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Advanced Metallic Fuselage Cost Study

Peter Frederic
Tecolote Research, Inc., Santa Barbara, California

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Peter Frederic
Tecolote Research, Inc., Santa Barbara, California

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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LIST OF ACRONYMS

BTS	Bureau of Transportation Statistics
CER	Cost Estimating Relationship
DOC	Direct Operating Cost
FY	Fiscal Year
DOC+I	Direct plus Interest Operating Cost
ISC	Integrally Stiffened Cylinder
khr	kilo-block hour
MDA	Manufacturing Demonstration Article
NASA	National Aeronautics and Space Agency
NR	non-recurring
PTIRS	Probabilistic Technology Investment Ranking System
RFSSW	Refill Friction Stir Spot Welding
T1	theoretical first

1. INTRODUCTION

This document comprises the final report for the Advanced Metallic Fuselage Cost Study. The purpose of this study was to explore the potential cost and production throughput benefits due to incorporating Integrally Stiffened Cylinder (ISC) and friction stir welding technologies into the manufacturing of outer fuselage shells for commercial aircraft

1.1. METHODOLOGY

This study was performed in the following steps:

1. **Select reference aircraft** – National Aeronautics and Space Agency (NASA) selected the Boeing 737-800 to serve as a point of comparison. Similarity to the target next-generation single aisle aircraft, as well as availability of technical data were the primary selection criteria.

2. **Establish technical descriptions for reference aircraft** – NASA provided technical descriptions of the reference aircraft in sufficient detail to support life cycle cost estimating.

3. **Estimate Direct Operating Costs (DOCs) for reference aircraft and compare to actual costs** – Tecolote used the Probabilistic Technology Investment Ranking System (PTIRS) to estimate DOCs for the reference aircraft Costs were then validated against actual costs from the Bureau of Transportation Statistics (BTS) database.

4. **Recalibrate cost model and assumptions as necessary** – based on the validation results, adjustments were made to certain key estimating assumptions to drive the estimated results to be as close as possible to the corresponding actual costs.

5. **Develop new cost estimating relationships for ISC hardware as required** – The PTIRS model includes Cost Estimating Relationships (CERs) for all commercial aircraft subsystems. However, ISC technology affects aircraft manufacturing cost at a lower level of detail than that at which PTIRS estimates. ISC technology only applies to the outer shell portion of the center fuselage, whereas PTIRS estimates cost at the total fuselage level. A cost estimating methodology was developed that would first isolate and remove the cost of the traditional, riveted skin-stringer outer fuselage shell and then replace it with the cost of an ISC-based outer fuselage.

6. **Develop technical descriptions of both the traditional skin-stringer outer fuselage shell and the new ISC outer shell** – NASA and Tecolote collaborated to develop a detailed understanding of traditional 737-800 outer shell manufacturing processes, as well as a

consensus understanding of how those processes would vary with the introduction of ISC technology.

7. **Augment PTIRS to estimate factory throughput** – A key potential benefit of ISC technology is the potential to improve factory throughput. Tecolote augmented the PTIRS with a factory floor model to estimate possible throughput benefits. The principle is that production time scales with effort required (staff-hours or tool-hours) divided by resources available (people or machines) and that resources available are constrained by factory floor space.

8. **Estimate DOC plus Interest (DOC+I) for baseline and ISC-enhanced aircraft to quantify economic impacts** – Tecolote used the PTIRS model to estimate DOC+I for the baseline configuration and the ISC-enhanced configuration to quantify the magnitudes and associated probabilities of economic impacts. Sensitivities to key parameters driving economic impacts can be determined from the body of results.

1.2. DIRECT OPERATING COST PLUS INTEREST

DOC+I includes the following elements:

- **Aircraft ownership costs** – Aircraft ownership cost is the cost to the airline of acquiring the aircraft amortized over the operating life of the aircraft The aircraft acquisition cost is the price paid by the airline to the manufacturer. The price includes the cost of manufacturing the aircraft as well as the cost of developing the aircraft amortized over all production units. Additionally, the price includes interest accrued by the manufacture for all money invested in developing and producing the aircraft during the time when the money was invested to the time the investment was recovered at the sale of the aircraft In actual reported airline costs, aircraft ownership cost is either shown as depreciation when the aircraft is owned by the airline or flight equipment rental cost when the aircraft is owned by a second party.

- **Energy costs** – Energy cost is the cost of jet fuel and in the case of electrified propulsion aircraft, also includes the ground-supplied electricity used in flight. Fuel taxes and cost of lubricants and other expendable fluids are included.

- **Maintenance costs** – Maintenance costs include the labor and material costs associated with engine, airframe, and subsystems. Included are flight-line maintenance as well as scheduled and unscheduled heavy maintenance and overhauls (C-checks and D-checks).

- **Flight crew costs** – Flight crew costs include all cost associated with cockpit personnel including salaries, payroll taxes, benefits, training costs, and overnighting costs.

- **Insurance** – Hull insurance is included.

- **Flight equipment financing cost** – DOC+I includes the interest (the "+I" in DOC+I) paid by the airline on money invested in purchasing aircraft during ownership of the aircraft This interest is accrued to the lessor and is embedded in the rent paid by the airline in the case of leased aircraft

DOC+I, as considered in this study, excludes technology maturation costs prior to full-scale development. At the other end of the life cycle, disposal costs, or credits for sale of aircraft not fully depreciated are also excluded. Finally, airline indirect costs, such as ticketing, promotions, and corporate management are excluded.

DOC+I estimates in this study are expressed in terms of cost per seat-mile for comparative purposes. This allows for meaningful comparisons of aircraft of different seat numbers when necessary.

DOC+I is an important economic metric to use for this study because it is a comprehensive metric that captures all aircraft-driven investment cost as well as aircraft-driven operating costs – DOC+I improvements correspond directly to profit increases for airlines. However, as the subject of this study is a manufacturing technology, it was also necessary to drill down and focus on manufacturing cost, since this corresponds to profit increases for manufacturers.

1.3. THE PTIRS MODEL

PTIRS is a tool used to build a business case for incorporating a technology or suite of technologies on a future system. PTIRS has the following features:

- Excel-based tool
- Combines a complete life-cycle economic analysis model
- Infinitely flexible technology cost estimating tool (CER library)
- Integrated weight resizing tool
- Pervasive Monte Carlo risk analysis capability

PTIRS is used to determine whether new technologies make economic sense:

- What is the probability that a technology will pay for itself over the lifetime of the aircraft?
- What is the expected magnitude of savings?

PTIRS was developed for NASA by Tecolote in support of the Environmentally Responsible Aviation Project in 2012. PTIRS is documented in the *Probabilistic Technology Investment Ranking System (PTIRS) Final Report* [1]. **Figure 1** depicts the flow of a business case analysis using PTIRS.

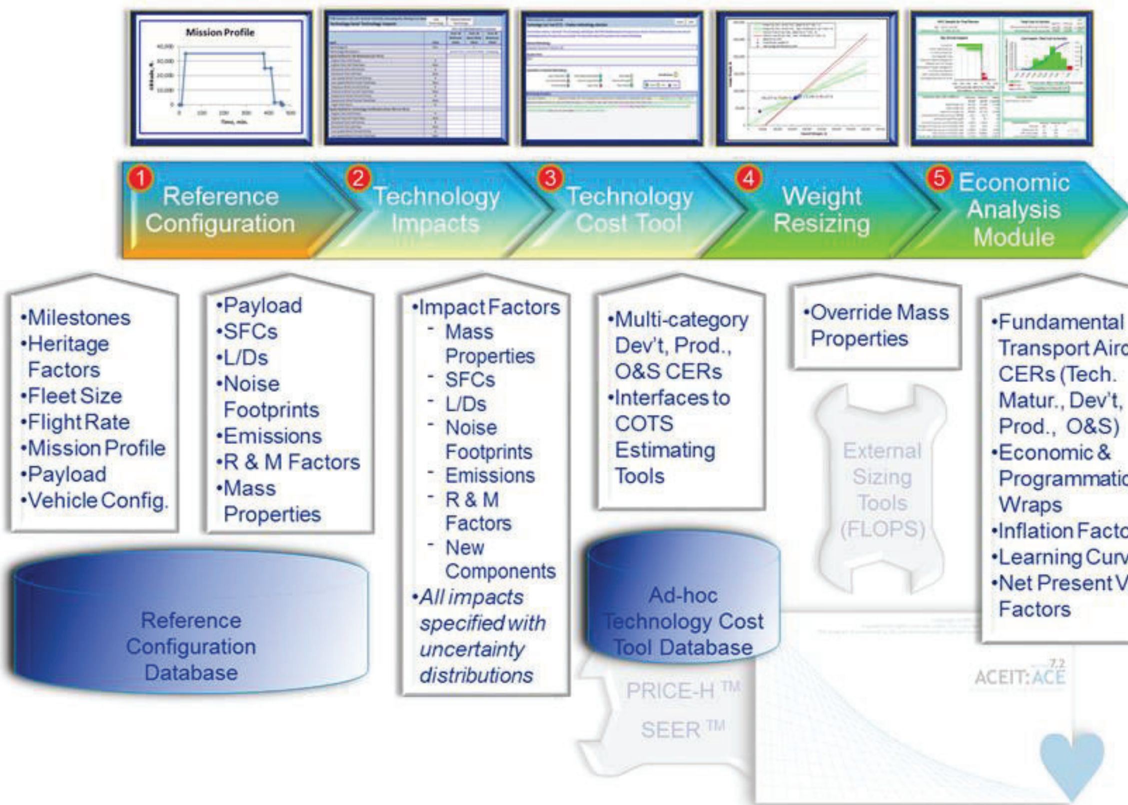

Figure 1. PTIRS analysis flow.

First, a reference configuration is selected, as depicted by the first orange-shaded arrow (①). The reference configuration defines a complete aircraft lifecycle including a moderately detailed description of the aircraft in terms of both performance and design, and well as programmatic details such as development and production milestones, fleet size, and operations life.

Next, the user describes the impact on the aircraft's design and performance of inserting a technology (or technologies), as denoted by the tan-shaded arrows (②). As part of this step, CERs for any new, unique hardware or software required to implement technologies are selected (③). The PTIRS Technology Cost Tool guides the user through this selection process.

Finally, the user can review the model results (including technical results) produced by the PTIRS Weight Resizing Module (④), plus the economic results produced by the PTIRS Economic Analysis Module (⑤).

2. VALIDATION OF PTIRS FOR 737-800 APPLICATION

The PTIRS model was originally developed with single aisle and wide body aircraft in mind, such as the 737-800-like baseline aircraft PTIRS was used to estimate DOCs for this baseline to verify the model by ensuring that the programmatic and operational inputs were realistic. The costs were then validated against actual costs from the Bureau of Transportation Statistics (BTS) database [2]. **Table 1**, **Table 2**, and **Table 3** list the inputs used to describe the baseline aircraft and associated development, production, and operating scenarios for cost estimating purposes.

Table 1. Programmatic Inputs for 737-800-like Cost Analysis Baseline

	Units	Value	
Development Start to Final Test Flight	mo	103	
Airframe Test Flight Hours	hr	4,000	
Engine Ground and Flight Test Hours	hr	10,000	
Test Unit Quantities (excluding partial units and technology maturation test articles)			
Test Unit Quantity, Complete Aircraft	#	10	
Test Unit Quantity, Engines	#	20	
Final Test Flight to Final Production Delivery	mo	180	
Fleet Size (exc. Maint. Pipeline Units)	#	6,600	*Actual total deliveries minus 340 assumed offline in maintenance*
Operations Period (Overall)	yr	20	
Depreciation Life	yr	30	
Peak Flight Rate, Fleet	flights/yr	8,220,317	*6,600 aircraft * 365.25 days/year * 3.41 flights/day/aircraft (3.41 flights per day = average over life of 737-800 from https://web.mit.edu/airlinedata)*
NPV Interest Rate	%/yr	10%	*Typical Weighted Average Cost of Capital (WACC) for Airlines and Aricraft Manufacturers*
Fuel Density	lb/gal	6.84	
Fuel Price	2013$/gal	1.795	*2.04 in 2020$/gal (actual realized cost of fuel over 737-life)*
Fuel Energy Density	kWh/gal	37.1	
Typical Flight Distance	nmi	1,175	*Actual*

Table 2. Performance Inputs for 737-800-like Cost Analysis Baseline [3]

	Units	Value
Cruise Thrust Specific Fuel Consumption	lb/hr/lb	0.61
Cruise Lift-to-Drag Ratio	lb/lb	16.4
Maximum Range	nmi	3,093
D Check	mo	96
Engine TBO	hr	23,000

Table 3. Aircraft Design Inputs for 737-800-like Cost Analysis Baseline [3]

	Units	Value
Number of Engines	#	2
Takeoff Thrust	lb	50,000
Cockpit Crew	#	2
Cabin Crew	#	3
Passengers	#	160
Weights		
Airframe	lb	42,479
Fuselage	lb	16,773
Forward Fuselage	lb	5,591
Center Fuselage	lb	5,591
Aft Fuselage	lb	5,591
Wing	lb	15,733
Empennage	lb	2,667
Landing Gear	lb	7,306
Propulsion	lb	17,583
Engine Installation	lb	14,331
Inlet	lb	601
Nacelle/Pylon	lb	3,474
Thrust Reverser	lb	1,338
Engine	lb	8,918
Controls	lb	2,558
Fuel System	lb	694

	Units	Value
Subsystems	lb	22,749
Flight Control Subsystem	lb	1,857
Auxiliary Power Subsystem	lb	1,008
Instrument Subsystem	lb	484
Hydraulic Subsystem	lb	1,079
Electrical Subsystem	lb	1,931
Furnishings and Equipment Subsystem	lb	14,597
Environmental Control Subsystem	lb	1,597
Anti-Icing Subsystem	lb	196
Avionics Hardware	lb	1,336
Empty Weight (EW)	lb	84,147
Cockpit Crew	lb	450
Cabin Crew	lb	465
Trapped Fuel, Lubricants, Other Fluids	lb	523
Passenger Service and Cargo Containers	lb	4,137
Operating Empty Weight (OEW)	lb	89,722
Passengers	lb	30,560
Cargo and Baggage	lb	7,200
Zero Fuel Weight (ZFW)	lb	127,482
Usable Fuel	lb	46,766
Takeoff Gross Weight (TOGW)	lb	174,248

2.1. 737-800 VALIDATION RESULTS

The PTIRS model was used to estimate DOCs for the 737-800-like reference configuration described by NASA. This estimate was compared to the actual DOCs for that aircraft As a significant portion of DOC is aircraft ownership cost, the PTIRS-estimated aircraft price was compared to the publicized price for the 737-800, adjusted by a factor representing typical markups between publicized prices and actual negotiated prices. This factor was derived from revenues and deliveries reported in Boeing annual "10K" reports.

