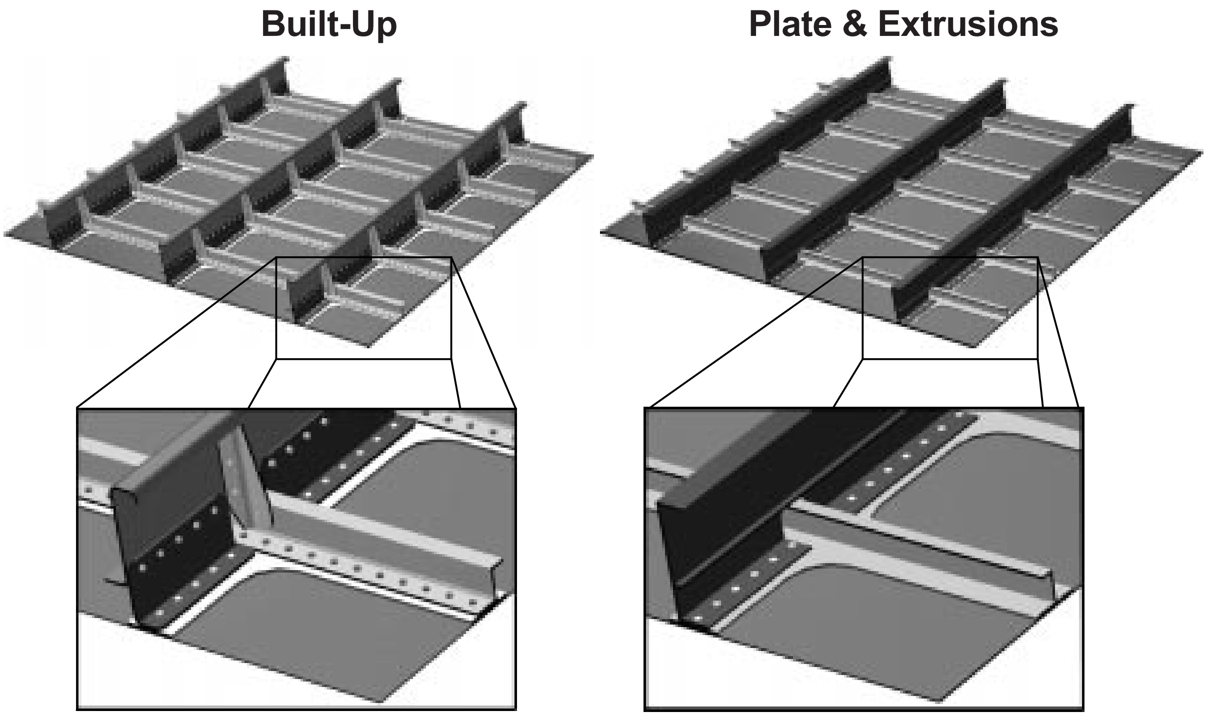

FIGURE 1. DESIGN CONFIGURATION USED IN COST STUDY

Figure 2 provides a view of the overall panel dimensions. This panel is ten feet by ten feet and is assumed to be a crown section fuselage panel for a theoretical airplane. All three design concepts were evaluated using process-based estimating techniques. The process coefficients were extrapolated from actual manufacturing data gathered during the conventional machining of Z-stiffened fuselage panels of a similarly sized wide-body aircraft. The cost equations were then calibrated to account for high-speed performance characteristics, using data gathered for frame stiffening members currently produced by high-speed machining.

During the high-speed machine evaluation, it was found that first-order effects were driven primarily by certain part features: the wetted area and the volume removed. Further analysis determined that this was true for both conventional and high-speed machining. Therefore, the statistical relevance of the calibration techniques employed are accurate to within 5% for the machining cost comparisons made during this study.

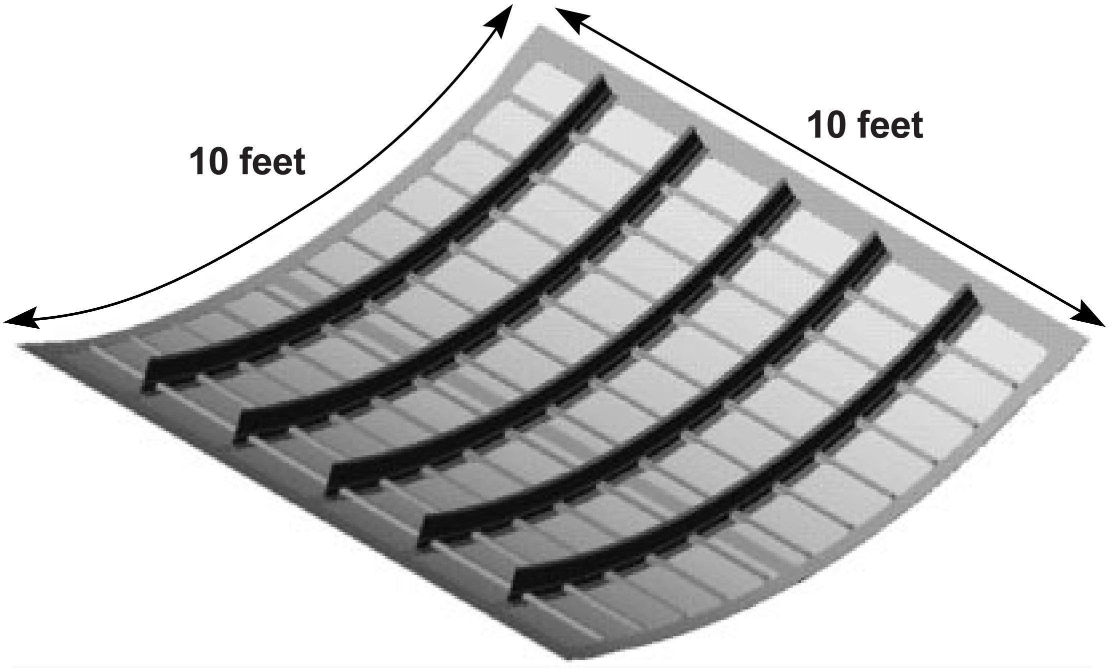

FIGURE 2. OVERALL PANEL DIMENSIONS AND COMPONENT FEATURES

2.2 Cost Model Selection

The cost model selection process was completed by the multi-discipline design team, or integrated product team (IPT), that supported this study. An IPT is a group of people with a common purpose, set of performance goals, and unified approach to which they hold each other mutually accountable. The Boeing Company has successfully used IPTs for ten years. IPTs have greatly improved cross-functional communication, which is needed to reach a common understanding of design and manufacturing issues and analysis techniques.

