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PRELIMINARY DESIGN OF THE HIGH SPEED CIVIL TRANSPORT BASED ON PRODUCTIVITY INDEX

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Abstract

Recent industry and NASA research suggests that improved technology could make the next generation High Speed Civil Transport economically and environmentally successful. The focus of the study presented in this paper was to investigate the effect of multi-disciplinary design changes on the criterion function - Productivity Index of the HSCT aircraft. Manufacturing costs were also investigated.

The study was performed using ACSYNT, a multi-disciplinary computer program for conceptual and preliminary design and evaluation of advanced aircraft configurations. The objective was to modify a baseline configuration to maximize the criterion function and to determine the ramifications of these changes on the design and production costs. The design variables manipulated included wing area, engine thrust, turbine inlet temperature, composite structural materials, and payload, as well as the effect of using drag reduction techniques such as Laminar Flow Control. Constraints such as landing fieldlength and approach speed were applied to the process.

The effect of these design variables on the criterion function and cost are presented. In addition, a comparison between the HSCT and the Boeing 747-400 is discussed.

Nomenclature

ACSYNT:	AirCraft SYNThesis Code
LFC:	Laminar Flow Control
HSCT:	High Speed Civil Transport
P.I.:	Productivity Index
t/c :	Thickness to chord ratio
SFC:	Specific Fuel Consumption
TOGW:	Takeoff Gross Weight

Introduction

Over the past five years, intensive research by the National Aeronautics and Space Administration (NASA), U.S. aircraft and engine manufacturers, as well as similar activities in Europe and Asia, has shown that improved technology could make the next generation High Speed Civil Transport (HSCT) commercially successful (1). This success would be judged by the HSCT's ability to be profitable, reliable and environmentally compatible (2).

HSCT Market Projections and Challenges

Supersonic flight is still extremely appealing. By flying faster, the HSCT would allow the airline industry to boost its number of passenger-miles while reducing the time in the air for the passengers. This high speed arena represents a marketplace in which the American industry must be competitive (2). New HSCTs would be required to have:

1) Approximately twice the range of the Concorde
2) Approximately three times the Concorde passenger capacity

3) Meet strict noise standards (FAR 36 -Stage 3)
4) A fare structure only modestly higher than those of current subsonic aircraft.

Study Objectives and Analysis Method

The scope of this study focuses on the effects of multi-disciplinary variations on the HSCT manufacturing costs and on the criterion function - Productivity Index. A baseline configuration of the HSCT, representing a "constrained" conceptual aircraft design similar to the one determined by Boeing, has been used.

The Productivity Index of a commercial transport aircraft is given by the equation:

$$P.I.\ (knots) = \frac{\text{Payload x Block Speed}}{\text{Operating Empty Weight + Block Fuel Weight}} \quad (1)$$

The P.I. is a function of many design variables that can be controlled by the multiple technical disciplines. These disciplines, such as Aerodynamics, Propulsion, and Structures can affect the Block Speed, Fuel Weight and Empty Weight respectively.

Additionally, this study addresses the effect of the multi-disciplinary design variables on the associated costs in the following areas:

1. Manufacturing Cost
    - First Unit Cost
    - Airframe
    - Avionics and Instrumentation
    - Assembly
2. Research and Development Cost
    - Airframe Development
    - Airframe Engineering
3. Aircraft Production Cost
    - Sustaining Engineering
    - Sustaining Tooling
    - Production Aircraft

These costs directly determine the selling price of the aircraft to the airline. Therefore, a careful understanding of the effect of the "upstream" design variables on the "downstream" manufacturing cost is necessary to ensure that the HSCT can be designed, manufactured, sold, and supported without significant financial risk.

The analysis conducted during this study was done using the Aircraft Synthesis Code - ACSYNT. ACSYNT is a multi-disciplinary computer program for the design of advanced aircraft configurations, and is the result of research conducted by the NASA Ames Research Center, and enhanced with a graphical interface by the Virginia Polytechnic Institute (VPI).