Figure 2 shows actual DOCs for the Boeing 737-800. This data is from the BTS Form 41 database [2], spans the timeframe from 1990 through 2020, and covers all U.S. domestic flights. The schematic depicts a Microsoft Power BI dashboard that was developed by Tecolote to summarize the DOCs for a selected aircraft in cost categories corresponding to those estimated by the PTIRS model. The donut graph in the upper left shows the breakout of DOC for the selected aircraft type in terms of cost per block hour (flight time plus taxi time). The block in the upper right shows the following metrics:

- **Typical Flight, Miles** – the total point-to-point distance, in nautical miles, for the fleet of aircraft of the selected type operating on domestic routes over the time span shown in the "Total Block Hours (khr) by Fiscal Year (FY)" graph, divided by the total number of flights of that aircraft type over that time period;

- **Typical Flight, Hours** – the total block hours for the fleet of aircraft of the selected type operating on domestic routes over the time span shown in the "Total Block Hours (khr) by FY" graph, divided by the total number of flights of that aircraft type over that time period;

- **Peak Departures/Year** – the total number of flights for the fleet of aircraft of the selected type operating on domestic routes in the year with the maximum number of flights;

- **Seat-Miles/Gallon** – the number of passenger seats available on the selected aircraft type, times the total point-to-point distance for the fleet of aircraft of the selected type operating on domestic routes over the time span shown in the "Total Block Hours (khr) by FY" graph, divided by divided by the total gallons of fuel consumed by that aircraft type over that time period;

- **FY2020$/Gallon** – the total amount paid for fuel for the fleet of aircraft of the selected type operating on domestic routes over the time span shown in the "Total Block Hours (khr) by FY" graph, normalized to FY2020 inflationary dollars, divided by the total gallons of fuel consumed by that aircraft type over that time period (i.e., the actual, realized cost of fuel);

- **Gallons/Hr** – the total gallons of fuel consumed by the fleet of aircraft of the selected type operating on domestic routes over the time span shown in the "Total Block Hours (khr) by FY" graph, divided by the total block hours flown by that fleet over that time period;

- **Seat Utilization** – the average number of passengers carried on each flight for the fleet of aircraft of the selected type operating on domestic routes over the time span shown in the "Total Block Hours (khr) by FY" graph, divided by the number of passenger seats available on the selected aircraft type; and

- **DOC/Seat-Mile** – the grand total DOC for the fleet of aircraft of the selected type operating on domestic routes over the time span shown in the "Total Block Hours (khr) by FY" graph, normalized to FY2020 inflationary dollars, divided by the product of the number of passenger seats available on the selected aircraft type, and the total point-to-point distance flow by that fleet over that time period.

The lower left panel of **Figure 2** shows the total block hours per year flown by the fleet of aircraft of the selected type operating on domestic routes on a year-by-year basis. The lower right panel lists the airlines operating the type and allows specific airlines' costs to be included or excluded. In this case, all operators are included.

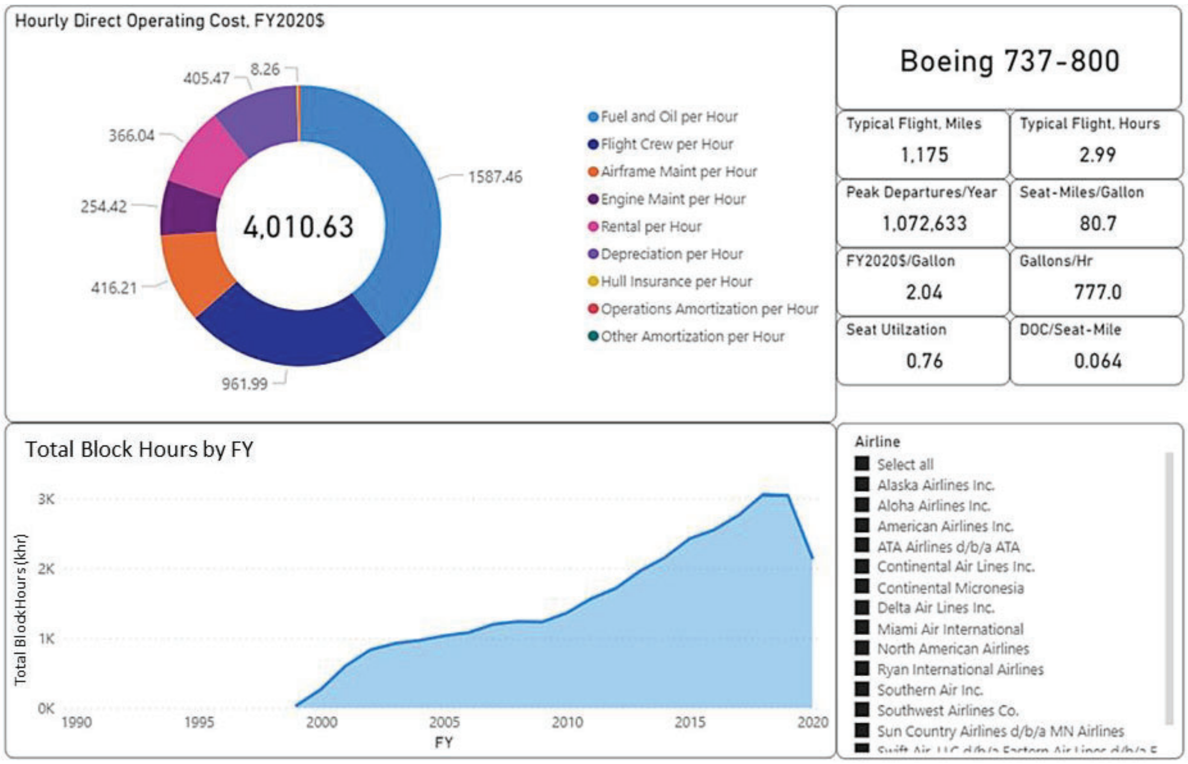

Figure 2. BTS DOC and usage data for 737-800.

Table 4 shows the actual costs from **Figure 2** side-by-side with the corresponding PTIRS-estimated costs. Airlines do not report interest costs by aircraft type in the Form-41 data. Therefore, interest cost (see Ground Rules and Assumptions) was added on flight capital in the center column to make the Rent/Depreciation costs equivalent to those estimated by PTIRS (i.e. DOC+I instead of just DOC).

Table 4. Actuals versus Estimates for 737-800

	Actual Cost/Price	Add Interest on Depreciation (+I)	Reference Configuration Estimate
	FY20$/hr		
Fuel	1,587.5	1,587.5	2,116.3
Crew	962.0	962.0	816.8
Maintenance	670.6	670.6	646.0
Rent/Depreciation	782.3	1,391.1	1,089.1
Insurance, etc.	8.3	8.3	4.2
Total DOC+I	4,010.6	4,619.4	4,672.4
	FY20$M		
Unit Price *	50.0		43.4

The most significant deviation between the estimate cost and Form-41 actual cost is the hourly cost of fuel. This appears to be partly because the NASA Flight Optimization System's estimated baseline fuel burn is 883 gal/hr but actual historical fuel burn is less at 775 gal/hr However, at the Total DOC+I level, results are reasonably close. The demonstrated accuracy is deemed sufficient, since the model is used for comparative estimating, and focus is on the cost difference between baseline and ISC-enhanced aircraft

2.2. ADJUSTMENTS DUE TO VALIDATION

During the model validation effort, it was discovered that an adjustment was needed to one of the key estimating assumptions. The PTIRS maintenance CERs are sensitive to aircraft utilization and if the aircraft utilization is low, then maintenance costs per flight hour will be unrealistically high. The utilization in the original baseline inputs was low. Utilization was adjusted based on the following formula: *Flights per Year = Fleet Size * 365* Typical Flight Duration * Flight Hours per Day*. For *Flight Hours per Day*, the worldwide average daily usage for single aisle aircraft of 3.4 hr/day [4] was used.

3. FUSELAGE COST ESTIMATING METHODS

ISC technology affects aircraft manufacturing cost at a lower level of detail than that at which PTIRS estimates. ISC technology only applies to the outer shell portion of the center fuselage, whereas PTIRS estimates cost at the total fuselage level. Tecolote developed a cost estimating methodology that would first subtract out the cost of the traditional, riveted skin-stringer outer fuselage and then add in the cost of an ISC-based outer fuselage. A new "mini-model" was developed to accomplish that substitution and added to the PTIRS CER library. That model was delivered to NASA as a stand-alone tool to be used in future studies focused strictly on manufacturing costs and factory throughput.

3.1. FUSELAGE PRODUCTION

The first step in assessing production cost impact was to determine the overall dimensions of the fuselage portion impacted, since ISC applies only to the outer shell of the constant-cross-section portion of the fuselage. Table 5 lists these dimensions and the figures referenced in the table show how the dimensions were derived. The parameter at the bottom of Table 5 represents the portion of the fuselage circumference in which the frames extend fully to the inner skin surface and are riveted directly to the skin (the bottom lobe) as shown in a "Spirit AeroSystems: 737 Rapid Build" video [5]. In the remaining portion (the top lobe), the fames do not attach directly to the skin [5].

Table 5. Key Technical Inputs Applicable to Both Baseline and ISC-based Configurations

Value	Description	Rational
63.0 ft	Overall length of section	Measured from [6]
12.33 ft	Outside diameter of section	Measured from [6]
50%	Portion of circumference where frames attach directly to skin in addition to stringers	Estimated from [5]

3.1.1. TRADITIONAL RIVETED SKIN AND STRINGER

The next step was to estimate the production cost of the affected portion of the fuselage so that the amount could be subtracted from the total fuselage cost once the overall dimension had been established. This required estimating the cost of fabricating and assembling only the components in a traditional skin-stringer fuselage that would be replaced with ISC technology, namely: outer skin panels, stringers, gussets to connect stringers to circumferential frames, and rivets to fasten these components together. Fortunately, a literature search revealed an openliterature model which estimates the costs of the fuselage production at the level of detail of drilling and setting individual rivets. This model which will be hereinafter referred to as the Castagne model. It is a detailed manufacturing process cost model, with parametric CERs that address each manufacturing step in terms of labor hours and material costs. The following is an example of a parametric CER from Castagne [7]:

$$c^f_{Z-\text{stringer}}\,[\text{unit time}] = 1.008 \times 10^{-1} L_{Z-\text{stringer}}\,[\text{mm}] + 67.455$$

This CER estimates labor cost for stringer fabrication ($c^f_{Z\text{-stringer}}$) in generic time units based on stringer length in mm ($L_{Z\text{-stringer}}$). The Castagne model includes CERs for skin sheet material, skin panel chemical milling labor and process costs, stringer material, stringer fabrication labor, gusset material, gusset fabrication labor, rivet material, and rivet drilling and setting (either manual or robotic).

The Castagne report [7] uses generic units to protect the proprietary cost data of their industrial partner, Bombardier, and to make the model currency-agnostic. All labor and process costs are estimated in generic units which are defined as the time in seconds to robotically set one rivet. A representative time for setting a rivet robotically was needed to make use of the model. A representative time of 8.336 seconds for each rivet was extracted from a 2013 Bombardier press release [8]. Material costs are estimated in generic units defined as the cost of one button-head aluminum rivet of unspecified size. To calibrate the material CERs, an average cost of $0.035 per rivet for rivet sizes ranging from 3/32 in by 1/8 in to 3/16 in by 1 in was calculated based on catalog prices from Aircraft Spruce [9]. While these calibration factors may not be precisely the ones used in normalizing the CERs in the Castagne report [7], the values adopted should be of the right order of magnitude. The estimated theoretical first (T1) unit cost for the skin-stringer outer shell of the constant-cross-section part of the fuselage, from the calibrated Castagne model ($5.2M from **Table 6** below), was compared to the total fuselage T1 estimated by PTIRS for the Boeing 737-800-like baseline ($20.8M) to verify that the calibration factors used are reasonable. That the outer shell of the constant-cross-section portion of the fuselage would cost roughly a quarter of the complete fuselage cost is intuitively pleasing given that the total fuselage cost includes the cost of heavy and complex features such as landing gear tie-ins and enclosures, wing carry-throughs, floor beams and panels, windows, doors, etc.

Table 6 lists and describes the elements of the Castagne-based model used to estimate the traditional riveted skin-stringer costs which will be subtracted from the PTIRS-estimated total fuselage costs. Included in the cost table are the rivet counts which are a key intermediate estimating result. The results shown are from the nominal case shown in the second row of the Results Summary (**Table 14**). Note that all the cost results were estimated by CERs from Castagne [7] except for the last row which was estimated by a generic cost factor from the PTIRS model relating Quality Control and recurring engineering costs to touch-labor cost.