Several estimating approaches were considered at the beginning of the study. The cost analysis team first determined the appropriate estimating method(s) (detailed process-based, parametric, etc.), and then assessed the capabilities of various software tools that could support the desired method(s). Several commercial tools that employ various estimating techniques are currently available on the market. Another tool that shows promise, the Process Cost Analysis Database (PCAD), was developed during a NASA-funded research and development program. For the most part, the selection of a particular tool constrains the user to estimating techniques unique to that tool, which meant that the tool evaluation had to consider the chosen estimating techniques.

It was decided that the design and process attributes driving the economies of the technologies under consideration could not be accurately represented by traditional estimating methods such a parametric or analogous estimating. These methods rely on subjective assumptions like complexity factors and/or weight-dependent extrapolations; they therefore provide little insight into the causal relationships between design features and process behavior that are considered critical for discreet technology evaluations.

After discussions with industry experts, the IAS team decided that detailed process-based cost analysis was the most appropriate way to provide the resolution for technology comparisons of this type. However, without software tools to automate some of the tasks, this technique could have easily overwhelmed the limited estimating resources on the IAS team. Therefore, the IAS team recognized that productivity and ease of use were also deciding factors for tool selection.

Figure 3 depicts the results of the comparison of cost analysis software tools. Although somewhat subjective in nature, this chart shows the primary functional requirements, along with the score that each tool received in each category. PCAD was originally chosen to store the data and perform analysis for the IAS study. At the time, it scored the highest of all tools available. The PCAD analysis was used to develop the interim cost analysis results presented at NASA Langley in April 1998.

Relative Weighting	20%	15%	10%	20%	15%	20%	100%
Cost Analysis Methodology	**Ease of Use**	**Flexibility**	**Hierarchical Data Storage**	**Process Physics Based**	**Visibility Down to Process Step Level**	**Integration with Office**	**Score**
COSTRAN **(TeamVision Inc)**	**High**	**High**	**High**	**High**	**High**	**High**	**100%**
PCAD **(Nasa - LARC)**	**Med**	**Med**	**Med**	**Med**	**Med**	**Med**	**66%**
SEER - DFM **(Galorath Inc)**	**Med**	**None**	**Med**	**Low**	**Low**	**Low**	**38%**
Cost Advantage **(Cognition Inc)**	**Low**	**None**	**Med**	**Low**	**Low**	**None**	**25%**
Price - H **(Price Systems Inc)**	**Low**	**None**	**Med**	**None**	**None**	**Low**	**20%**

Score	
High	**100**
Med	**66**
Low	**33**
None	**0**

FIGURE 3. RESULTS OF THE COST ANALYSIS SOFTWARE TOOL COMPARISONS

In March 1998, The Boeing Company purchased a license to an advanced software tool called COSTRAN, produced by TeamVision Inc. (www.teamvisioninc.com) to support the HSCT program in their cost analysis efforts. This commercial software has lineage in the NASA-funded PCAD development. When used with the HSCT program, COSTRAN had greater capabilities and higher productivity than its predecessor. As a result, in July 1998, the IAS team decided to utilize COSTRAN and proceeded to migrate the IAS data from PCAD to COSTRAN. The results of this effort are the basis of the cost information contained in this document.

To understand the primary advantage of COSTRAN as compared to the other tools that were considered, consider the Windows architecture. The Windows architecture includes an object technology called the Component Object Model (COM). Most computer users routinely depend upon COM for everyday tasks. For example, when object linking and embedding (OLE) is used to cut or copy an Excel graph and paste it into a PowerPoint presentation or a Word document, COM makes it possible.

COM allows objects to communicate with other objects without regard to their internal details or the PCs on which they were created. COM states only how objects will communicate by expressing attributes of the objects, their associated values, and their relationship to other objects.

COSTRAN is a client/server COM administration tool that utilizes a robust object-oriented database. The COM links are written to the Microsoft Office Suite, Web Browsers, and other popular PC software.

There are several advantages to this innovative tool. Most importantly, the TeamVision approach recognizes that the cost analyst needs the flexibility to represent various levels of information, from parametric to detailed, at different points during the design scale-up, in order to estimate maturing designs accurately. This is because all projects suffer from inconsistent levels of data maturation across the design space; this only becomes exaggerated by product complexity and IPT size and logistics.

At the beginning of design development, parametric or cost estimating relationships (CERs) may be suitable, because minimal information is available, and they at least allow high-level configuration decisions to be sufficiently addressed. However, process technology trades eventually require more rigorous evaluation. Therefore, process physics-based cost models, which provide greater accuracy and design/process sensitivity, are more desirable. COSTRAN allows the analyst to construct models at any resolution where data is available, and to simultaneously link the inputs and outputs of these disparate models in order to roll up the cost for an entire project. For a single project, parametric models could represent some items, and detailed process-based models could represent others. As the design matures and more information becomes available, rapid and intuitive updates to the overall project cost analysis is supported by continuously updating the spreadsheets containing the lower-level information.

To accomplish this, COSTRAN uses its COM engine to integrate all data used to represent a project. The input variables and resultants (outputs) of each spreadsheet can quickly and easily be linked to one another and/or to other COM-compliant software like web browsers and graphics tools. TeamVision developed a technology called Object Synonyms that scans the spreadsheet, builds a list of all known equation variables, and provides a graphical method to define the relationship between these and any other objects used to identify the design and process technologies under consideration. This information is then stored in an object-oriented database that provides the basis for cost calculations and can be used as the starting point for future evaluations.