The coupling of the design variables with the optimization of the system is illustrated in figure 1. In order to optimize the preliminary design of the HSCT with respect to cost and other criteria, constraints have to be applied to the process. These operational constraints are usually related to performance characteristics such as:

- Landing Field Length - 11500 feet maximum
- Approach Speed - 145 knots
- TOGW - 900000 pound maximum

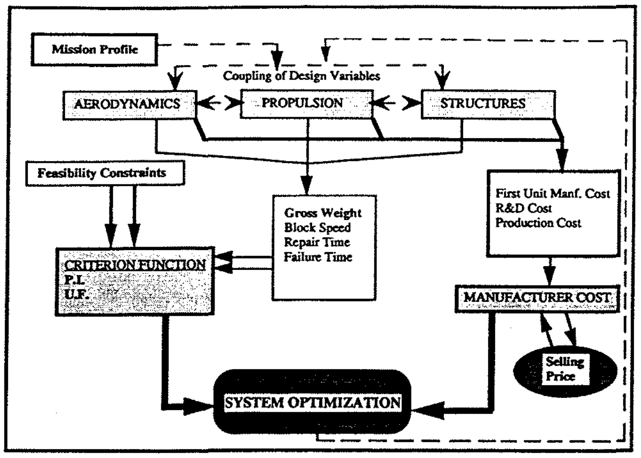

FIGURE 1. Methodology for Optimum Design

Baseline Aircraft

The Georgia Tech baseline airplane used for this study was similar to Boeing 1992-1993 Model 1080 aircraft. In its studies, Boeing determined that a cruise speed of Mach 2.4 would provide a good balance in trip time benefit and technology risk $^{(3)}$. Figure 2 shows the baseline model that was created in ACSYNT.

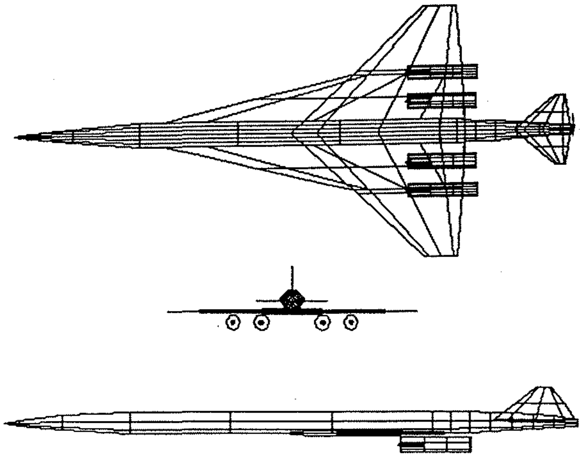

FIGURE 2. HSCT Baseline Aircraft

The mission profile for the initial analysis of the baseline aircraft was determined based on the following criteria:

- Continuous over open water trans-Pacific travel
- HSCT city pairs less than 5000 nautical miles apart
- HSCT market pairs with runways in excess of 11500 feet

The initial mission profile which will be referred here as mission 1, was specified to have a takeoff and climb segment to an initial cruise altitude of 54000 feet, after which a step cruise was implemented. Following a step cruise to approximately 65000 feet, a descent to 5000 feet was specified, followed by approach and landing.

This mission 1 profile was modified once the revised baseline was determined This modification is referred to as mission 2. In addition to this, the revised baseline was "flown" through several subsonic/supersonic cruise missions. This was done to evaluate these mission effects on the P.I. and the manufacturing costs. Currently, the HSCT will be operationally limited by regulations which prohibit overland supersonic flight (4). The subsonic/supersonic segments involved the following profiles.

Mission 3: 500 nmi. Mach 0.85 cruise / ~ 4500 nmi supersonic cruise.
Mission 4: 750 nmi Mach 0.85 cruise / ~ 4250 nmi supersonic cruise.
Mission 5: 1000 nmi Mach 0.85 cruise / ~ 4000 nmi supersonic cruise.
Mission 6: 1250 nmi Mach 0.85 cruise / ~ 3750 nmi supersonic cruise.

The subsonic/supersonic mission profile is illustrated in figure 3.

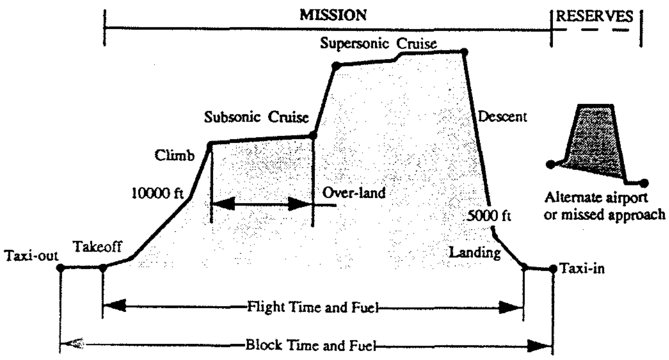

FIGURE 3. Revised Mission Profile

Multi-Disciplinary Analysis Methodology

To evaluate the effect of design changes on the baseline aircraft, several design variables were manipulated. For aerodynamics, focus was placed on variables that impacted block speed and the operating empty weight (OEW). Propulsion changes were targeted at the fuel weight. Similarly, structures variations impacted the OEW. Overall, all of these variations affected the aircraft cost.