Table 6. Cost Elements Applicable to Baseline Skin-Stringer Configuration

Name	FY2022$	Description
SkinStringer_TFU	$5,209,627.2	first unit cost of constant-cross-section portion of fuselage outer shell
SSNumFlushRivets	70,131.0	total number of flush rivets
CircJointRivets	3,770.0	number of rivets used in circumferential joints
StringerRivets	34,776.0	number of rivets used in for regular stringers
LapRivets	22,680.0	number of rivets used in lap joints (longitudinal)
FrameSkinRivets	8,905.0	number of rivets used to attach frames to skin in lower lobe
SSNumPrtdgRivets	28,269.0	total number of protruding-head rivets
FrameAtchRivets	16,931.0	number of rivets used to attach frames to stringers
FrameJointRivets	11,338.0	number of rivets used to splice frame segments into continuous rings
RivetMtrlDlr	$4,180.4	first shipset material cost of all rivets
RivetLbrDlr	$2,250,506.6	first shipset labor and machine cost for drilling and setting all rivets
SkinMtrlDlr	$37,289.0	first shipset material cost of skin blanks
SkinLbrDlr	$338,259.7	first shipset labor and machine cost for forming, masking, chemical milling, cleaning and trimming of skin segments
StringerMtrlDlr	$28,124.5	first shipset material cost of all stringers
StringerLbrDlr	$520,530.2	first shipset labor and machine cost for forming stringers
CleatMtrlDlr	$1,608.1	first shipset material cost of all cleats/gussets used to fasten frames to stringers
CleatLbrDlr	$315,895.6	first shipset labor and machine cost for forming cleats/gussets used to fasten frames to stringers
QCandEng	$1,713,233.1	quality control and production engineering costs

Table 7 shows the parametric inputs, which correspond to the costs shown in **Table 6**, that are used for the model. The rightmost column in the table identifies the source for each input and the figures referenced in the table illustrate the inputs.

Table 7. Technical Inputs Applicable to Baseline, Skin-Stringer Configuration

Value	Description	Rationale
2	Number of circumferential joints	[10]
4	Rows of rivets per circumferential joint	[11]
46	Number of regular stringers	[12]
0.458	Width of unformed stringer, feet	Stringers are inverted "hat" 3 across "brim", 1.5 in high [10]
10	Number of lap joints (and frame sections)	[10]
3	Rows of rivets at lap joints	[10]
1.667	Average frame spacing, feet	737 window spacing of 20 in [6]
8	Number of rivets at each stringer-to-ring attachment	[5]
30	Number of rivets to attach two ring segments together	[5]
.5	Width of circumferential joints, feet	[11]
.333	Width of lap joints, feet	[10]
50%	Percentage of rivets set manually	[5]
0.072	Thickness of blank skin sheets, inches	Estimated
0.036	Minimum thickness of chem-milled skin sheets, inches	[10]
1	Number of steps of chem-milling	Estimated

The portion of rivets set robotically has a significant impact on riveting cost. As mentioned above, the labor and machine time portions of the Castagne cost model were calibrated to the time to set an individual rivet robotically, which was estimated herein as 8.336 seconds. The corresponding time to manually set an individual rivet was estimate by the Castagne model as 2.22 times that, or 18.51 seconds. No attempt has been made to allocate manual or automatic riveting to specific applications – the cost factors were applied to the total number of rivets, with half the rivets estimated at 8.336 seconds per rivet and half the rivets estimated at 18.51 seconds per rivet.

3.1.2. ISC

The final step in determining production cost impact was to estimate the production cost of the affected portion of the fuselage incorporating ISC technology so that it could be added back into the total fuselage production cost.

A parametric CER was developed to estimate the cost of forming ISC barrel sections and joining them together via friction stir welding. This CER was based on observed costs for production of an ISC Manufacturing Demonstration Article (MDA) provided by NASA [13] as well as estimates from a prior NASA study of production of ISC-based launch vehicle stage structures [14]. **Figure 3** shows resulting parametric CER which was fit using log-least-squares regression.

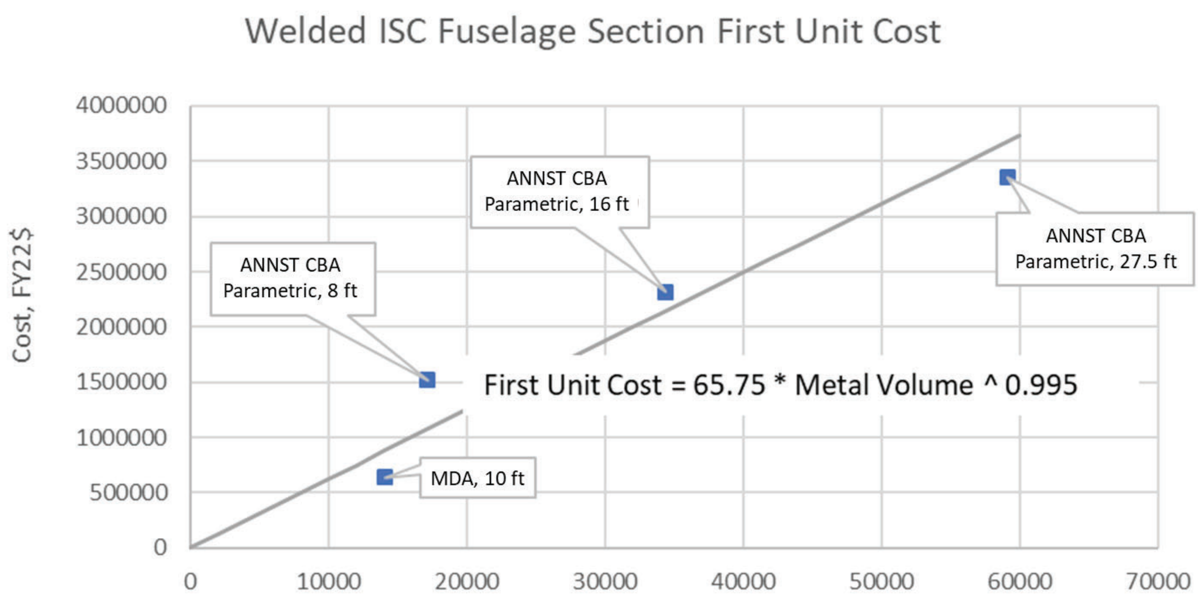

Figure 3. CER for Forming ISC Barrel Sections and joining via Friction Stir Welding.

Only the NASA-provided MDA cost data [13] included a clean breakout of the cost of friction stir welding the barrel sections together. Therefore, that data was used to develop a breakout factor to determine the portion of the overall cost estimated by the parametric CER above that is represented by welding. This factor is 0.33, meaning that one third of the cost estimated by the CER above is accounted for by friction stir welding the barrel sections together.

Table 8 lists and describes the elements of the new cost model used to estimate the ISC-based costs that will be added to the PTIRS-estimated total fuselage cost to replace the tradition riveted skin-stringer cost. The second row of **Table 8** shows the ISC forming cost. The third row shows the cost of friction stir welding the ISC barrel sections together. The rivet counts and riveting costs are still included in the new model, since frame rings are still attached to the ISCs partially by rivets. However, the total number of rivets is much lower, since stringers are integral to the ISCs. Also, automated riveting has been replaced with Refill Friction Stir Spot Welding (RFSSW) in the new cost model. Similar to the baseline case where half of rivets are assumed to be set robotically, in the ISC case, half of the attachments are assumed to be made with RFSSW and half via manual riveting, with no attempt made to allocate the robotic portion to particular applications. Results shown are from the nominal case shown in the second row of the Results Summary (**Table 14**).

Table 8. Cost Elements Applicable to ISC-based Configuration

Name	FY2022$	Description
ISC_TFU	$3,865,316.1	first unit cost of constant-cross-section portion of fuselage outer shell
ISCFormFinish	$1,081,757.1	
ISCWeld	$530,061.0	
ISCNumFlushRivets	4,452.0	total number of flush rivets
ISCCircJointRivets	0.0	number of rivets used in circumferential joints
ISCFrameSkinRivets	4,452.0	number of rivets used to attach frames to skin in lower lobe
ISCNumPrtdgRivets	14,135.0	total number of protruding-head rivets
ISCFrameAtchRivets	8,466.0	number of rivets used in circumferential joints
ISCFrameJointRivets	5,669.0	number of rivets used in circumferential joints
ISCNumSpotWelds	18,587.0	number of robotic spot welds
ISCFrameAtchSpotWelds	8,466.0	number of welds used to attach frames to stringers
ISCFrameJointSpotWelds	5,669.0	number of welds used to splice frame segments into continuous rings
ISCFrameSkinSpotWelds	4,452.0	number of welds used to attach frames to skin in lower lobe
ISCSkinMtrlDlr	0.0	first shipset material cost of backing strips if isc sections joined by riveting rather than welding
ISCRivetMtrlDlr	$697.3	first shipset material cost of all rivets
ISCRivetLbrDlr	$659,777.4	first shipset labor and machine cost for drilling and setting all rivets
ISCSpotWeldLbrDlr	$195,603.0	first shipset labor and machine cost for all spot welds
ISCChemMillDlr	$338,833.3	first shipset labor and machine cost for forming, masking, chemical milling, cleaning and trimming of post-formed isc cylinders
ISCCleatMtrlDlr	$1,608.1	first shipset material cost of all cleats/gussets used to fasten frames to stringers
ISCCleatLbrDlr	$315,895.6	first shipset labor and machine cost for forming cleats/gussets used to fasten frames to stringers
ISCQCandEng	$741,083.2	quality control and production engineering costs

Table 9 shows the inputs to the model corresponding to the results above. The rightmost column in the table identifies the source for each input and the figures referenced in the table illustrate the inputs.

Table 9. Key Inputs Applicable to ISC-Based Configuration

Value	Description	Rationale
56.000	number of stringers	Assume same as riveted structure
0.245	stringer thickness, inches	Set to yield overall weight same as riveted structure, adjusted to vary weight
1.250	stringer height, inches	Guess, only drives cost as a contributor to material volume/weight
0.125	thickness of post-formed ISC, inches	Guess, sensitivity studies examined different values
0.036	min. thickness of chem-milled ISC, inches	Goal would be same as riveted structure to keep weight in line
1.667	average frame spacing, feet	Assume based on window spacing, same as riveted structure
50%	percentage of attachments made with spot welds versus (manual) rivets	Assume spot-welding would be one-for-one replacement for automatic rivets
1.000	number of steps of chem-milling	Guess, zero if ISC forming can achieve 0.036" thickness
8.000	number of attach points (rivets or spot welds) at each stringer-to-ring attachment	Assume same as riveted structure
30.000	number of attach points to attach two ring segments together	Assume same as riveted structure
10.000	number of frame segments	Assume same as riveted structure
0.500	Cost of locating and performing spot weld relative to cost of locating, drilling, and setting an automatic rivet	Guess, sensitivity studies examined different values
5.000	number of circumferential joints	Based on maximum ISC segment length of 10 ft 6 in, sensitivity studies examined different values
1.000	1 if circumferential joints welded, 0 if riveted	Enables sensitivity study between FSW-joined and rivet-joined circumferential joints

The *thickness of post-formed ISC* input represents the skin thickness of the ISC barrel assumed to be achieved by the ISC forming process, with no additional mechanical milling for thickness reduction. Reduction to the final *min. thickness of chem-milled ISC* is assumed to be achieved solely via chemical milling. The minimum thickness achievable via the ISC forming process has yet to be determined. However, should that minimum be thick enough to require mechanical milling to reach flight-weight skin thickness, additional research will be required to determine the cost impact.

3.1.3. PRODUCTION LEARNING CURVE

Although production learning curve experience for commercial transport aircraft is not generally publicized, available references indicated that a learning curve slope of 80% (i.e. unit cost is reduced by 20% with each doubling of quantity) is typical for airframe manufacturing. The PTIRS model estimates production costs by first estimating T1 costs and then estimating the cost of every production unit by the formula: $Cost_n = T1 * n \wedge ^{\log2(.80)}$ where n is the production sequence number of the unit. Regarding the cost impact of replacing traditional riveted skin stringer fuselage production with ISC-based production, both parts of the model estimate T1 costs for estimation of total production run cost impact, and both parts of the model propagate costs down the same 80% learning curve slope. While it might be tempting to hope that a new manufacturing technology such as ISC fuselage manufacturing might benefit from a steeper learning curve, historical precedent does not support this. In fact, looking across commodities (e.g. missiles, launch vehicles, electronics, ground vehicles, etc.), more highly automated manufacturing processes (e.g. integrated circuits) tend to exhibit less steep learning curve slopes. Typically, when a new product is developed, for example, a new aircraft family, an effectively new factory is set up to produce the new product. It may be in the same building as the factory for the last product, but it will have newly-designed workflows and modernized tooling. Although a Boeing 737-800-like configuration was adopted as the baseline, for cost estimating purposes, it was assumed that it would be a totally new, first-in-family aircraft, built in a new factory. However, examining a case in which ISC technology is inserted into an existing aircraft might be an interesting sequel to this study.