Another attractive feature is intuitive data representation. Design configurations are typically represented by work breakdown structures (WBSs) that depict the relationship between parts, sub-assemblies, and larger assemblies. COSTRAN employs a graphical tree, like Windows Explorer, to realistically represent the project. It has a “look and feel” familiar to anyone who has used a personal computer in the last five years.

In short, this software provides the flexibility to describe and update process and product information specific to one’s unique data maturity, in a format that is very understandable and easy to learn. At the same time, the client/server object-oriented database maintains data integrity, and it allows multiple people on the IPT to access and share information quickly and make updates as necessary.

2.3 Process/Design Cost Evaluation Matrix

The process/design cost evaluation matrix shown in Figure 4 below, depicts the various scenarios that were considered during the IAS cost evaluation. Several material forms were investigated over a range of potential processing technologies for the components and assemblies comprising each of the desired design configurations.

		Design Options			
Process & Material	Design Detail	Built-Up	Plate	Extrusions	Hybrid
Material	Skin	Sheet	Plate	Extrusion	Plate
	Stringers	Extrusion			
	Frames	Extrusion	Plate	Extrusion	Extrusion
	Shear Ties	Extrusion			
Forming	Skin	Break Form	Break Form	Break Form	Break Form
	Frames	Roller			
	Shear Ties	Roller			
Machining	Skin	Machine	Machine	Machine	Machine
	Stringers	Machine			
	Frames	Machine	Machine	Machine	Machine
	Shear Ties	Machine			
Assembly	Skin/Skin			Friction Stir Weld	
	Stringer/Skin	Auto Rivet			
	Shear Ties/Skin	Auto Rivet	Auto Rivet	Auto Rivet	Auto Rivet
	Frames/Shear Ties	Hand Rivet			
	Panel/Panel	Auto Rivet	Auto Rivet	Friction Stir Weld	Auto Rivet

FIGURE 4. DESIGN AND PROCESS TECHNOLOGIES STUDIED

The built-up configuration is the baseline approach for the panel. The skin is aluminum sheet that is mechanically fastened to the stringers, frames, and shear ties, which are conventionally machined extrusions. The raw skin extrusion width was 30 inches, so two friction stir weld seams were required to reach a raw material size comparable to the plate and built-up designs. The shear tie-to-skin fastener process represents the frame foot-to-skin attachment process for plate, extrusions, and hybrid designs. The remaining configurations are variations of the components and assemblies found in the baseline—variations created by changing the material forms to plate and extrusion while applying conventional and high-speed technologies.

This format will be the basis of all of the cost analysis and results presented below. It should also be noted that the hybrid design depicted in this chart is the result of the study. It employs the best design and process technologies with respect to the IAS cost study goals.

2.4 Cost Evaluation Ground Rules and Assumptions

The cost evaluation ground rules and assumptions are shown in Figure 5. At a high level, a labor wrap rate of $100 per hour was assumed for all fabrication and assembly comparisons. Labor wrap rates are created by dividing the total expenses of a business unit for a given time period by the corresponding number of direct labor hours. However, this practice is typically misleading for process technology comparisons. The use of a generalized wrap rate favors the high-speed machining process, as these machines are typically more expensive to procure and maintain than conventional technology. Further discussion of this and suggestions for possible improvements in future IAS cost studies are presented in Section 4 Outstanding Issues. All recurring labor comparisons are shown at theoretical production unit 100.

Labor

- **$100/hr recurring wrap rate**
- **Labor hours comparisons shown at unit 100**

Material

- **Section extrusions, 5.00 $/lb**
- **Skin/Stringer panel extrusions, 30 $/lb**
- **Plate, 1.60 $/lb**
- **Skin, 2.50 $/lb**

Key Cost Sensitivity Modeling Assumptions

- **Skin/Stringer panel extrusions material cost, 10 - 30 $/lb**
- **Machining velocity, 300 - 3,000 in^3/hr**
- **Recurring labor and material costs only**

FIGURE 5. GROUND RULES AND KEY MODELING ASSUMPTIONS

Material costs were taken from vendor quotes at typical production order quantities, except for the skin/stringer extrusion. The actual cost for this extrusion, taken from the test panel fabrication trials, was used. This cost can be expected to decrease with order quantity; therefore, a cost range was used in the sensitivity analysis.

The cost range used for these extrusions is broad, from $10 to $30 per pound. The upper bound represents current prices based on exclusive low-volume demand from the aerospace community, which greatly increases cost for the material vendor. The lower bound assumes order quantities typical of section extrusions that are used in various industries, which justifies investment in automation.

Key cost sensitivity modeling assumptions are also shown in Figure 5. These were used as the basis of sensitivity analysis presented in Figure 10 and Figure 11.

3 Results

This section provides a database of cost information on various manufacturing processes and design concepts for integrally stiffened fuselage panels.

3.1 Skin/Stringer Design and Process Cost Results

The first cost results presented are the design and process technology trades for the skin/stringer portion of the panel, which are shown in Figure 6. The only approach requiring assembly is the baseline, because the other two approaches are monolithic structures. The single curvature forming cost was considered to be the same in all cases. The effects of double curvature forming were not addressed, because there was insufficient data to reasonably address this process.