Aerodynamics Methodology of Parametric Variations

The economic viability of the High Speed Civil Transport depends significantly on the cruise aerodynamic efficiency. A one percent reduction in the cruise drag will save approximately 4900 pounds of fuel, and reduce the mission sized takeoff weight by some 7700 pounds (5). The design variables selected to influence the aerodynamic efficiency of the aircraft included:

1. The wing surface area
2. The cruise Mach number
3. The t/c ratio of the wing root
4. The drag reduction technique (LFC)

According to recent studies, with the LFC technology being developed by NASA cooperative research, it is reasonable to assume that approximately 90 percent of the aircraft wing could be laminarized (6). This would result in an approximate drag reduction of 11 %. Further studies indicate that an approximately 6 % reduction in drag could be achieved if HLFC was employed exclusively on the wing leading 'edge. To determine the effect of HLFC technology on the baseline, a laminar to turbulent factor was used in the ACSYNT calculations. The weight of the system was assumed to be approximately 4000 pounds (5).

The wing area of the baseline aircraft was manipulated to observe its effect on the criterion function. The baseline area of 7700 square feet was varied between 7000 and 8500 square feet, while maintaining a constant wing sweep and aspect ratio. Additionally, the wing root thickness to chord ratio and cruise Mach numbers were also varied.

TABLE 1. Multi-disciplinary variations

AERODYNAMICS				PROPULSION					STRUCTURES			
Wing Area(ft^2)	Cruise Mach #	Wing Root t/c	LFC	Engine Thrust (lb)	BPR	Engine Weight (lb)	SFC factor	TIT(R)	Wing factor	Fuselage factor	Engine factor	PL(pax)
									0.85 (-15%)	0.85 (-15%)	0.85 (-15%)	
7000 (-9.1%)	2.2 (-8.3%)	0.028 (-12.5%)				6000 (-25%)	0.60 (-14.3%)		0.90 (-10%)	0.90 (-10%)	0.90 (-10%)	280 (-6%)
7500 (-2.6%)	2.3 (-4.2%)	0.030 (-6.3%)		50000 (-5.7%)		7000 (-12.5%)	0.65 (-7.1%)	2400 (-1.2%)	0.95 (-5%)	0.95 (-5%)	0.95 (-5%)	290 (-2.7%)
7700 **(0%)**	**2.4** **(0%)**	**0.032** **(0%)**	**none** **(0%)**	**53048** **(0%)**	**0.0**	**8000** **(0%)**	**0.70** **(0%)**	**2430** **(0%)**	**1.0** **(0%)**	**1.0** **(0%)**	**1.0** **(0%)**	**298** **(0%)**
8000 (3.9%)	2.5 (4.2%)	0.034 (6.3%)	6%	55000 (3.7%)	0.1	9000 (12.5%)	0.75 (7.1%)	2500 (2.8%)				310 (4%)
8500 (10.4%)	2.6 (8.3%)	0.036 (12.5%)	11%	60000 (13.1%)	0.3	10000 (25%)	0.80 (14.3%)	2550 (4.9%)				
					0.5			2600 (7%)				
					0.8							

Propulsion Methodology of Parametric Variations

Five key areas were targeted for this propulsion system analysis. These were:

1. Maximum engine static thrust
2. Engine bypass ratio
3. Engine weight
4. Specific fuel consumption at cruise
5. Turbine inlet temperature

Several of these variables are coupled. The bypass ratio, for example, would affect both the engine weight and the SFC.

The baseline maximum static thrust was set at approximately 53000 pounds. To evaluate the thrust sensitivity, the static thrust was varied from 50000 pounds to 60000 pounds, levels which represent feasible engine performance. Thrust levels below 50000 pounds were insufficient for the climb segment of the mission. The propulsion system used in this study was an engine with zero bypass ratio. This ratio was marginally increased through 0.8.

The engine weight is a variable that is deeply coupled with technology. For this study, the engine weight, exclusive of the nacelle, nozzle and strut, was varied between 6000 and 10000 pounds.

The fuel required for a stated mission is heavily dependent on the specific fuel consumption of the propulsion system. A weighted factor was used by the synthesis code to represent the current trends in the propulsion system SFC performance. During this study, this factor was specified between 0.6 and 0.8, values representative of available technology. Finally, the turbine inlet temperature which dictates the cycle efficiency of the engine, was varied between 2400 and 2550 degrees Rankine. These numbers, although low, should enables the observation of the propulsion sensitivities.