3.2. FUSELAGE NON-RECURRING DEVELOPMENT

Estimates of non-recurring (NR) developmental costs assumed that such costs are driven by the size and complexity of the end-item, since no historical cost data exists for full-scale development of aircraft fuselages based on ISC technology. Fuselage-level ISC NR cost impact was scaled based on the cost reduction factor observed in fuselage production costs using the following simple equation:

$$ISC\ NR\ Cost\ Impact = Center\ Fuselage\ NR\ Cost\ \frac{ISC\ Production\ Cost\ Impact}{Center\ Fuselage\ Production\ Cost}$$

where

ISC NR Cost Impact	=	the total cost added to or subtracted from the PTIRS-estimated center fuselage NR cost
Center Fuselage NR Cost	=	the PTIRS-estimated center fuselage NR cost
ISC Production Cost Impact	=	The cost of fabricating and assembling the ISC-based center fuselage outer shell (as described in Section 3.1.2) minus cost of fabricating and assembling the riveted skin-stringer based center fuselage outer shell (as described in Section 3.1.2)
Center Fuselage Production Cost	=	the PTIRS-estimated center fuselage production cost

The following non-recurring tooling costs were also added:

- 8.7 FY22$M * 10 for ISC process machines [14]
- $1.0 FY22$M * 10 for RFSSW weld heads (Rough Order of Magnitude estimate, assuming RFSSW weld heads can be built into existing automated rivet fixtures)

3.3. FUSELAGE MAINTENANCE

Estimates of fuselage-level maintenance costs assumed that such costs are driven by the size and complexity of the end-item because, again, no historical cost data exist for maintenance of aircraft fuselages based on ISC technology. Additionally, the estimations are based on the center section of the fuselage, not the entire length and evolving shape of the whole fuselage. Fuselage-level maintenance cost impact was scaled based on the cost reduction factor observed in fuselage production costs using the following simple equation:

$$ISC\ Maintenance\ Cost\ Impact = Center\ Fuselage\ Maintenance\ Cost\ \frac{ISC\ Production\ Cost\ Impact}{Center\ Fuselage\ Production\ Cost}$$

where;

ISC Maintenance Cost Impact	=	the total cost added to or subtracted from the PTIRS-estimated center fuselage maintenance cost
Center Fuselage Maintenance Cost	=	the PTIRS-estimated center fuselage Maintenance cost
ISC Production Cost Impact	=	The cost of fabricating and assembling the ISC-based center fuselage outer shell (as described in Section 3.1.2) minus the cost of fabricating and assembling the riveted skin-stringer based center fuselage outer shell (as described in Section 3.1.1)
Center Fuselage Production Cost	=	the PTIRS-estimated center fuselage production cost

Additionally, ISC technology may impact heavy maintenance (D-check) intervals. Presumably, a unitized structure free of rivets and rivet holes might be less susceptible to fatigue and require less frequent inspection and repair. D-check interval is a direct input to PTIRS, so sensitivity cases were run with D-check interval both increased from 96 to 108 months and reduced to 84 months.

4. FUSELAGE PRODUCTION THROUGHPUT

One possible benefit of ISC technology is the potential to improve factory throughput. A factory floor model was developed linked to PTIRS based on the principle that production time scales with effort required (staff-hours or tool-hours) divided by resources available (people or machines) and that resources available are constrained by factory floor space.

The labor CERs described in the Fuselage Production section above estimate staff hours or tool hours which are translate to costs by applying a $/hr rate. For the production throughput model, the estimated staff or machine hours representing one fuselage shipset worth of effort for each manufacturing step were divided by the number of resources available – either people or machines – to get elapsed time. The unit-to-unit completion interval will be determined by the manufacturing step with the longest elapsed time (the bottle neck) since fuselages will be produced in a production line environment where numerous end items simultaneously proceed through the manufacturing steps. The goal was to maximize overall throughput (i.e. minimize unit-to-unit completion interval) by allocating factory floor space to different operations such that all manufacturing steps were completed in the same elapsed time (no bottle necks).

The minimum unit-to-unit completion interval can be determined from known estimates of the effort required to complete each manufacturing step for a complete fuselage, knowledge of both the overall factory floor space constraint, and the amount of floor space required by each resource for each manufacturing step. Algebra yields the following equation:

$$t = \frac{\sum_{i=1}^{n} e_i f_i}{f_f}$$

Where

t = minimum unit-to-unit completion interval, hr

n = number of manufacturing steps (i.e. rows in **Table 10** and

)

e_i = effort required to complete manufacturing step i for one fuselage, staff hr or machine hr

f_i = floor space required by one resource associated with manufacturing step i, ft^2

f_f = total factory floor space, ft^2

The optimum number of resources required for each manufacturing step can be determined once the minimum unit-to-unit completion interval is known. The calculation comprises the estimated staff hours, or machine hours, representing one fuselage-worth of effort for each manufacturing step, divided by the completion interval. This is shown in **Table 10** and

simply to verify that the approach produces the calculated time interval given the factory floor space specified.

The factory floor modeled does not include transportation aisles between operations, office space, restrooms, break areas, tool cribs, utility enclosures, etc. It does not include space for any operations other than construction of constant-cross-section fuselage outer shell and attachment of frames. All of these were assumed to be equal for either a tradition riveted skin-stringer facility or an ISC-based facility.

4.1. TRADITIONAL RIVETED SKIN AND STRINGER

The traditional riveted skin-stringer factory was modeled first, beginning with effort estimates from the CERs comprising the cost model for comparison. The floor space required was estimated for each resource associated with each manufacturing step based on factors such as machine size, workpiece size, or the maximum imaginable concentration of personnel performing a manufacturing step, as described in the Notes column of Table 10 and the inputs in Table 10. The factory floor space constraint shown at the bottom of

Table 11 was adjusted such that the Maximum Elapsed Hr at the bottom of **Table 10** equaled 24.0, because the maximum throughput achieved at the Spirit AeroSystems plant in Wichita is 31 shipsets per month [15], or roughly one every 24 hours. This gave established the representative baseline factory floor size.

Table 10. Factory Throughput Model Applicable to Baseline, Skin-Stringer Configuration

Step		Labor (hr)	Number of People (per shift)	Tool (hr)	Tool Workstations	Elapsed Time (hr)	Footprint per Workstation (ft^2)	Total Footprint (ft^2)	Notes
Receive/store blank sheets				--	2	0	593	1186	1 bay per individual sheet type, 3 ft access back and sides, 15 ft loading access
Form sheets and mask		747	32	--	--	24	692	21,919	Labor hours from [7]; forming tool and masking table, 4 ft access; two people per station
Pre-etch handling		113	5	--	--	24	346	1,656	Labor hours from [7]
Acid bath		--	--	15	1	24	346	226	Etchant rate used was 0.178 cm/hr [16]
Post-etch cleaning		502	21	--	--	24	346	7,366	Labor hours from [7]
Dry/store		--	--	720	31	24	80	2,437	5% at 8 ft spacing, 20% at 3 ft and remainder at 2 in
Form stringers		2,097	89	--	--	24	95	8,398	Labor hours from [7]; footprint split over 4 people per lane
Form gussets		1,273	54	--	--	24	36	1,942	Labor hours from [7]; estimated footprint (6 ft x 6 ft)
Manual drilling and riveting	Attach stringers	2,681	114	--	--	24	24	2,727	Labor hours from [7]; Assume riveter teams spaced 6 ft apart with 4 ft on either side of panel
	Lap join sections[1]	1,399	59	--	--	24	62	3,646	Labor hours from [7]; Assume riveter teams spaced 6 ft apart on inside and outside of either side of lobe with 4 ft for outside person
	Attach frames[2]	3,158	134	--	--	24	62	8,230	Labor hours from [7]; Assume riveter teams spaced 6 ft apart on inside and outside of either side of lobe with 4 ft for outside person
Auto-rivet[3]		--	--	986	42	24	769	32,119	Size of lobe plus 4 ft at each end and 7 ft on each side; Labor hours from [7]
Lap join upper and lower lobes (manual)		460	19	--	--	24	62	1,199	Assume Riveter teams spaced 6 ft apart on inside and outside of either side of fuselage with 4 ft for outside person; Labor hours from [7]
Butt join sections (manual)		382	16	--	--	24	182	2,948	Assume 4 people working at each section joint; Labor hours from [7]
Total		12,813	543	1,722	75	307	--	96,000	

[1]To upper and lower lobes

[2]To upper and lower lobes and splice

[3]Remainder of upper and lower lobe

Table 11. Technical Inputs Applicable to Factory Throughput in Traditional Configuration

Value	Description	Rationale
23.6	Calculated per-fuselage time for all steps if non-integral people or workstations allowed (hr)	Based on factory size, estimate total labor hours, and tool hours above
15	Number of aluminum sheet blank types per fuselage	Assume each sheet on a side is cut to unique dimensions, but port and starboard sides are symmetric
3	Height of storage bay for each type of blank skin panel (ft)	Based on [5]
30	Height of storage racks (ft)	Based on [5]
2	Time to form one sheet (hr)	Engineering estimate
24	Time to dry each sheet after etching and cleaning (hr)	Engineering estimate
96,000	Factory floor space constraint, fuselage outer shell processes only (ft^2)	Chosen to yield target time ~24 hours which equate to stated capacity of Spirit facility (31 shipments per month) [15]

4.2. ISC

A modified version of the factory floor model was invoked once the effective factory floor constraint was established, which was driven by effort estimates from the CERs in the ISC-based portion of the cost model. In this case, the factory floor space was held constant with the objective of determining the minimum unit-to-unit completion interval for a given factory size.

This version of the model is shown Table 11 with rationale for resource floor sizing in the Notes column, additional inputs with rationale in Table 12, and supporting figures below.

Two additional assumptions are embedded in the model:

- ISC forming is done in-house
- ISC rings arrive at factory annealed and ready for forming

In the nominal case shown in

, the inclusion of ISC technology and the elimination of the majority of riveting operations has allowed factory space to be reallocated such that the unit-to-unit completion interval has been reduced to 16 hours or a throughput of 46.5 shipsets per month.

Table 12. Factory Throughput Model Applicable to ISC-based Configuration

Step	Labor (hr)	Manual Workstations	Tool hours (hr)	Total Workstations	Elapsed Time (hr)	Footprint per Workstation (ft^2)	Total Footprint (ft^2)	Notes
Receive/store cylinder blanks	--	--	--	38	0	589	22,382	Diameter of ring, 3 ft access back and sides, 15 ft loading access
Form ISCs	--	--	18	1	15.6	1,089	1,256	Two times diameter of ring based on MT Aero photograph (Figure 4) plus 4 ft on each side[1]
Heat treat / cure	--	--	288	18	15.6	379	6,996	Size of formed cylinder plus 4 ft on each side
Mask	747	48	--	--	15.6	63	3,026	Labor hours from [7]; Size of formed cylinder plus 4 ft on each side; 6 people working per cylinder
Pre-etch handling	113	7	--	--	15.6	63	457	Labor hours from [7]; Size of formed cylinder plus 4 ft on each side; 6 people working per cylinder
Acid bath	--	--	8	0	15.6	379	185	Etchant rate used was 0.178 cm/hr [16]
Post-etch cleaning	505	32	--	--	15.6	63	2,043	Labor hours from [7]; Size of formed cylinder plus 4 ft on each side; 6 people working per cylinder
Dry/store	--	--	144	9	15.6	379	3,498	Size of formed cylinder plus 4 ft
Form gussets	1,273	82	--	--	15.6	36	2,935	Labor hours from [7]; estimated footprint (6 ft x 6 ft)
Attach frames[2]	2,658	170	--	--	15.6	62	10,471	Labor hours from [7]; Assume riveter teams spaced 6 ft apart with 4 ft on either side of fuselage with 4 ft for outside person
RFSSW	--	--	788	50	15.6	769	38,790	Labor hours from [7]; size of cylinder plus 4 ft at each end and 7 ft on each side
Butt join sections (FSW)	--	--	42	3	15.6	1,456	3,961	Size of ISC portion of fuselage plus 4 ft on each side and end
Total	5,296	339	1,288	121	172	--	96,000	

[1]Overhead height needs to be more than twice length of formed cylinder

[2]To upper and lower lobes and splice (manual drilling and riveting)

[3] Remainder of upper and lower lobe

Table 13. Technical Inputs Applicable to Factory Throughput in Traditional Configuration

Value	Description	Rationale
15.6	Calculated per-fuselage time for all steps if non-integral people or workstations allowed (hr)	Based on factory size, estimate total labor hours, and tool hours above
31	Number of fuselages worth of material stored (1 month production)	31 shipsets per month which is stated capacity of Spirit facility [15]
6	Height of storage bay for each type of blank skin panel (ft)	2 ft 10 in blank ring radius with 10 ft finished length, scale by required finished length and add 3 ft for vertical clearance
30	Height of storage racks (ft)	Based on [5]
3	Empirical forming time of 5 ft ISC, doubled for larger end item, and set up, fixturing and removal (hr)	NASA communication [13]
48	Number of ring frame segments required for 10 ft ISC fuselage	NASA communication [13]
400	FSW welding speed (mm/min)	NASA communication [13]
8	Time to set up each FSW run (hr)	NASA communication [13]

Figure 4. ISC forming machine.

5. ISC AIRCRAFT DOC+I ESTIMATES

ISC Aircraft DOC+1 includes estimates of investment cost, fuselage manufacturing cost, and impact on manufacturing throughput. The plan for this study was to estimate life cycle costs for a 737-800-like baseline aircraft, developed and manufactured as a new, first-in-family model, and operated according to a 737-800-like operating scenario (fleet size, utilization rate, economic range, etc.). Additionally, numerous sensitivity studies were performed to examine how the cost and production throughput models respond to variations in key inputs and assumptions.

5.1. GROUND RULES AND ASSUMPTIONS

The following ground rules and assumptions have been incorporated in this study:

- Fuel cost is assumed to be $2.03/gal (FY20) which is the historical average cost for fuel across all 737-800 operations (Ref. 15).
- Cost calculations are based on worldwide fleet size for the 737 Next Generation family: 6,600 aircraft, plus spares.