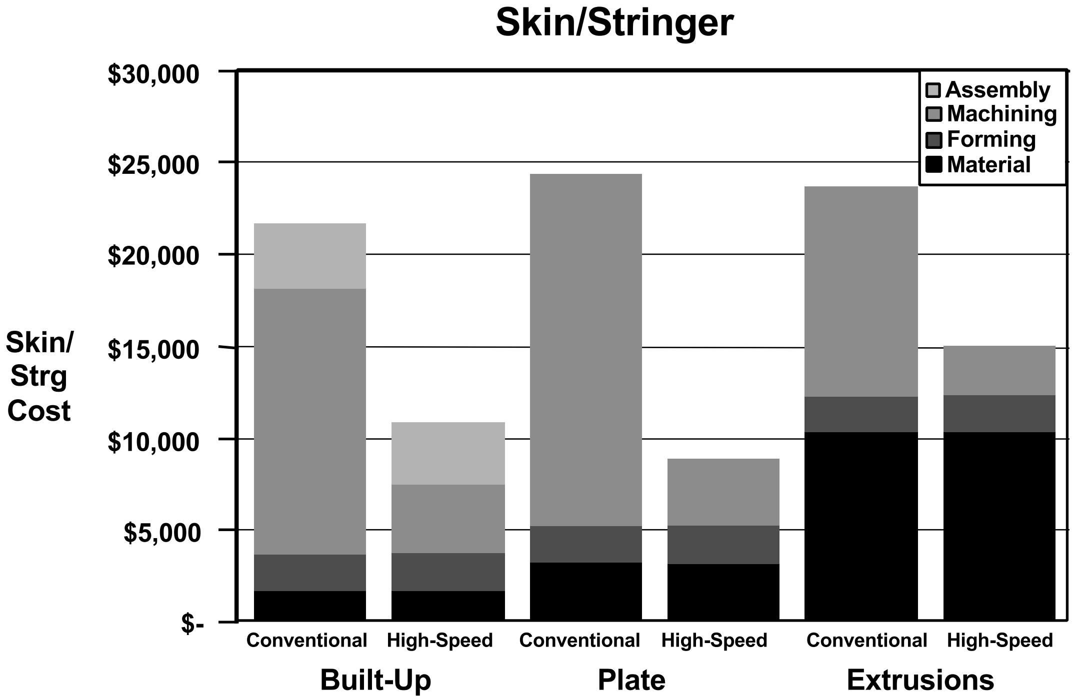

FIGURE 6. RESULT FOR THE SKIN/STRINGER PANEL COMPARISON

Conventional machining of monolithic details adds considerable cost to plate design as compared to the baseline. This is attributable to the absolute material volume that must be removed from plate to arrive at the finished detail. The extrusion design fared better with conventional machining, but it ultimately suffered from the combined raw material and conventional machining cost.

Intuitively, extruded materials seems to offer the advantage of requiring less material removal, which would lower the machining cost for both conventional and high-speed technologies as compared to plate. However, extrusions are more expensive to procure, so the net result, for either of the machining processes studied, is a cost increase compared to the baseline.

High-speed machining substantially improved the cost for all three approaches. Even so, the huge reductions in machining time could not offset the raw material cost for the extrusion, or remedy the additional assembly cost for the baseline. As a result, the cost-optimal solution for the skin/stringer component is a high-speed machined monolithic panel made from plate.

3.2 Frame Design and Process Cost Results

In the case of the frames, a slightly different trend was discovered. As shown in Figure 7, the baseline approach is the most expensive regardless of the machining technology used. This is related to the high assembly costs for built-up structure. It is also affected by the lack of material cost savings that were previously noted for the skin/stringer component and, to a lesser degree, by the forming method that is used to arrive at the proper curvature. In all cases, built-up design requires frame-to-shear tie fastening, which significantly increases the total frame cost.

The economies of the plate design are also interesting when applied to the frame components. In this case, conventional machining for the frames results in near cost equivalence to the baseline. This is primarily due to the elimination of assembly and forming. Since raw plate material must be procured in blocks containing the entire frame curvature envelope, the material cost is higher than the other two configurations. These large blocks also increase the material removal volume, which substantially increases the cost for conventional machining and moderately impacts the high-speed technology as well. However, Figure 7 shows that the application of high-speed machining to the plate and baseline design greatly reduces the total frame cost and results in a 47% cost improvement as compared to the baseline.

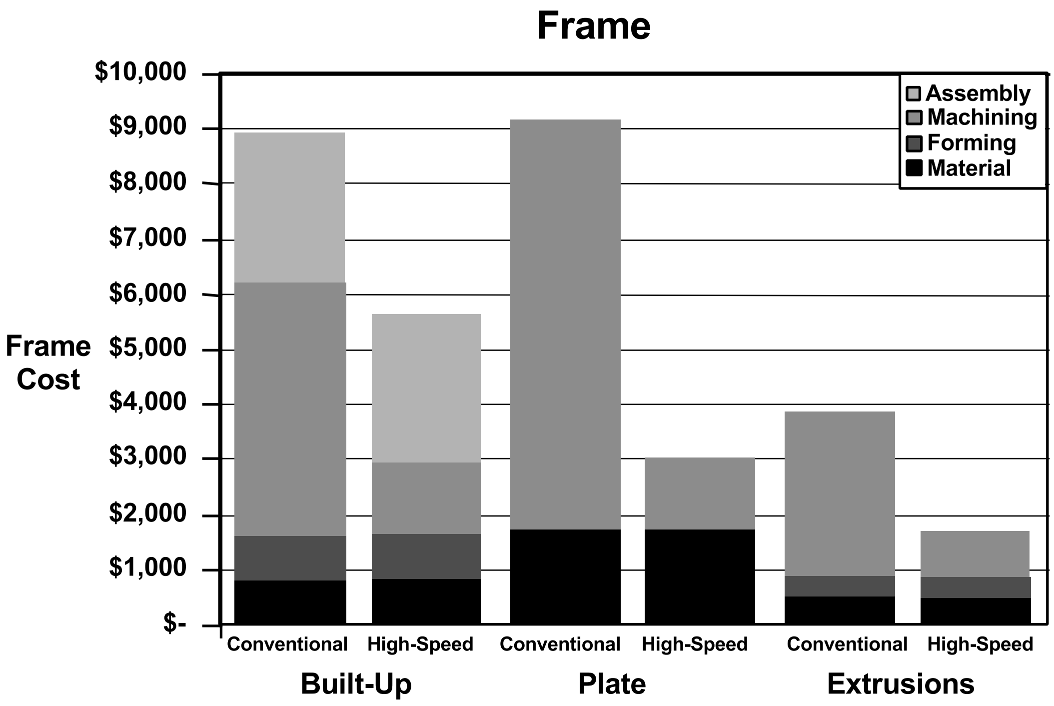

FIGURE 7. RESULTS FOR THE FRAME COMPARISON

The frame components are a good application for extruded materials. This is primarily due to the production quantity material cost for section extrusions. Although some forming would have to be used to provide the proper curvature, the lower material cost provides ample room to absorb the forming cost.