Structures Methodology of Parametric Variations

Advanced technology aircraft such as the HSCT require projections to account for anticipated developments in technology. Structures technology on the HSCT can be measured according to the following criteria:

1. Temperature Resistance
2. Environmental Resistance
3. Material Cost / Availability
4. Processibility

In this study, material projections were made with the use of technology factors. These factors were applied to the wing structure, the fuselage and the engine. In ACSYNT, these factors account for the reduction in the weight of a component with the advancement of technology. The baseline value of 1.0 (aluminum) was reduced to 0.85.

In summary, the variations are tabulated in Table 1. The normalized percentage is shown in parenthesis ( ).

Discussion of Variations on the Baseline Aircraft

Productivity Index Results

The effect of these parametric variations on the baseline Productivity Index can now be presented. Figure 4 shows the effect of increasing and decreasing the aerodynamic design variables. As shown, the cruise Mach number exhibited the greatest sensitivity with the P.I. By increasing the Mach number from 2.4 to 2.6, the unconstrained P.I. was increased approximately 6%. Reducing the Mach number to 2.2 resulted in a P.I. of 107.07 knots, a drop of 11.93 knots. The LFC factor also resulted in an increase in the Productivity Index. Leading edge LFC (6% turbulent drag reduction) resulted in a 1.48% P.I. increase whereas full wing LFC improved the P.I. by 2.62%. The wing area and wing root t/c only increased the criterion function marginally.

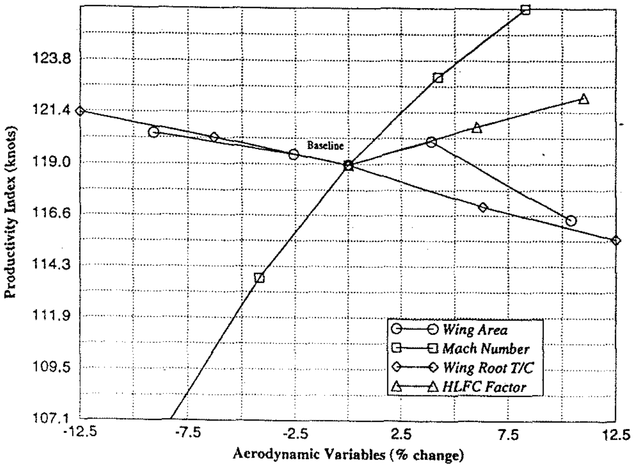

FIGURE 4. Productivity Index Sensitivity to Aerodynamics

The sensitivity of the propulsion variables are shown in figure 5. The P.I. was extremely sensitive to the SFC factor. As the SFC factor is reduced from 0.7 to 0.6, the P.I. is increased significantly. Engine weight was also influential. A 2000 pound reduction in engine weight resulted in a 5.78% increase. The study also indicated that the turbine inlet temperature and the maximum thrust will also have to be increased to maximize the Productivity Index. As shown in figure 5, the bypass ratio had a negligible effect on the criterion.

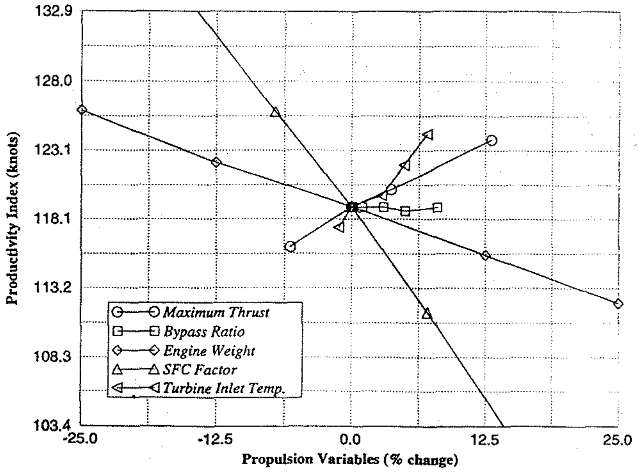

FIGURE 5. Productivity Index Sensitivity to Propulsion

The structures technology factors simply applied a weight reduction scheme to account for yearly improvements in structures technology. Figure 6 shows the structures sensitivity.