- Utilization in flights per year is calculated based on worldwide average daily usage: 3.4 hr/day for single aisle aircraft (Ref 11).

- All baselines and technology-enhanced concepts have been assumed to be new designs (no design reuse) for non-recurring cost estimating.

- The cost of capital is assumed to be 10% per year (Ref. 18).

- Technology maturation costs prior to full-scale development are excluded.

- Not included in analysis – assumed to be the same for baseline and ISC cases:
  - Nose and tail (non-constant cross section)
  - Landing gear attachment and housing structures
  - Wing carry-through structure
  - Windows, doors, and associate reinforcements
  - Any attachment fittings or equipment brackets other than gussets used to attach frames to stringers
  - Forming of the frames (although attachment of frames to stringers and skins is included)
  - Coatings, membranes, or adhesives applied between skin sections

- Rivet spacing is globally assumed to be 1 in based on drawings of 737 skin-stringer structure (Ref. 1).

- The factory floor modeled does not include transportation aisles between operations, any operations other than construction of constant-cross-section fuselage outer shell and attachment of frames, office space, restrooms, break areas, tool cribs, utility enclosures, etc. All are assumed to be equal for either the traditional or ISC case.

- ISC forming is done in-house.

- ISC rings arrive at factory annealed and ready for forming.

- Post-forming machining cost for ISC is equivalent to any cutting, trimming and additional structural element site preparation required in skin-stringer manufacturing and not estimated as a cost impact.

- The minimum thickness achievable by the ISC process is assumed to be thin enough that flight-weight skin thickness can be reached by chemical milling only, without additional mechanical milling.

- Chem-mill masking is represented by a uniform grid of 4 in wide strips, one for each stringer and one for each frame.

- Although a 737-800-like configuration was adopted as a baseline, for cost estimating purposes it is assumed that the aircraft will be a totally new, first-in-family aircraft, built in a new factory.

- A learning curve slope of 80% (i.e. unit cost is reduced by 20% with each doubling of quantity) is applied to all airframe hardware including ISCs (Refs. 16 and 17).

- All elements of production cost assumed to start at T1 (for flight test aircraft).

5.2. ESTIMATES FOR NASA-GENERATED CONFIGURATIONS

Table 14 shows the cost and factory throughput results for the baseline configuration, and all the ISC-based analyses performed.

The first column describes each sensitivity case. The second column shows the DOC+I per seat-mile impact of ISC technology for each case at the 50th percentile confidence level. The 50th percentile level has been used throughout this figure because the purpose of the figure is to convey the notion that either the ISC concept does or does not show promise. Probability distributions for each sensitivity case are provide in the Appendix should higher confidence levels be of interest to support future go/no go decisions.

The third column shows the probability of a cost reduction. The fourth column shows the impact on total investment cost at the 50th percentile confidence level. Total investment cost includes the complete cost of development and flight testing, as well as the production cost of all aircraft of the model in the world-wide fleet. The fifth column focuses on the fuselage T1 production cost at the 50th percentile confidence level. The sixth column shows the impact on production throughput in terms of shipsets per month at the 50th percentile confidence level. The seventh and final column shows the fuel burn impact in terms of seat-miles per gallon at the 50th percentile confidence level for cases in which a weight impact was specified.

The first row in **Table 14** shows the absolute costs and fuselage manufacturing throughput for the 737-800 baseline. The remaining rows show the relative impact of ISC technology for various assumption sets.

Table 14. Summary of Results

Case	DOC/seat-mile impact (2020$; - is good)	Probability of DOC Reduction	Investment Cost Impact (2020$M; - is good)	Fuselage T1 Production Cost Impact (2020$M; - is good)	Fuselage Production Rate Impact (units/mo; + is good)	Fuel Economy Impact (seat-mile/gal; + is good)
Baseline	0.0525	--	271,841	25.1	31.0	78.0
Basic ISC, no weight impact, no maintenance impact	-0.0001	100%	-1,062	-1.7	+18.6	0.0
5% outer shell weight reduction with resizing	-0.0003	100%	-2,379	-1.8	+18.8	+0.3
20% outer shell weight reduction with resizing	-0.0008	100%	-6,272	-2.0	+19.4	+1.3
5% outer shell weight reduction with resizing and fuel at $4.07/gal	-0.0004	100%	-2,366	-1.8	+18.6	+0.3
5% outer shell weight increase with resizing	0.0001	2%	+299	-1.6	+18.9	-0.3
5% outer shell weight increase with resizing and fuel at $4.07/gal	0.0002	0%	+300	-1.7	+18.7	-0.3
Heavy maintenance interval increased from 96 mo to 108 mo	-0.0003	100%	-1,265	-1.7	+18.9	0.0
Heavy maintenance interval increased from 96 mo to 84 mo	0.0001	0%	-828	-1.7	+18.9	0.0
ISC section circumferential joints riveted rather than welded together	-0.0001	100%	-1,221	-2.0	+20.3	0.0
ISC section length 15 ft	-0.0001	100%	-1,174	-1.9	+22.1	0.0
ISC section length 20 ft	-0.0001	100%	-1,237	-2.0	+31.5	0.0
Spot weld vs rivet cost factor = 0.2	-0.0001	100%	-1,171	-1.9	+40.4	0.0
Spot weld vs rivet cost factor = 0.8	-0.0001	100%	-945	-1.6	+6.5	0.0
Post-formed ISC thickness = 0.072 in	-0.0001	100%	-1,059	-1.7	+19.0	0.0
Post-formed ISC thickness = 0.036 in	-0.0001	100%	-1,440	-2.3	+26.0	0.0
75% robotic riveting	-0.0001	100%	-907	-1.5	+22.8	0.0
98% robotic riveting	-0.0001	100%	-761	-1.3	+25.4	0.0

5.3. SPECIFIC CASES

The Basic ISC case in the first row of Table 14 corresponds to the stated assumptions from the Ground Rules and assumptions section.

The next five cases explore scenarios in which incorporation of ISC technology resulted in either a weight reduction or a weight increase to the constant-cross-section portion of the fuselage outer shell. The direct cost of outer shell weight changes in ISC-based fuselages versus skin-stringer fuselages was captured by varying stringer width in the ISC case. For the nominal case, the stringer width was set such that the total estimated weight (based on simple geometry) of the ISC fuselage shell was equal to the estimated weight of the skin-stringer outer shell. For cases where the ISC weight was assumed to be more or less than the skin-stringer weight, stringer width ISC stringer width was adjusted to achieve the desired weight impact. In addition, the PTIRS weight resizing module [19] was enabled, resulting in weight changes rippling throughout the overall aircraft This led to magnified swings in DOC+I impact, investment cost impact, and fuel burn impact.

The following two cases examine the potential impacts of changes in heavy maintenance interval. As would be expected, the impact on direct operating cost is noticeable. Less obvious is the impact on investment cost. Changes in the heavy maintenance interval causes changes in investment cost because decreasing the heavy maintenance causes the total required inventory of aircraft to increase because more aircraft are tied up in maintenance at any given time. Conversely, increasing the heavy maintenance interval causes the total required inventory of aircraft to decrease.

The next case looks at joining the ISC barrels together via rivets rather than friction stir welding. This results in decreased total investment and fuselage production T1 costs as well as increased factory footprint because riveting appears to be less costly and less floor space-intensive that friction stir welding for very large assemblies.

The following two cases examine the impact of varying the cost of RFSSW. Estimates of the per-weld cost of RFSSW were available to NASA but were not released for use in time to support this study. However, it can be said that the cost of a friction stir weld could be related to the cost of a drilled and set rivet by a factor somewhere between 0.0 and 1.0. In the nominal case, this factor was assumed to be 0.5 but in these two cases, decreasing this assumed factor to 0.2 and increasing it to 0.8 were examined. A large throughput increase was observed for spot-weld-versus-rivet factor of 0.2 due to a significant reduction in number of spot-welding workstations which freed up vast amounts of floor space for other operations.

Similarly, the next two cases examine the impact of varying the assumed thickness of the post-formed ISC skins. The nominal assumption was 0.125 in thick. In these two cases, decreasing the achievable post-formed thickness first to 0.072 in and then to 0.036 in was examined. Decreasing to 0.072 in had no perceptible impact. However, decreasing to 0.036 in represents the case where sections emerge from the ISC forming process at “net shape”, ready for assembly, with no chemical milling required to meet the weight-driven thickness requirement of 0.036 in. This created significant benefits in both cost and production throughput.

The last two cases examine the impact of altering the baseline, riveted skin-stringer case by varying the percentage of rivets assumed to be set robotically rather than manually. The baseline assumption was 50% based on a statement in Spirit AeroSystems’ 2022 First Quarter Report [15]. The 50% assumption was varied to 75% of rivets set robotically, and then 98% of rivets set robotically. Both cases lower the apparent ISC cost reductions because the baseline cost of the riveted skin-stringer case is decreased. However, both cases increased the relative production throughput benefit, implying that manual riveting is more efficient relative to floor space than robotic riveting.

6. CONCLUSIONS

The conclusions from this Advanced Metallic Fuselage Cost study are as follows:

- ISC technology has a high probability of reducing overall Direct Operating Costs + Investment (DOC+I) if the technology does not cause weight increases or maintenance interval decreases. However, the potential magnitudes of DOC+I reductions are relatively small.
- ISC technology has a very strong potential for increasing factory throughput significantly given constrained factory floor space. This potential alone makes this technology attractive and warrants much more detailed data collection and research, ideally with the direct involvement of industrial partners.
- While the ISC technology alone shows cost and throughput benefits, a significant portion of the cost and throughput benefits observed in this study depend on the cost benefit of RFSSW relative to drilling and robotic riveting. This area requires and deserves more research, ideally with the direct involvement of industrial partners.
- Weight reductions from ISC technology could increase both DOC+I and investment cost benefits significantly.

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APPENDIX – PROBABILISTIC RESULTS

A.1 BASIC ISC, NO WEIGHT IMPACT, NO MAINT IMPACT

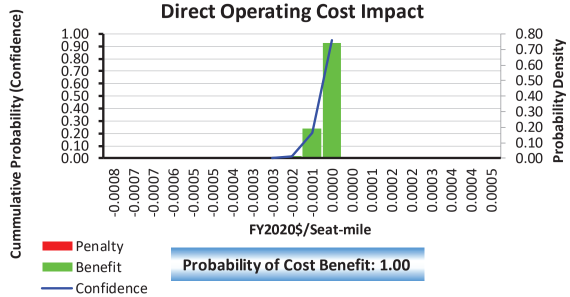
Results

737-800 with ISC center fuselage

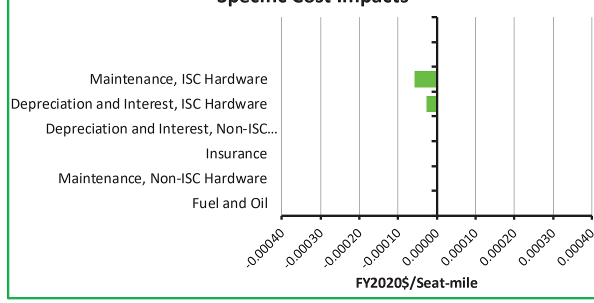
Date: 2/9/23 3:09 PM
Baseline Aircraft: NASA 737-800-like, 160 pax, 2022 adj

Operator's Cost (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact (- is good)
Direct Operating Cost per Seat-mile (FY2020$, 50%)	0.0522	0.0521	-0.0001
Total Operating Cost per Seat-mile (FY2020$, 50%)	0.1500	0.1499	-0.0001
Minimum Coach Ticket Price (FY2020$, 50%)	152.6	152.5	-0.1

Direct Operating Cost Impact



Specific Cost Impacts



Comparative Values (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact
Takeoff Weight (lb, + impact is bad)	174,248	174,248	0
Empty Weight (lb, + impact is bad)	84,147	84,147	0
Useable Fuel Weight (lb, + impact is bad)	46,766	46,766	0
Seat-miles (statute) per Gallon (+ impact is good)	78.7	78.7	0.0
Seat-miles per equivalent kWh (+ impact is good)	2.12	2.12	0.00

Technologies Included

- Replace skin-stringer with ISC

Study Parameters	Assumed	Break-even (50%)
Fleet Size	6,600	N/A
Investment Interest Rate	10%	N/A
Fuel Price (FY2020$/gal)	2.03	N/A
Electricity Price (FY2020$/kWh)	0.11	N/A

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Manufacturer's Investment (50% Confidence)	Reference Aircraft	Enhanced Aircraft	Impact (- is good)
Investment Total (FY2020$M, 50%)	269,756	268,784	-1,062
Minimum Unit Price (FY2020$M, 50%)	42.4	42.4	-0.1