Extrusions also have less material removal volume and therefore are very cost-effective with both conventional and high-speed machining. Obviously, high-speed machining is the best overall. Therefore, extruded materials combined with high-speed machining is the most cost-effective design and process combination.

3.3 Panel Design and Process Cost Results

The next step is to apply this information to the entire IAS panel. This exercise will begin with a summary of the design and process comparisons presented above, and then assess the thresholds for various design attributes and process behaviors driven by the assumptions used in the analysis. In this way, realistic guidelines can be established that may not be readily apparent in the preceding analysis and could prove significant to future studies.

Figure 8 depicts the cost results for the entire IAS panel by combining the data presented in the previous sections plus the cost associated with panel assembly. Conventional machining makes the plate design the least attractive approach. The remaining approaches are within 10% of each other. They would therefore be considered cost neutral, because even the slightest error in estimating assumptions could cause a difference of this size.

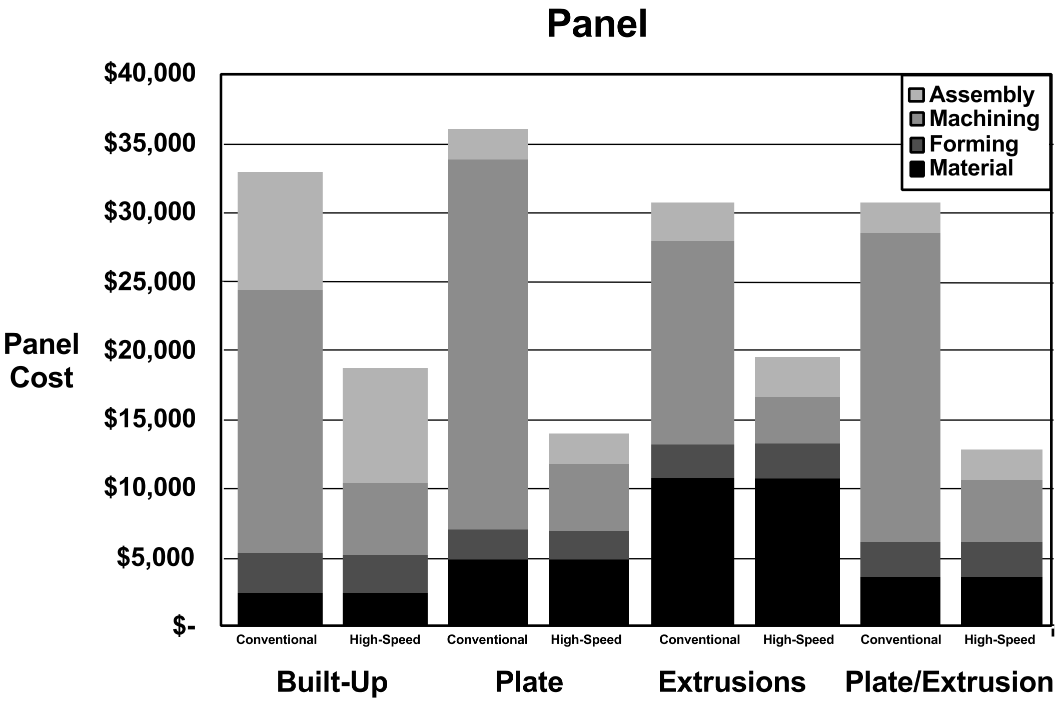

FIGURE 8. COMPLETE PANEL COST RESULTS

High-speed machining substantially improved the cost of all design concepts as compared to their conventionally machined counterparts, with the extruded materials being the least attractive application. As noted earlier, the raw material cost is the greatest contributor to this result and will be discussed in greater detail later in this section. The comparisons already shown demonstrate that the plate design is the most attractive high-speed machining approach. However, an even better alternative can be inferred by the study results.

The new configuration, also shown in Figure 8, is referred to as the hybrid or plate/extrusion design. It is the product of combining the least costly approaches found in each of the previous component sections. Optimal cost can be achieved by mechanically fastening extruded frames to a skin/stringer panel made from plate, then applying high-speed machining.

The next step in the IAS cost analysis is to dive below the surface of these conclusions and discern the cost savings sensitivity to the assumptions made during the study. Seventy-six assumptions were used to estimate the cost of the various design and process combinations. These assumptions range from material recycling cost to surface inspection rates. Comparing the various design permutations and identifying the significant cost savings drivers for each can reduce the number of sensitivity studies that must be performed. The overall results of this effort are shown in Figure 9.