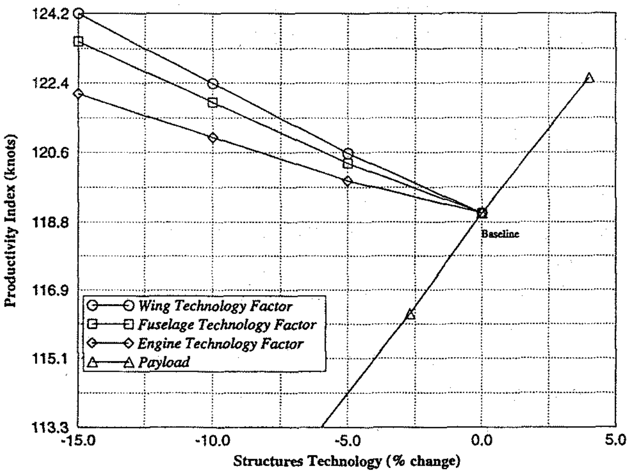

FIGURE 6. Productivity Index Sensitivity to Structures Technology

The wing factor exhibited the greatest sensitivity. The payload had a positive effect on the P.I. when the total number of passengers was increased from 298 to 310.

Having found the maximum unconstrained Productivity Index, the landing fieldlength feasibility constraint was applied. The maximum constrained P.I. for aerodynamic variables occurred at the following points:

- Wing Area = 8000 ft^2
- Cruise Mach = 2.5
- Wing t/c = 0.028
- LFC = Full wing application

TABLE 2. Revised Baseline Design variables

	Value	P.I.(kt)	ΔP.I(kt)		Value	P.I.(kt)	ΔP.I.(kt)		Value	P.I.(kt)	Δ P.I(kt)
Area	8000	120.07	1.08	Thrust	60000	123.83	4.84	WingF	0.85	124.24	5.25
Mach	2.5	123.05	4.06	BPR	0.0	118.99	0.00	FuseF	0.85	123.51	4.52
Wing t/c	0.028	121.37	2.38	Weight	7000	122.19	3.20	Engine F	0.85	122.12	3.13
LFC	11%	122.12	3.13	SFC	0.65	125.81	6.82	PayldF	298	118.99	0.00
				TIT	2550	124.23	5.24				

TABLE 3. Revised Mission Results and Constraints.

Mission	TOGW	OEW	Block Fuel	BlockSpeed	P.I.	Fieldlength
1	717492	322634	270369	1184	118.99	11400
2	554250	271911	179627	1219.9	161.01	9069
3	581980	275753	198892	1050.9	131.96	9347
4	703960	291911	284233	983.6	101.74	10568
5	900679	315705	423689	921.9	74.31	12490
6	901114	310717	428062	863.0	69.62	11585

The remaining results for propulsion and structures changes are listed in Table 2.

Revised Missions

To observe the effect of segment cruise speed on the Productivity Index, the revised baseline was "flown" through a series of subsonic legs. These effects are shown in Table 3. The subsonic mission segments resulted in a heavier aircraft and in a reduction in P.I. Missions 5 and 6 did not meet the TOGW and landing fieldlength feasibility constraints.

Multi-Disciplinary Effects on Manufacturing

The Manufacturing costs of the High Speed Civil Transport were assessed following the design variations. As mentioned earlier, the aircraft costs were divided into three primary categories.

1. Manufacturing Costs
2. Research and Development Costs
3. Aircraft Production Costs

First Unit Manufacturing Cost.

From figure 7, it can be seen that the manufacturing cost of manufacturing the first aircraft unit is very sensitive to an increase in the cruise Mach number. By increasing this Mach number from 2.4 to 2.6, the baseline first unit cost of 1.041 billion dollars was raised by 19 million dollars. A wing area increase results in a 0.57 % increase or approximately 6.02 million dollars. The effect of root t/c and LFC were less pronounced. A note of caution must be added to the LFC results; ACSYNT does not account for the added complexity of machining and assembly of the tubes, pumps and associated hardware necessary for Laminar Flow Control systems. Thus, with this correction, the manufacturing slope should change slightly upwards. The revised baseline first unit cost is also shown in figure 7.

For propulsion changes, the greatest sensitivity was exhibited by the SFC factor. This is due to the fact that an increase in the SFC factor resulted in a significant increase in the TOGW, a primary factor in the manufacturing cost calculation. Maximum thrust and engine weight were also sensitive. Finally, as shown in figure 8, an increase in the Turbine Inlet Temperature had a favorable effect.

Figure 9 shows cost sensitivity to structural design factors. From this figure, it can be seen that the fuselage is a primary driver in the first unit cost estimate. The results presented suggest that a cost reduction of $21 million could be achieved with aggressive structures technology applied to the fuselage. Wing and engine factors were less sensitive.