Production Rate Impact	
Pobability	Increase, Units/mo.
10%	33.8
50%	18.6
90%	8.5

Inputs

Cost Driver	Units	Observed Low	Observed High	Default Value	Minimum Value	Most Likely Value	Maximum Value
Diameter of fuselage section	feet	0.000	0.000	0.000	12.500	12.500	12.500
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of frame segments	number	0.000	0.000	0.000	8.000	10.000	12.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Min. thickness of chem-milled ISC	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000
Percentage of attachments made with spot welds versus (manual) rivets	percent	0.000	0.000	0.000	0.330	0.500	0.670
Number of attach points (rivets or spot welds) at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of attach points to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of post-formed ISC	inches	0.000	0.000	0.000	0.100	0.125	0.150
Stringer height	inches	0.000	0.000	0.000	0.750	1.000	1.250
Stringer thickness	inches	0.000	0.000	0.000	0.100	0.200	0.300
Length of fuselage section	feet	0.000	0.000	0.000	58.000	63.000	68.000
Portion of circumference where frames attach directly to skin in addition to stringers	percent	0.000	0.000	0.000	0.400	0.500	0.600
percentage of rivets set manually	percent	0.000	0.000	0.000	0.330	0.500	0.670
Cost of locating and performing spot weld ralative to cost of locating, drilling, and setting an automatic rivet	factor	0.000	0.000	0.000	0.100	0.500	0.900
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of circumfrential joints	number	0.000	0.000	0.000	2.000	2.000	2.000
width of circumfrential joints	feet	0.000	0.000	0.000	0.400	0.500	0.600
Rows of rivets per circumfrential joint	number	0.000	0.000	0.000	4.000	4.000	6.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Number of lap joints (and frame segments)	number	0.000	0.000	0.000	8.000	10.000	12.000
width of lap joints	feet	0.000	0.000	0.000	0.300	0.333	0.366
rows of rivets at lap joints	number	0.000	0.000	0.000	3.000	3.000	3.000
Min. thickness of chem-milled skin sheets, inches	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of rivets at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of rivets to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of blank skin sheets	inches	0.000	0.000	0.000	0.050	0.072	0.094
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000

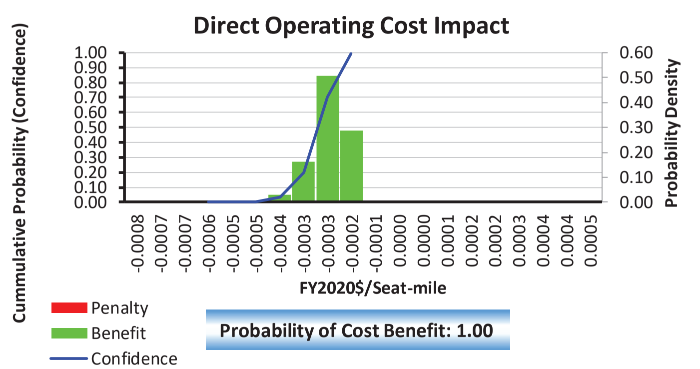
A.2 5% OUTER SHELL WEIGHT REDUCTION WITH RESIZING

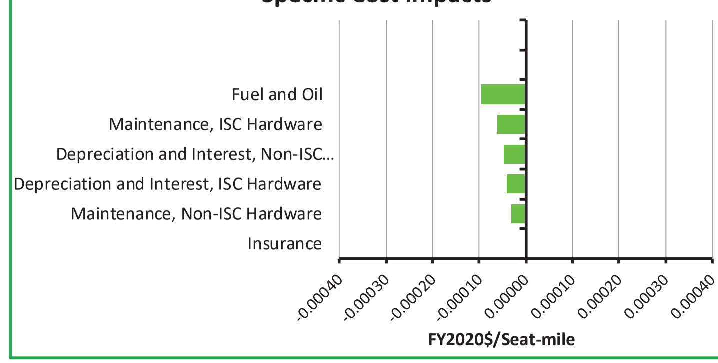
Results

737-800 with ISC center fuselage

Date: 2/17/23 9:58 PM
Baseline Aircraft: NASA 737-800-like, 160 pax, 2022 adj

Operator's Cost (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact (- is good)
Direct Operating Cost per Seat-mile (FY2020$, 50%)	0.0524	0.0521	-0.0003
Total Operating Cost per Seat-mile (FY2020$, 50%)	0.1502	0.1499	-0.0003
Minimum Coach Ticket Price (FY2020$, 50%)	152.8	152.5	-0.3





Comparative Values (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact
Takeoff Weight (lb, + impact is bad)	174,248	173,551	-697
Empty Weight (lb, + impact is bad)	84,147	83,639	-508
Useable Fuel Weight (lb, + impact is bad)	46,766	46,577	-189
Seat-miles (statute) per Gallon (+ impact is good)	78.7	79.0	0.3
Seat-miles per equivalent kWh (+ impact is good)	2.12	2.13	0.01

Technologies Included

- Replace skin-stringer with ISC

Study Parameters	Assumed	Break-even (50%)
Fleet Size	6,600	N/A
Investment Interest Rate	10%	N/A
Fuel Price (FY2020$/gal)	2.03	N/A
Electricity Price (FY2020$/kWh)	0.11	N/A

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Version: 1.2

Manufacturer's Investment (50% Confidence)	Reference Aircraft	Enhanced Aircraft	Impact (- is good)
Investment Total (FY2020$M, 50%)	270,448	268,168	-2,379
Minimum Unit Price (FY2020$M, 50%)	42.4	42.1	-0.3

Production Rate Impact	
Pobability	Increase, Units/mo.
10%	33.4
50%	18.8
90%	8.6

Inputs

Cost Driver	Units	Observed Low	Observed High	Default Value	Minimum Value	Most Likely Value	Maximum Value
Diameter of fuselage section	feet	0.000	0.000	0.000	12.500	12.500	12.500
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of frame segments	number	0.000	0.000	0.000	8.000	10.000	12.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Min. thickness of chem-milled ISC	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000
Percentage of attachments made with spot welds versus (manual) rivets	percent	0.000	0.000	0.000	0.330	0.500	0.670
Number of attach points (rivets or spot welds) at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of attach points to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of post-formed ISC	inches	0.000	0.000	0.000	0.100	0.125	0.150
Stringer height	inches	0.000	0.000	0.000	0.750	1.000	1.250
Stringer thickness	inches	0.000	0.000	0.000	0.075	0.175	0.275
Length of fuselage section	feet	0.000	0.000	0.000	58.000	63.000	68.000
Portion of circumference where frames attach directly to skin in addition to stringers	percent	0.000	0.000	0.000	0.400	0.500	0.600
percentage of rivets set manually	percent	0.000	0.000	0.000	0.330	0.500	0.670
Cost of locating and performing spot weld ralative to cost of locating, drilling, and setting an automatic rivet	factor	0.000	0.000	0.000	0.100	0.500	0.900
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of circumfrential joints	number	0.000	0.000	0.000	2.000	2.000	2.000
width of circumfrential joints	feet	0.000	0.000	0.000	0.400	0.500	0.600
Rows of rivets per circumfrential joint	number	0.000	0.000	0.000	4.000	4.000	6.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Number of lap joints (and frame segments)	number	0.000	0.000	0.000	8.000	10.000	12.000
width of lap joints	feet	0.000	0.000	0.000	0.300	0.333	0.366
rows of rivets at lap joints	number	0.000	0.000	0.000	3.000	3.000	3.000
Min. thickness of chem-milled skin sheets, inches	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of rivets at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of rivets to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of blank skin sheets	inches	0.000	0.000	0.000	0.050	0.072	0.094
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000

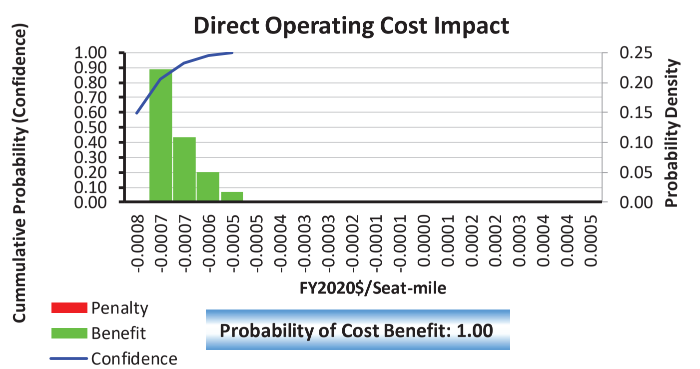
A.3 20% OUTER SHELL WEIGHT REDUCTION WITH RESIZING

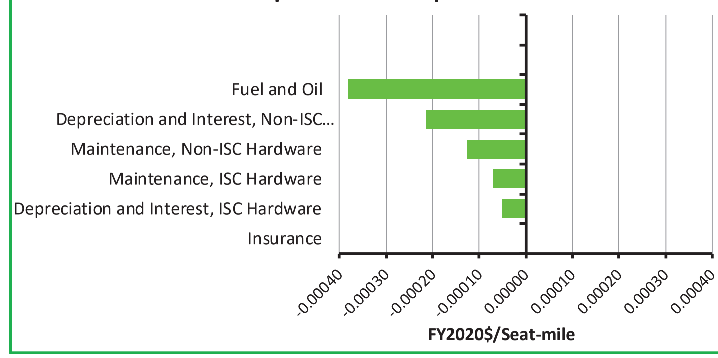
Results

737-800 with ISC center fuselage

Date: 2/19/23 10:12 AM
Baseline Aircraft: NASA 737-800-like, 160 pax, 2022 adj

Operator's Cost (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact (- is good)
Direct Operating Cost per Seat-mile (FY2020$, 50%)	0.0524	0.0516	-0.0008
Total Operating Cost per Seat-mile (FY2020$, 50%)	0.1502	0.1494	-0.0008
Minimum Coach Ticket Price (FY2020$, 50%)	152.8	152.0	-0.9





Comparative Values (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact
Takeoff Weight (lb, + impact is bad)	174,248	171,474	-2,774
Empty Weight (lb, + impact is bad)	84,147	82,126	-2,021
Useable Fuel Weight (lb, + impact is bad)	46,766	46,013	-753
Seat-miles (statute) per Gallon (+ impact is good)	77.8	79.1	1.3
Seat-miles per equivalent kWh (+ impact is good)	2.10	2.13	0.03

Technologies Included

- Replace skin-stringer with ISC

Study Parameters	Assumed	Break-even (50%)
Fleet Size	6,600	N/A
Investment Interest Rate	10%	N/A
Fuel Price (FY2020$/gal)	2.03	N/A
Electricity Price (FY2020$/kWh)	0.11	N/A

PTIRS
Version: 1.2

Manufacturer's Investment (50% Confidence)	Reference Aircraft	Enhanced Aircraft	Impact (- is good)
Investment Total (FY2020$M, 50%)	271,368	264,968	-6,272
Minimum Unit Price (FY2020$M, 50%)	42.4	41.5	-0.9

Production Rate Impact	
Pobability	Increase, Units/mo.
10%	34.3
50%	19.4
90%	9.0

Inputs

Cost Driver	Units	Observed Low	Observed High	Default Value	Minimum Value	Most Likely Value	Maximum Value
Diameter of fuselage section	feet	0.000	0.000	0.000	12.500	12.500	12.500
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of frame segments	number	0.000	0.000	0.000	8.000	10.000	12.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Min. thickness of chem-milled ISC	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000
Percentage of attachments made with spot welds versus (manual) rivets	percent	0.000	0.000	0.000	0.330	0.500	0.670
Number of attach points (rivets or spot welds) at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of attach points to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of post-formed ISC	inches	0.000	0.000	0.000	0.100	0.125	0.150
Stringer height	inches	0.000	0.000	0.000	0.750	1.000	1.250
Stringer thickness	inches	0.000	0.000	0.000	0.075	0.105	0.145
Length of fuselage section	feet	0.000	0.000	0.000	58.000	63.000	68.000
Portion of circumference where frames attach directly to skin in addition to stringers	percent	0.000	0.000	0.000	0.400	0.500	0.600
percentage of rivets set manually	percent	0.000	0.000	0.000	0.330	0.500	0.670
Cost of locating and performing spot weld ralative to cost of locating, drilling, and setting an automatic rivet	factor	0.000	0.000	0.000	0.100	0.500	0.900
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of circumfrential joints	number	0.000	0.000	0.000	2.000	2.000	2.000
width of circumfrential joints	feet	0.000	0.000	0.000	0.400	0.500	0.600
Rows of rivets per circumfrential joint	number	0.000	0.000	0.000	4.000	4.000	6.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Number of lap joints (and frame segments)	number	0.000	0.000	0.000	8.000	10.000	12.000
width of lap joints	feet	0.000	0.000	0.000	0.300	0.333	0.366
rows of rivets at lap joints	number	0.000	0.000	0.000	3.000	3.000	3.000
Min. thickness of chem-milled skin sheets, inches	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of rivets at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of rivets to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of blank skin sheets	inches	0.000	0.000	0.000	0.050	0.072	0.094
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000

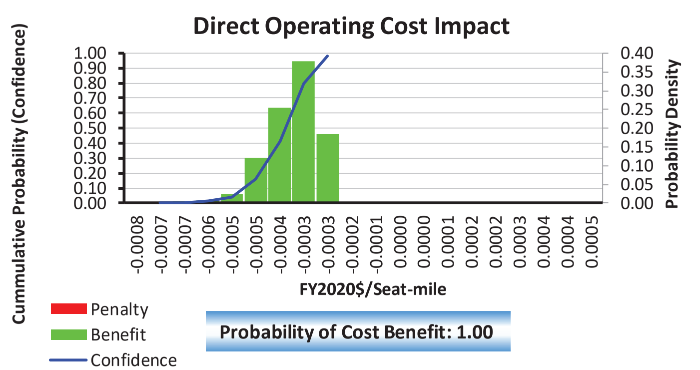
A.4 5% OUTER SHELL WEIGHT REDUCTION WITH RESIZING AND FUEL AT $4.07/GAL

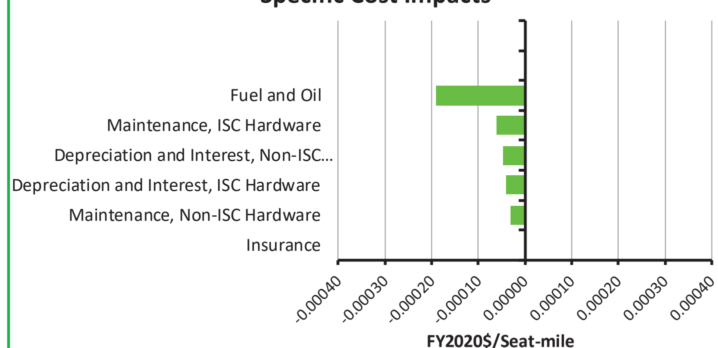
Results

737-800 with ISC center fuselage

Date: 2/19/23 10:17 AM
Baseline Aircraft: NASA 737-800-like, 160 pax, 2022 adj

Operator's Cost (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact (- is good)
Direct Operating Cost per Seat-mile (FY2020$, 50%)	0.0757	0.0753	-0.0004
Total Operating Cost per Seat-mile (FY2020$, 50%)	0.1744	0.1741	-0.0004
Minimum Coach Ticket Price (FY2020$, 50%)	177.5	177.1	-0.4