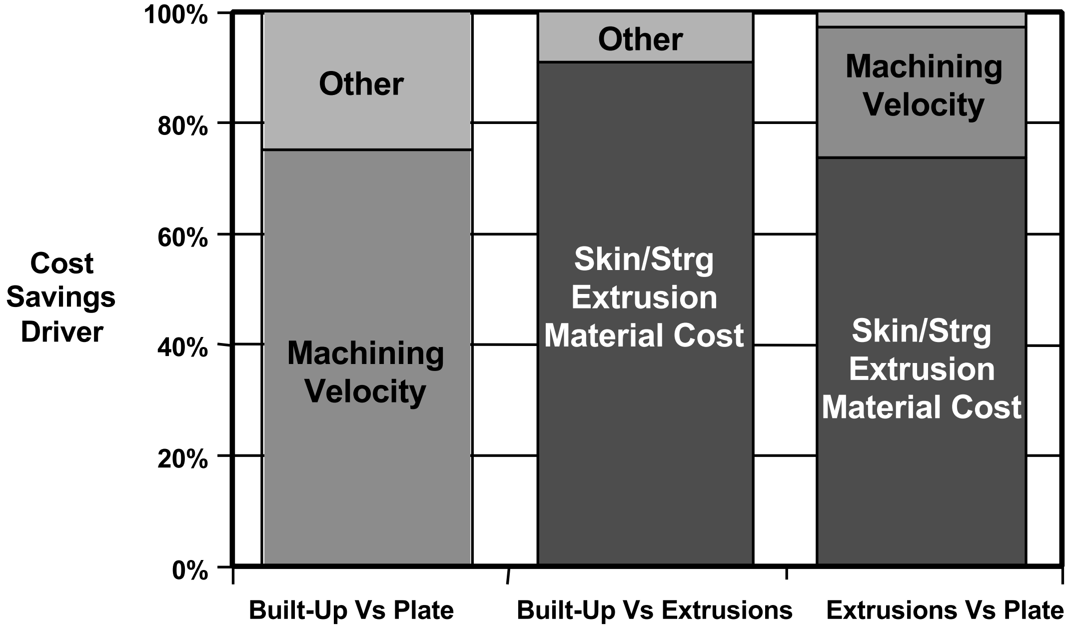

FIGURE 9. COST SAVINGS DRIVER COMPARISON

The “other” category represents the total cost contribution for the assembly and forming processes, which for the most part are negligible. In no case was an assumption in the “other” category above 2%. Figure 9 clearly shows that this category, although represented by several variables in the analysis, has little affect on the results. Therefore, the cost savings drivers to be further studied are as follows:

- In the case of built-up versus plate, roughly 75% of the cost savings is sensitive to the machining velocity.

- In the case of built-up versus extrusion, more than 90% of the cost savings is sensitive to the extruded material cost for the skin/stringer panel.

- In the third case, extrusions versus plate, the assumed extruded material cost savings nearly 73% of the cost savings, and the remainder is attributable to the machine velocity.

The identification of two significant cost savings drivers for sensitivity analysis is complete. The cost of extruded materials and possible range of attainable machining velocities will be investigated in the following charts. (See Figure 5 for assumed values.)

Figure 10 depicts machining velocity as an improvement factor over the conventional removal rates. High-speed machining has been found to be at least ten times faster than conventional machining for three-axis parts. Each design approach has been plotted as a function of the machining improvement factor to determine the resulting cost that could be expected if removal rates were increased to high-speed removal rates. As the machining rate is increased by a factor of 2.9 and beyond, the plate design becomes cost-optimal. Another interesting conclusion that is clear from this analysis is that, once the machining velocity increases beyond a factor of 7, it no longer impacts total panel cost, because the cost of materials and other processes now takes precedence and sets the minimum achievable cost under the study conditions.

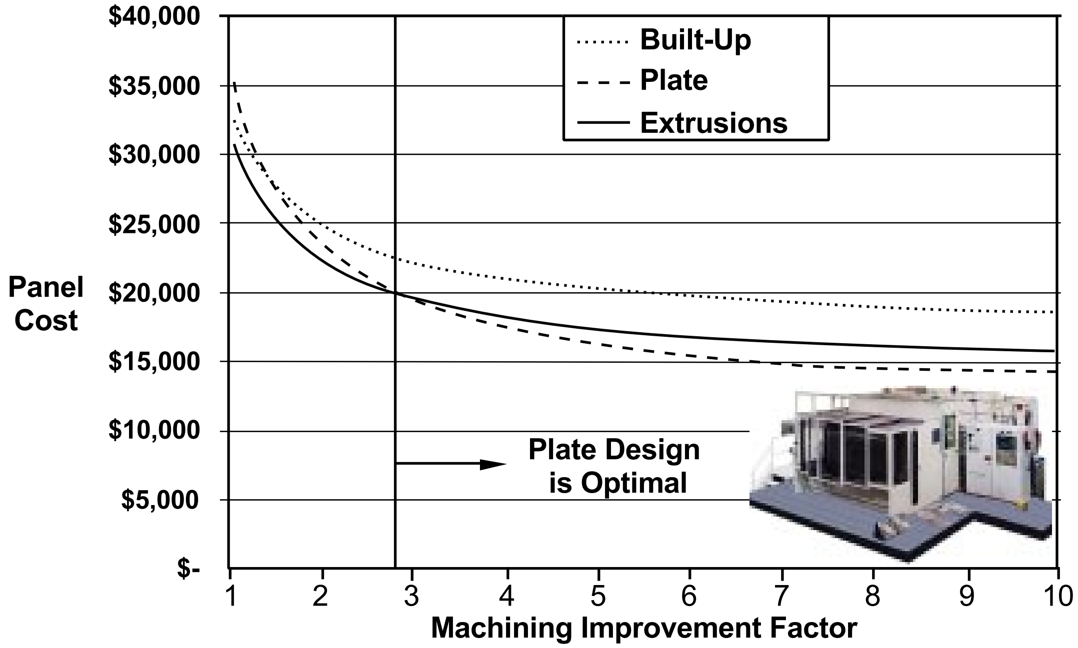

FIGURE 10. SENSITIVITY RESULTS FOR PANEL COST SAVINGS DRIVER CASES 1 AND 3

Figure 11 shows the panel cost for each design concept plotted as a function of increasing skin/stringer extrusion cost. If the machining improvement factor is held constant at 10, cost equivalence between the extrusion and built-up concepts occurs when the skin/stringer extrusion cost is roughly $27 per pound.