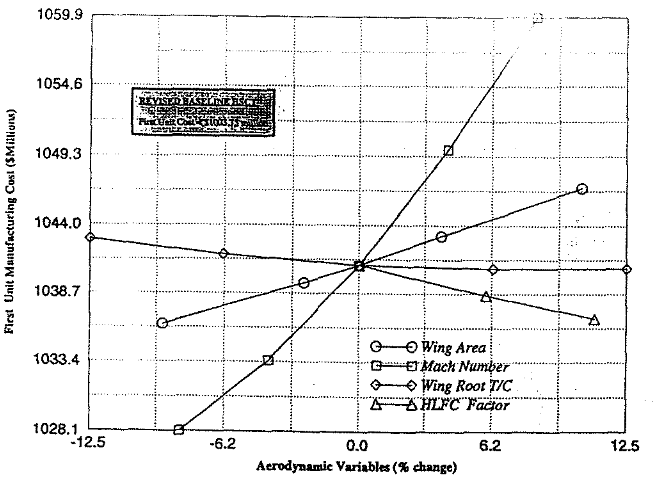

FIGURE 7. First Unit Manufacturing Cost Sensitivity to Aerodynamics

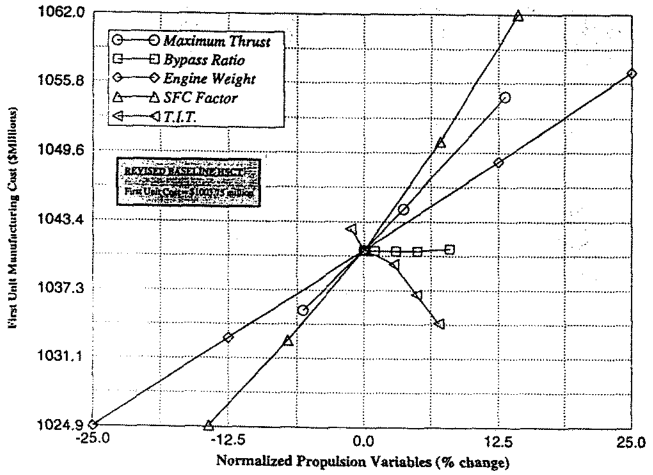

FIGURE 8. First Unit Manufacturing Cost Sensitivity to Propulsion

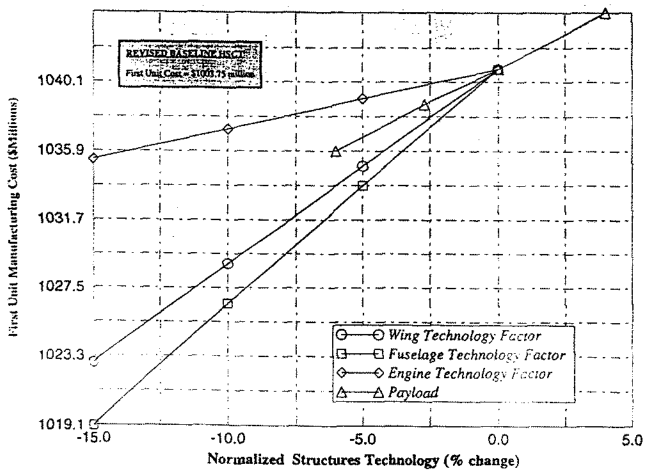

FIGURE 9. First Unit Manufacturing Cost Sensitivity to Structures

Research and Development Cost

As figure 10 illustrates, the wing area has the highest sensitivity of all the variables. As wing area is increased, the costs associated with wing research, development and validation increase linearly.

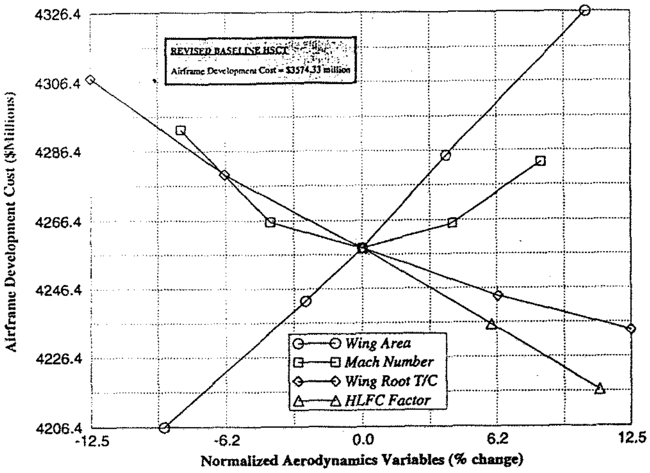

FIGURE 10. Airframe Development Cost Sensitivity to Aerodynamics

The opposite effect holds for the wing root thickness to chord changes. According to the calculation done in ACSYNT, a reduction in t/c from the baseline value to 0.028 results in an increase in airframe development costs. The Mach number variation exhibits a peculiar quality. As shown in figure 10, a Mach increase or decrease results in additional airframe development costs. Results for propulsion and structures effects were also found.