Comparative Values (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact
Takeoff Weight (lb, + impact is bad)	174,248	173,551	-697
Empty Weight (lb, + impact is bad)	84,147	83,639	-508
Useable Fuel Weight (lb, + impact is bad)	46,766	46,577	-189
Seat-miles (statute) per Gallon (+ impact is good)	77.5	77.8	0.3
Seat-miles per equivalent kWh (+ impact is good)	2.09	2.10	0.01

Technologies Included

- Replace skin-stringer with ISC

Study Parameters	Assumed	Break-even (50%)
Fleet Size	6,600	N/A
Investment Interest Rate	10%	N/A
Fuel Price (FY2020$/gal)	4.06	N/A
Electricity Price (FY2020$/kWh)	0.11	N/A

PTIRS
Version: 1.2

Manufacturer's Investment (50% Confidence)	Reference Aircraft	Enhanced Aircraft	Impact (- is good)
Investment Total (FY2020$M, 50%)	266,758	264,463	-2,366
Minimum Unit Price (FY2020$M, 50%)	42.3	42.0	-0.3

Production Rate Impact	
Pobability	Increase, Units/mo.
10%	34.2
50%	18.6
90%	8.2

Inputs

Cost Driver	Units	Observed Low	Observed High	Default Value	Minimum Value	Most Likely Value	Maximum Value
Diameter of fuselage section	feet	0.000	0.000	0.000	12.500	12.500	12.500
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of frame segments	number	0.000	0.000	0.000	8.000	10.000	12.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Min. thickness of chem-milled ISC	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000
Percentage of attachments made with spot welds versus (manual) rivets	percent	0.000	0.000	0.000	0.330	0.500	0.670
Number of attach points (rivets or spot welds) at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of attach points to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of post-formed ISC	inches	0.000	0.000	0.000	0.100	0.125	0.150
Stringer height	inches	0.000	0.000	0.000	0.750	1.000	1.250
Stringer thickness	inches	0.000	0.000	0.000	0.075	0.175	0.275
Length of fuselage section	feet	0.000	0.000	0.000	58.000	63.000	68.000
Portion of circumference where frames attach directly to skin in addition to stringers	percent	0.000	0.000	0.000	0.400	0.500	0.600
percentage of rivets set manually	percent	0.000	0.000	0.000	0.330	0.500	0.670
Cost of locating and performing spot weld ralative to cost of locating, drilling, and setting an automatic rivet	factor	0.000	0.000	0.000	0.100	0.500	0.900
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of circumfrential joints	number	0.000	0.000	0.000	2.000	2.000	2.000
width of circumfrential joints	feet	0.000	0.000	0.000	0.400	0.500	0.600
Rows of rivets per circumfrential joint	number	0.000	0.000	0.000	4.000	4.000	6.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Number of lap joints (and frame segments)	number	0.000	0.000	0.000	8.000	10.000	12.000
width of lap joints	feet	0.000	0.000	0.000	0.300	0.333	0.366
rows of rivets at lap joints	number	0.000	0.000	0.000	3.000	3.000	3.000
Min. thickness of chem-milled skin sheets, inches	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of rivets at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of rivets to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of blank skin sheets	inches	0.000	0.000	0.000	0.050	0.072	0.094
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000

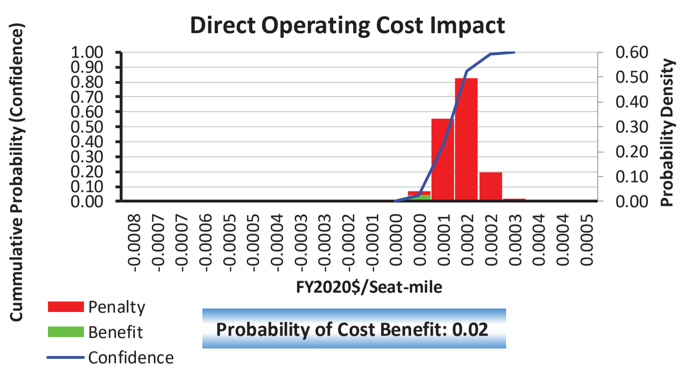
A.5 5% OUTER SHELL WEIGHT INCREASE WITH RESIZING

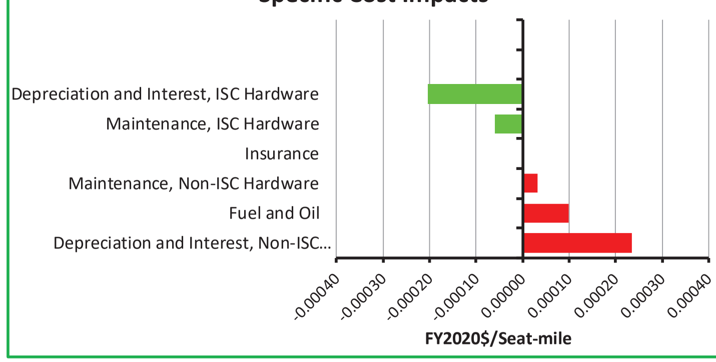
Results

737-800 with ISC center fuselage

Date: 2/9/23 4:14 PM
Baseline Aircraft: NASA 737-800-like, 160 pax, 2022 adj

Operator's Cost (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact (- is good)
Direct Operating Cost per Seat-mile (FY2020$, 50%)	0.0525	0.0526	0.0001
Total Operating Cost per Seat-mile (FY2020$, 50%)	0.1503	0.1504	0.0001
Minimum Coach Ticket Price (FY2020$, 50%)	152.9	153.0	0.1





Comparative Values (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact
Takeoff Weight (lb, + impact is bad)	174,248	174,947	699
Empty Weight (lb, + impact is bad)	84,147	84,657	510
Useable Fuel Weight (lb, + impact is bad)	46,766	46,956	190
Seat-miles (statute) per Gallon (+ impact is good)	78.5	78.1	-0.3
Seat-miles per equivalent kWh (+ impact is good)	2.11	2.11	-0.01

Technologies Included

- Replace skin-stringer with ISC

Study Parameters	Assumed	Break-even (50%)
Fleet Size	6,600	N/A
Investment Interest Rate	10%	N/A
Fuel Price (FY2020$/gal)	2.03	N/A
Electricity Price (FY2020$/kWh)	0.11	N/A

PTIRS Version: 1.2

Manufacturer's Investment (50% Confidence)	Reference Aircraft	Enhanced Aircraft	Impact (- is good)
Investment Total (FY2020$M, 50%)	269,063	269,458	299
Minimum Unit Price (FY2020$M, 50%)	42.5	42.6	0.1

Production Rate Impact	
Pobability	Increase, Units/mo.
10%	33.1
50%	18.9
90%	8.5

Inputs

Cost Driver	Units	Observed Low	Observed High	Default Value	Minimum Value	Most Likely Value	Maximum Value
Diameter of fuselage section	feet	0.000	0.000	0.000	12.500	12.500	12.500
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of frame segments	number	0.000	0.000	0.000	8.000	10.000	12.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Min. thickness of chem-milled ISC	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000
Percentage of attachments made with spot welds versus (manual) rivets	percent	0.000	0.000	0.000	0.330	0.500	0.670
Number of attach points (rivets or spot welds) at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of attach points to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of post-formed ISC	inches	0.000	0.000	0.000	0.100	0.125	0.150
Stringer height	inches	0.000	0.000	0.000	0.750	1.000	1.250
Stringer thickness	inches	0.000	0.000	0.000	0.145	0.245	0.345
Length of fuselage section	feet	0.000	0.000	0.000	58.000	63.000	68.000
Portion of circumference where frames attach directly to skin in addition to stringers	percent	0.000	0.000	0.000	0.400	0.500	0.600
percentage of rivets set manually	percent	0.000	0.000	0.000	0.330	0.500	0.670
Cost of locating and performing spot weld ralative to cost of locating, drilling, and setting an automatic rivet	factor	0.000	0.000	0.000	0.100	0.500	0.900
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of circumfrential joints	number	0.000	0.000	0.000	2.000	2.000	2.000
width of circumfrential joints	feet	0.000	0.000	0.000	0.400	0.500	0.600
Rows of rivets per circumfrential joint	number	0.000	0.000	0.000	4.000	4.000	6.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Number of lap joints (and frame segments)	number	0.000	0.000	0.000	8.000	10.000	12.000
width of lap joints	feet	0.000	0.000	0.000	0.300	0.333	0.366
rows of rivets at lap joints	number	0.000	0.000	0.000	3.000	3.000	3.000
Min. thickness of chem-milled skin sheets, inches	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of rivets at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of rivets to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of blank skin sheets	inches	0.000	0.000	0.000	0.050	0.072	0.094
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000

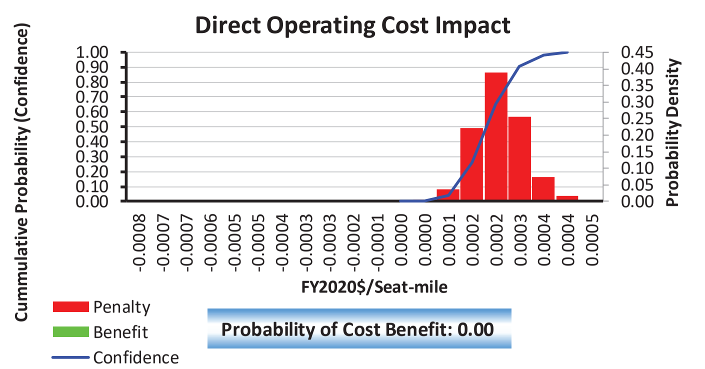
A.6 5% OUTER SHELL WEIGHT INCREASE WITH RESIZING AND FUEL AT $4.07/GAL

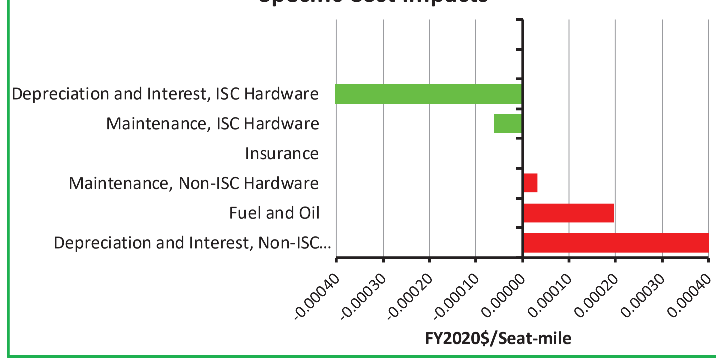
Results

737-800 with ISC center fuselage

Date: 2/9/23 5:12 PM
Baseline Aircraft: NASA 737-800-like, 160 pax, 2022 adj

Operator's Cost (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact (- is good)
Direct Operating Cost per Seat-mile (FY2020$, 50%)	0.0764	0.0766	0.0002
Total Operating Cost per Seat-mile (FY2020$, 50%)	0.1751	0.1753	0.0002
Minimum Coach Ticket Price (FY2020$, 50%)	178.2	178.4	0.2





Comparative Values (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact
Takeoff Weight (lb, + impact is bad)	174,248	174,947	699
Empty Weight (lb, + impact is bad)	84,147	84,657	510
Useable Fuel Weight (lb, + impact is bad)	46,766	46,956	190
Seat-miles (statute) per Gallon (+ impact is good)	77.1	76.8	-0.3
Seat-miles per equivalent kWh (+ impact is good)	2.08	2.07	-0.01

Technologies Included

- Replace skin-stringer with ISC

Study Parameters	Assumed	Break-even (50%)
Fleet Size	6,600	N/A
Investment Interest Rate	10%	N/A
Fuel Price (FY2020$/gal)	4.06	N/A
Electricity Price (FY2020$/kWh)	0.11	N/A

PTIRS Version: 1.2

Manufacturer's Investment (50% Confidence)	Reference Aircraft	Enhanced Aircraft	Impact (- is good)
Investment Total (FY2020$M, 50%)	269,545	269,775	300
Minimum Unit Price (FY2020$M, 50%)	42.7	42.8	0.1