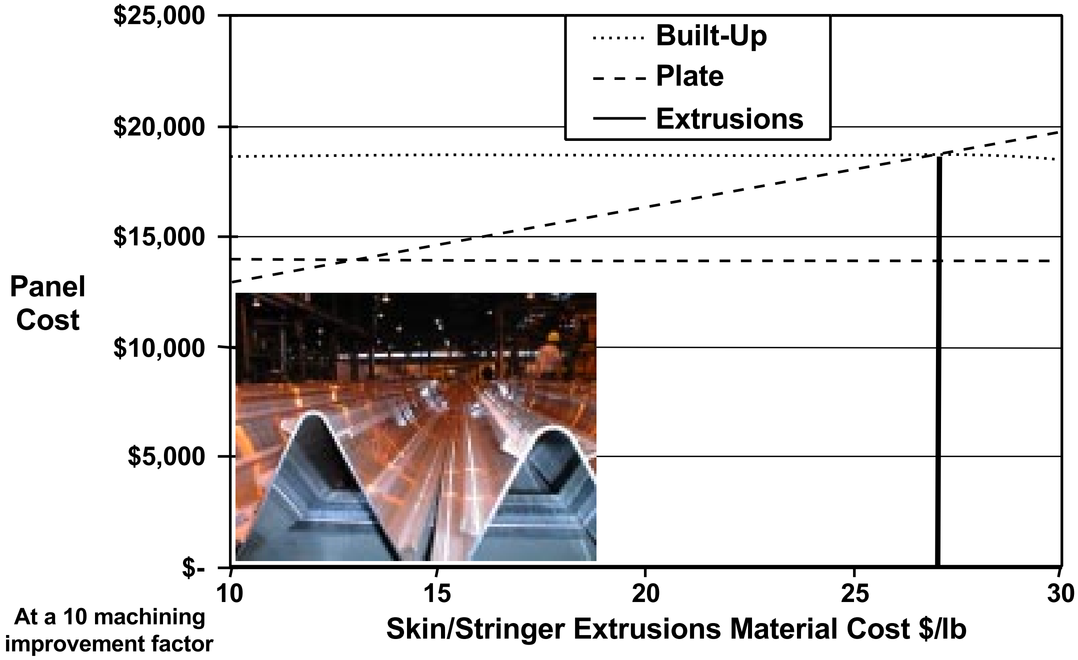

Figure 11. Sensitivity Results for Panel Cost Savings Driver Cases 2 and 3

Continuing this comparison further to investigate possible extrusion cost reductions, the plate concept remains preferred until the extrusion cost crosses the $12 per pound threshold. Below that threshold, very little could be done to compete with extrusions on a pure cost basis. However, it should be noted that this is a substantial extrusion cost reduction, one highly unlikely in the foreseeable future, unless significant material technologies are developed, and volumes increase with multi-industry demand.

Figure 12 summarizes all preceding sensitivity analysis into one convenient chart. This is a convenient way to visualize the cost dependencies of, and quantify potential thresholds that exist between, the three design concepts, at varying extruded material costs and machining velocities.

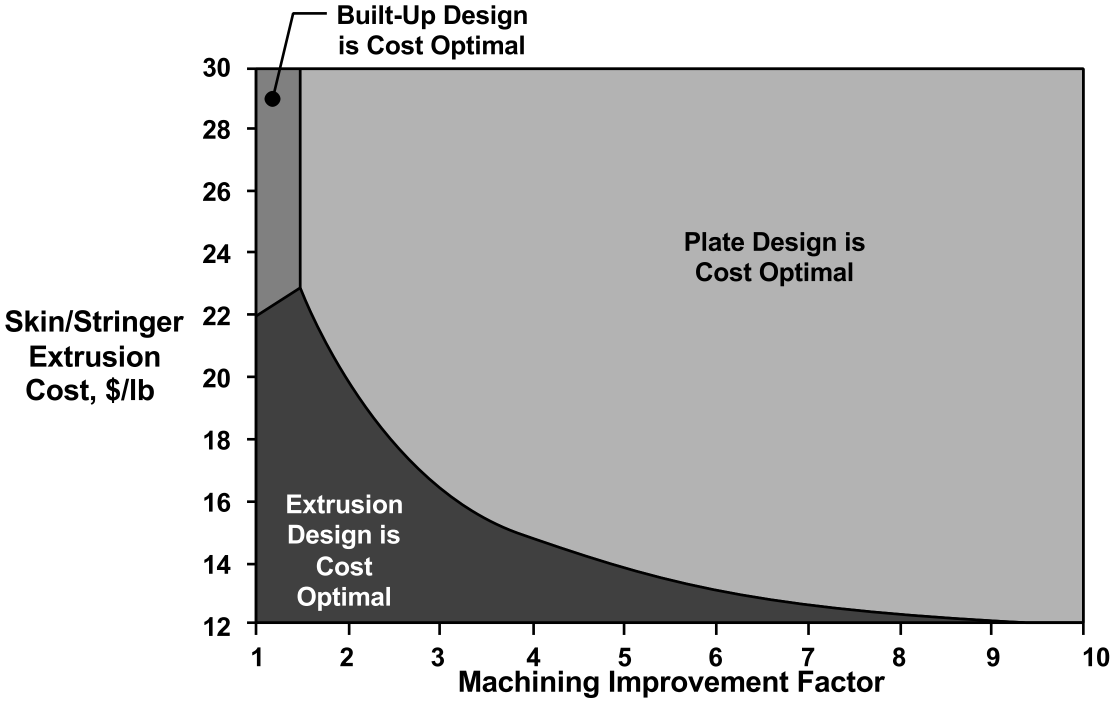

FIGURE 12. COMBINED SENSITIVITY RESULTS FOR DESIGN/COST-OPTIMAL SPACES

According to this chart, if the extruded material cost is greater than $22 per pound and the machining improvement factor is less than 1.7, then the built-up structure is the most cost effective design concept. The extrusion concept becomes most cost effective when the combination of raw material cost and the machining improvement factors stay within the labeled area. The plate concept is the most robust approach, because it covers a broader and more reasonable range of extruded material cost and machining improvement factor combinations.

In summary, as shown in Figure 13, the high-speed hybrid design is the most cost-effective. This is realized by changes first to the machining technology and then to the design. The application of high-speed machining to the baseline provides a 43% cost reduction as compared to the current technology baseline. By itself, this is a rather attractive cost improvement, considering that very little development cost would be incurred (because the design remains constant and high-speed machining is well understood for this application). However, to achieve maximum cost reduction, the hybrid panel (the plate skin/stringer panel with extruded frames) should be considered. It reduces the cost by another 18% as compared to the high-speed machining baseline.