Aircraft Production Cost

The costs associated with the full scale production of a new aircraft are quite large. Historically, transport aircraft manufacturers have recouped their investment costs after selling 400 - 600 airplanes. Key variables in the production of these aircraft have been the costs of sustaining the assembly line, costs such as engineering and tooling. As such, the sustaining costs of producing 445 HSCT type aircraft are investigated (2). Figure 11 shows the effect of aerodynamic variables on the sustaining engineering costs.

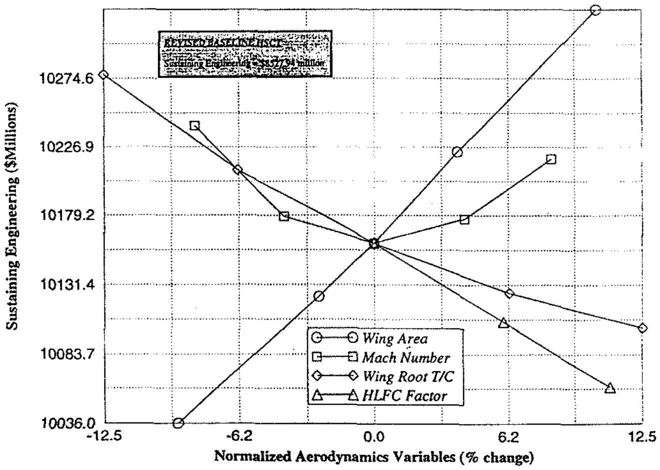

FIGURE 11. Production Cost Sensitivity to Aerodynamics

The trends associated with these variables bears resemblance to those observed in the R & D analysis. Once again we observe that the costs are extremely sensitive to the wing area and the wing root t/c ratio. The HLFC factor results in a decrease in production costs. As noted in earlier, the slope of the HLFC factor should once again be carefully interpreted. The slopes of propulsion and structures variables are similar to the ones observed in the R & D section.

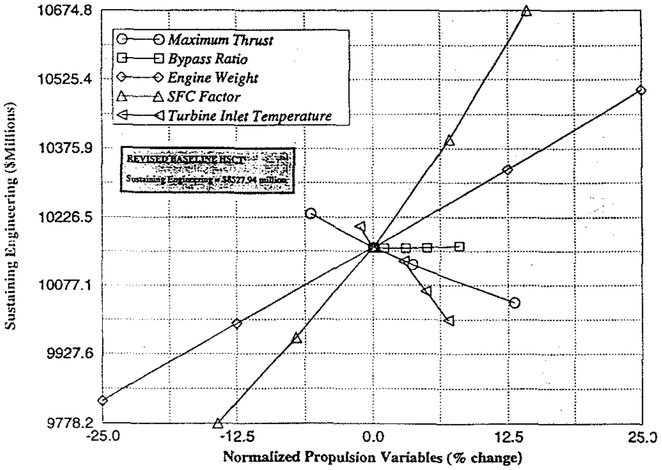

FIGURE 12. Production Cost Sensitivity to Propulsion

Comparison of HSCT with 747-400

Transport aircraft with high payload capacity and long ranges have been in operation for over 2 decades. In terms of mission characteristics and size, the HSCT's closest operational jet competitor is the Boeing 747. Although the 747 lacks the speed of the High Speed Civil Transport, it exceeds the supersonic transport in range and payload capacity.

In this study, both aircraft are evaluated over a common 5000 nautical mile mission using the ACSYNT code. They were evaluated on their Productivity Index. Additionally, production runs of 445 aircraft were specified to compare the manufacturing costs associated with the design and production of these aircraft.