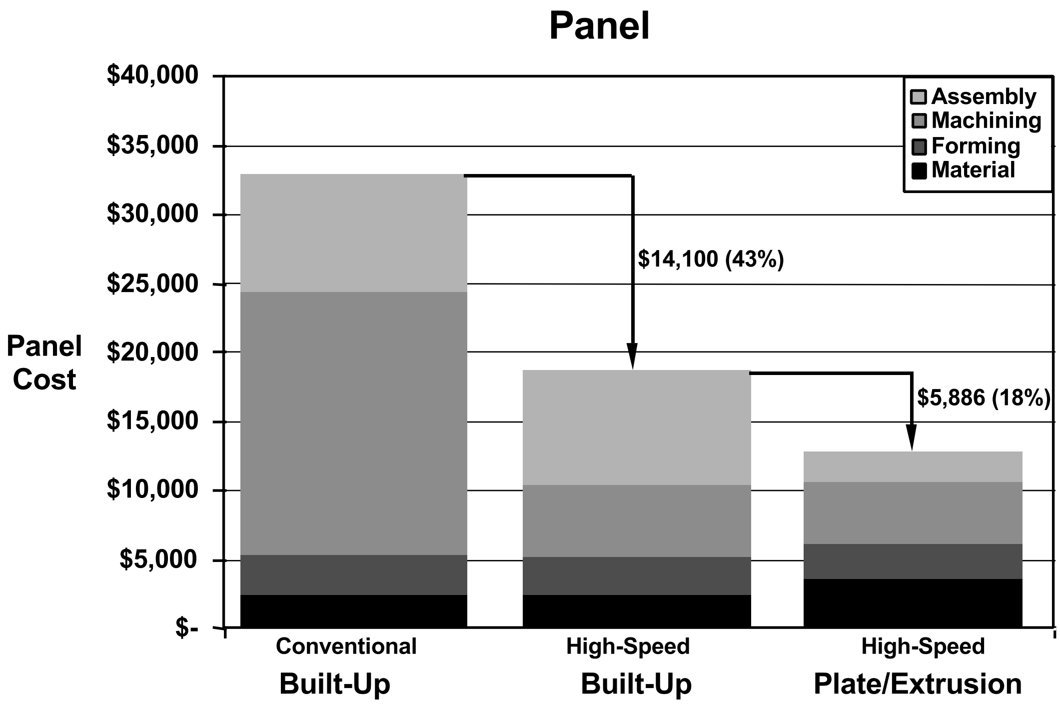

FIGURE 13. BASELINE COMPARISON OF RECURRING COST SAVINGS

4 Outstanding Issues

There are two outstanding issues that need to be explored during future studies. Hopefully they can be resolved before large investments are committed in response to the cost savings results presented in this report.

Overall, the use of generalized wrap rates to convert recurring labor hours into dollars can be misleading when disparate technologies are compared. It is generally understood that manufacturing processes consume an array of resources and thereby have a specific “cost of capacity.” To provide greater cost accuracy, it is recommended that follow-on estimates consider: the differences in capital costs; labor skill levels and support personnel to operate such equipment; quality yield rates of particular material forms under different machining conditions; and any other applicable cost entities. The cost of capacity of conventional machines may or may not be different than that of high-speed machines, although it might intuitively appear that they most certainly do. A more thorough investigation into these cost uncertainties will improve clarity and accuracy.

More significantly, fuselage skins are critical appearance items for commercial aircraft. They are not acceptable to customers if the surface finish is degraded. Under the current manufacturing scenario, neither the hybrid design nor any other monolithically machined panel would provide the same surface finish as built-up structure. A polishing process that meets skin finish tolerances could be conceived, but neither the process nor its associated costs were considered during this analysis. If an acceptable finish could not be achieved through polishing, or if the addition of a polishing process increased the recurring cost by more than 18%, the high-speed built-up structure would be preferred on the basis of cost.

Figure 13 shows that a cost savings of 43% is achieved simply by applying high-speed machining to the current built-up panel design. The majority of the cost savings can be attributed to the application of high-speed machining; by focusing on this portion of the savings, the design development costs could be decreased. Replacing the built-up frames with extruded frames that are mechanically fastened to the built-up skin-and-stringer panel could potentially enhance the recurring cost savings. This semi-monolithic approach offers the best blend of achieving surface finish requirements, providing considerable recurring cost savings, and reducing design development costs. All these factors contribute to accelerated positive cash flows for the project. However, this alternative was not envisioned at the onset of the IAS study. It is the professional recommendation of the supporting cost analyst, and is presented here for potential future consideration.

5 Conclusions and Recommendations

The hybrid design is recommended for down selection and further design review. This recommendation is based on the design concepts, ground rules, and assumptions provided by the IAS team. A high-level summary of the expected cost benefits is shown in Figure 14.

HYBRID DESIGN, made from high-velocity machined Plate Skin and Extruded Frames is the most cost effective design and offers:

- **61% recurring labor and material cost savings vs. Built-Up design using high-speed machining process.**
- **$200/sq.ft. savings vs. conventional Built-Up sheet metal.**
- **1.7 million dollar savings per 777 sized aircraft. (1.4% of list price).**

FIGURE 14. IAS COST ANALYSIS CONCLUSIONS

REPORT DOCUMENTATION PAGE

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13. ABSTRACT *(Maximum 200 words)*

The objective of the Integral Airframe Structures (IAS) program was to demonstrate, for an integrally stiffened structural concept, performance and weight equal to “built-up” structure with lower manufacturing cost. This report presents results of the cost assessment for several design configuration/manufacturing method combinations. The attributes of various cost analysis models were evaluated and COSTRAN selected for this study. A process/design cost evaluation matrix was developed based on material, forming, machining, and assembly of structural sub-elements and assembled structure. A hybrid design, made from high-speed machined extruded frames that are mechanically fastened to high-speed machined plate skin/stringer panels, was identified as the most cost-effective manufacturing solution. Recurring labor and material costs of the hybrid design are up to 61 percent less than the current built-up technology baseline. This would correspond to a total cost reduction of $1.7 million per ship set for a 777-sized airplane. However, there are important outstanding issues with regard to the cost of capacity of high technology machinery, and the ability to cost-effectively provide surface finish acceptable to the commercial aircraft industry. The projected high raw material cost of large extrusions also played an important role in the trade-off between plate and extruded concepts.

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