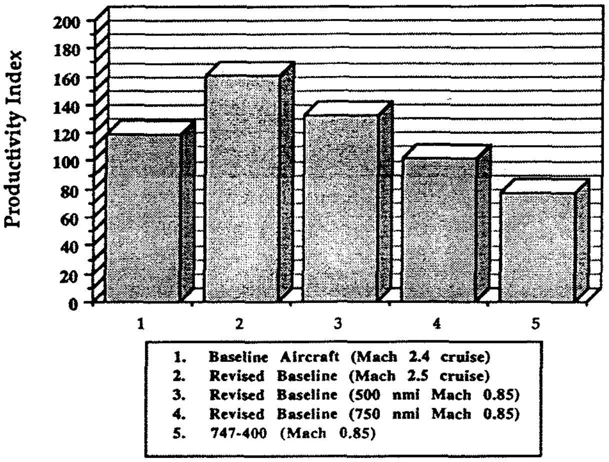

FIGURE 13. Comparison of P.I. for HSCT & 747

The 747 still has a significantly lower Productivity Index when compared to the supersonic aircraft. This is due to the significantly lower block speed of the subsonic aircraft. For a mission of 5000 nautical miles, the block speed of the 747-400 was 461 knots, roughly 758 knots slower than the revised baseline HSCT. Manufacturing costs for the aircraft are listed in Table 4. Projected selling prices are also shown. The HSCT is projected using 2005 dollars.

The costs associated with the 747-400 are significantly lower for several primary reasons. Firstly, the aircraft is a derivative aircraft. Thus, the tremendous expense of bringing a totally new aircraft to market is avoided. Also, the 747 uses 1960s - 70s technology, therefore the need for technological breakthroughs are not much of an issue in the research and design phase of the program.

TABLE 4. Projected Engineering Costs for HSCT and 747-400.

	Baseline (M2.4)	Rev. Baseline (M2.5)	Rev. Baseline (M0.85-500nmi)	Rev. Baseline (M0.85-750nmi)	747-400 (M0.85)
First Unit Cost	$1040.88 M	$1003.75 M	$1009.89 M	$1035.35 M	$221.08 M
R & D Cost	$4258.35 M	$3485.15 M	$3542.13 M	$3780.92 M	$1632.83 M
Sus. Engineering	$10159.92 M	$8527.94 M	$8663.88 M	$9233.61 M	$4093.33 M
Avg .Unit Cost	$364.93 M	$347.42 M	$350.104 M	$361.28 M	$138.79 M

Limitations of the Parametric Study

There are several limitations with the study just completed. These limitations can be divided into two categories:

1. Framework used to determine optimum aircraft.
2. Shortcomings of the synthesis program.

This project's framework allows for a top level observation of the effect of external factors on the criterion functions. Figure 1, however, does not fully address the noise factors that affect the design variables as "upstream" decisions are made. These noise factors include effects over which the designer has no control, such as the price of fuel. Additionally, the number and variety of runs conducted could have been managed using a Taguchi scheme. Further improvements in the optimization of the design variables could be achieved through the use of formal optimization methods such as a global sensitivity approach similar to analyses proposed by Sobieski (7).

The second limitation is inherent to aircraft synthesis software. This is due to the fact that many of the equations used in the program are based on empirical curvefits, a procedure that works most of the time, but not all. Examples of these deficiencies can be found in the following area:

- Mission profile, primarily climb and descent
- Fuel burn during descent
- Aircraft component slope factors
- Manufacturing cost slope factors

Synthesis programs determine component costs based on weights, however if the weight calculation is erroneous or poorly matched, the associated component costs will be misleading.

Conclusion

This study has demonstrated a multidisciplinary variations approach to the preliminary design of a High Speed Civil Transport. By determining the effect of these variations on criteria such as cost and aircraft productivity, a model for preliminary design studies has been developed. These criteria are key measures in determining the economic viability of the next generation supersonic transport.

The analysis of these design variables indicates that the baseline aircraft could be improved with respect to the Productivity Index. The preliminary results from the study suggest that a slight increase in wing area and the application of Hybrid Laminar Flow Control would improve the vehicle's productivity. Major improvements were also projected from increases in engine Turbine Inlet Temperature and decreases in Specific Fuel Consumption.

A brief comparison between the High Speed Civil Transport and the 747-400 indicated that the HSCT could be produced and sold for a price that was several times more expensive than its subsonic counterpart. It was also determined that the Productivity Index of the revised HSCT aircraft, for both supersonic and subsonic mission segments, was still greater than the 747.

The objective of this study was not to determine the detailed technical specifications for all of the design variables. Instead, the goal was to determine the areas of design leverage. This determination would allow for the allocation of R & D resources in a more objective fashion. Additionally, the processes used in this analysis fit well into the framework of Concurrent Engineering.

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