Production Rate Impact	
Pobability	Increase, Units/mo.
10%	34.7
50%	18.7
90%	8.0

Inputs

Cost Driver	Units	Observed Low	Observed High	Default Value	Minimum Value	Most Likely Value	Maximum Value
Diameter of fuselage section	feet	0.000	0.000	0.000	12.500	12.500	12.500
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of frame segments	number	0.000	0.000	0.000	8.000	10.000	12.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Min. thickness of chem-milled ISC	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000
Percentage of attachments made with spot welds versus (manual) rivets	percent	0.000	0.000	0.000	0.330	0.500	0.670
Number of attach points (rivets or spot welds) at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of attach points to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of post-formed ISC	inches	0.000	0.000	0.000	0.100	0.125	0.150
Stringer height	inches	0.000	0.000	0.000	0.750	1.000	1.250
Stringer thickness	inches	0.000	0.000	0.000	0.145	0.245	0.345
Length of fuselage section	feet	0.000	0.000	0.000	58.000	63.000	68.000
Portion of circumference where frames attach directly to skin in addition to stringers	percent	0.000	0.000	0.000	0.400	0.500	0.600
percentage of rivets set manually	percent	0.000	0.000	0.000	0.330	0.500	0.670
Cost of locating and performing spot weld ralative to cost of locating, drilling, and setting an automatic rivet	factor	0.000	0.000	0.000	0.100	0.500	0.900
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of circumfrential joints	number	0.000	0.000	0.000	2.000	2.000	2.000
width of circumfrential joints	feet	0.000	0.000	0.000	0.400	0.500	0.600
Rows of rivets per circumfrential joint	number	0.000	0.000	0.000	4.000	4.000	6.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Number of lap joints (and frame segments)	number	0.000	0.000	0.000	8.000	10.000	12.000
width of lap joints	feet	0.000	0.000	0.000	0.300	0.333	0.366
rows of rivets at lap joints	number	0.000	0.000	0.000	3.000	3.000	3.000
Min. thickness of chem-milled skin sheets, inches	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of rivets at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of rivets to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of blank skin sheets	inches	0.000	0.000	0.000	0.050	0.072	0.094
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000

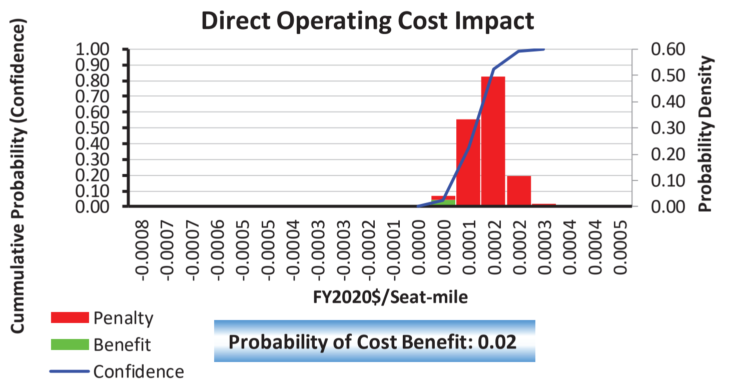
A.7 HEAVY MAINTENANCE INTERVAL INCREASED FROM 96 MO TO 108 MO

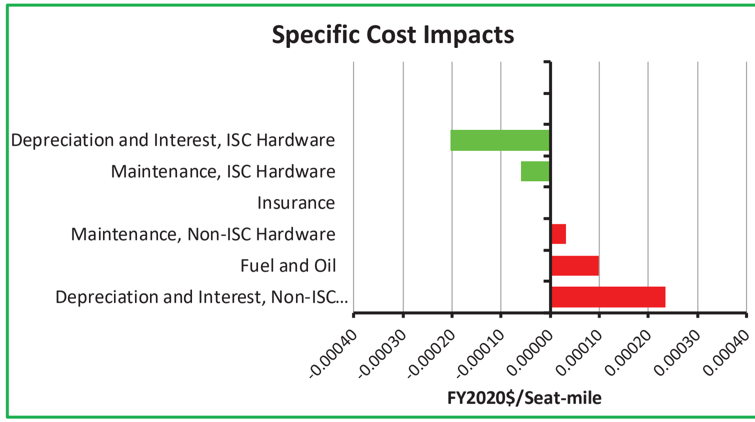
Results

737-800 with ISC center fuselage

Date: 2/9/23 4:14 PM
Baseline Aircraft: NASA 737-800-like, 160 pax, 2022 adj

Operator's Cost (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact (- is good)
Direct Operating Cost per Seat-mile (FY2020$, 50%)	0.0525	0.0526	0.0001
Total Operating Cost per Seat-mile (FY2020$, 50%)	0.1503	0.1504	0.0001
Minimum Coach Ticket Price (FY2020$, 50%)	152.9	153.0	0.1





Comparative Values (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact
Takeoff Weight (lb, + impact is bad)	174,248	174,947	699
Empty Weight (lb, + impact is bad)	84,147	84,657	510
Useable Fuel Weight (lb, + impact is bad)	46,766	46,956	190
Seat-miles (statute) per Gallon (+ impact is good)	78.5	78.1	-0.3
Seat-miles per equivalent kWh (+ impact is good)	2.11	2.11	-0.01

Technologies Included

- Replace skin-stringer with ISC

Study Parameters	Assumed	Break-even (50%)
Fleet Size	6,600	N/A
Investment Interest Rate	10%	N/A
Fuel Price (FY2020$/gal)	2.03	N/A
Electricity Price (FY2020$/kWh)	0.11	N/A

PTIRS
Version: 1.2

Manufacturer's Investment (50% Confidence)	Reference Aircraft	Enhanced Aircraft	Impact (- is good)
Investment Total (FY2020$M, 50%)	269,063	269,458	299
Minimum Unit Price (FY2020$M, 50%)	42.5	42.6	0.1

Production Rate Impact	
Pobability	Increase, Units/mo.
10%	33.1
50%	18.9
90%	8.5

Inputs

Cost Driver	Units	Observed Low	Observed High	Default Value	Minimum Value	Most Likely Value	Maximum Value
Diameter of fuselage section	feet	0.000	0.000	0.000	12.500	12.500	12.500
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of frame segments	number	0.000	0.000	0.000	8.000	10.000	12.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Min. thickness of chem-milled ISC	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000
Percentage of attachments made with spot welds versus (manual) rivets	percent	0.000	0.000	0.000	0.330	0.500	0.670
Number of attach points (rivets or spot welds) at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of attach points to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of post-formed ISC	inches	0.000	0.000	0.000	0.100	0.125	0.150
Stringer height	inches	0.000	0.000	0.000	0.750	1.000	1.250
Stringer thickness	inches	0.000	0.000	0.000	0.100	0.200	0.300
Length of fuselage section	feet	0.000	0.000	0.000	58.000	63.000	68.000
Portion of circumference where frames attach directly to skin in addition to stringers	percent	0.000	0.000	0.000	0.400	0.500	0.600
percentage of rivets set manually	percent	0.000	0.000	0.000	0.330	0.500	0.670
Cost of locating and performing spot weld ralative to cost of locating, drilling, and setting an automatic rivet	factor	0.000	0.000	0.000	0.100	0.500	0.900
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of circumfrential joints	number	0.000	0.000	0.000	2.000	2.000	2.000
width of circumfrential joints	feet	0.000	0.000	0.000	0.400	0.500	0.600
Rows of rivets per circumfrential joint	number	0.000	0.000	0.000	4.000	4.000	6.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Number of lap joints (and frame segments)	number	0.000	0.000	0.000	8.000	10.000	12.000
width of lap joints	feet	0.000	0.000	0.000	0.300	0.333	0.366
rows of rivets at lap joints	number	0.000	0.000	0.000	3.000	3.000	3.000
Min. thickness of chem-milled skin sheets, inches	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of rivets at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of rivets to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of blank skin sheets	inches	0.000	0.000	0.000	0.050	0.072	0.094
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000

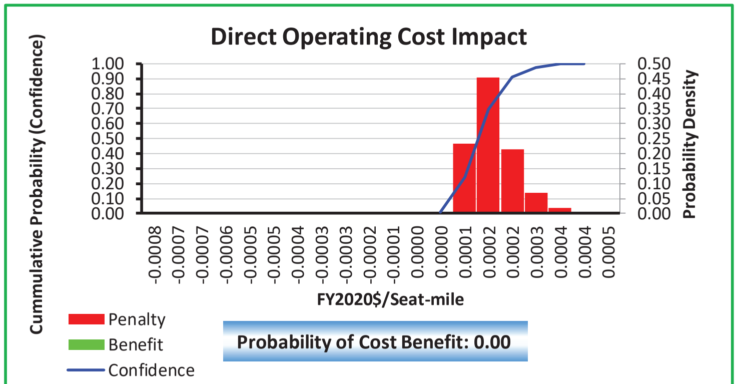
A.8 HEAVY MAINTENANCE INTERVAL DECREASED FROM 96 MO TO 84 MO

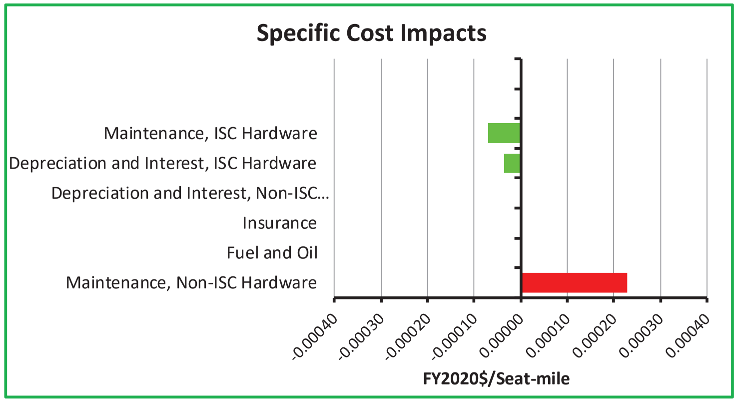
Results

737-800 with ISC center fuselage

Date: 2/9/23 5:26 PM
Baseline Aircraft: NASA 737-800-like, 160 pax, 2022 adj

Operator's Cost (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact (- is good)
Direct Operating Cost per Seat-mile (FY2020$, 50%)	0.0523	0.0524	0.0001
Total Operating Cost per Seat-mile (FY2020$, 50%)	0.1501	0.1502	0.0001
Minimum Coach Ticket Price (FY2020$, 50%)	152.7	152.8	0.1





Comparative Values (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact
Takeoff Weight (lb, + impact is bad)	174,248	174,248	0
Empty Weight (lb, + impact is bad)	84,147	84,147	0
Useable Fuel Weight (lb, + impact is bad)	46,766	46,766	0
Seat-miles (statute) per Gallon (+ impact is good)	78.9	78.9	0.0
Seat-miles per equivalent kWh (+ impact is good)	2.13	2.13	0.00

Technologies Included

- Replace skin-stringer with ISC

Study Parameters	Assumed	Break-even (50%)
Fleet Size	6,600	N/A
Investment Interest Rate	10%	N/A
Fuel Price (FY2020$/gal)	2.03	N/A
Electricity Price (FY2020$/kWh)	0.11	N/A

PTIRS Version: 1.2

Manufacturer's Investment (50% Confidence)	Reference Aircraft	Enhanced Aircraft	Impact (- is good)
Investment Total (FY2020$M, 50%)	269,563	268,629	-828
Minimum Unit Price (FY2020$M, 50%)	42.3	42.2	-0.1

Production Rate Impact	
Pobability	Increase, Units/mo.
10%	33.1
50%	18.9
90%	8.5

Inputs

Cost Driver	Units	Observed Low	Observed High	Default Value	Minimum Value	Most Likely Value	Maximum Value
Diameter of fuselage section	feet	0.000	0.000	0.000	12.500	12.500	12.500
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of frame segments	number	0.000	0.000	0.000	8.000	10.000	12.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Min. thickness of chem-milled ISC	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000
Percentage of attachments made with spot welds versus (manual) rivets	percent	0.000	0.000	0.000	0.330	0.500	0.670
Number of attach points (rivets or spot welds) at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of attach points to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of post-formed ISC	inches	0.000	0.000	0.000	0.100	0.125	0.150
Stringer height	inches	0.000	0.000	0.000	0.750	1.000	1.250
Stringer thickness	inches	0.000	0.000	0.000	0.100	0.200	0.300
Length of fuselage section	feet	0.000	0.000	0.000	58.000	63.000	68.000
Portion of circumference where frames attach directly to skin in addition to stringers	percent	0.000	0.000	0.000	0.400	0.500	0.600
percentage of rivets set manually	percent	0.000	0.000	0.000	0.330	0.500	0.670
Cost of locating and performing spot weld ralative to cost of locating, drilling, and setting an automatic rivet	factor	0.000	0.000	0.000	0.100	0.500	0.900
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of circumfrential joints	number	0.000	0.000	0.000	2.000	2.000	2.000
width of circumfrential joints	feet	0.000	0.000	0.000	0.400	0.500	0.600
Rows of rivets per circumfrential joint	number	0.000	0.000	0.000	4.000	4.000	6.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Number of lap joints (and frame segments)	number	0.000	0.000	0.000	8.000	10.000	12.000
width of lap joints	feet	0.000	0.000	0.000	0.300	0.333	0.366
rows of rivets at lap joints	number	0.000	0.000	0.000	3.000	3.000	3.000
Min. thickness of chem-milled skin sheets, inches	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of rivets at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of rivets to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of blank skin sheets	inches	0.000	0.000	0.000	0.050	0.072	0.094
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000

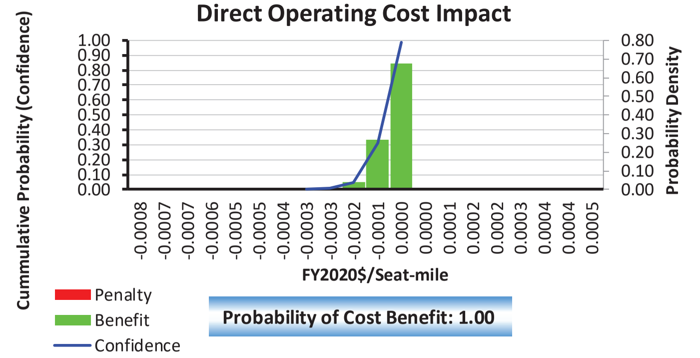
A.9 ISC SECTION CIRCUMFERENTIAL JOINTS RIVETED RATHER THAN WELDED TOGETHER

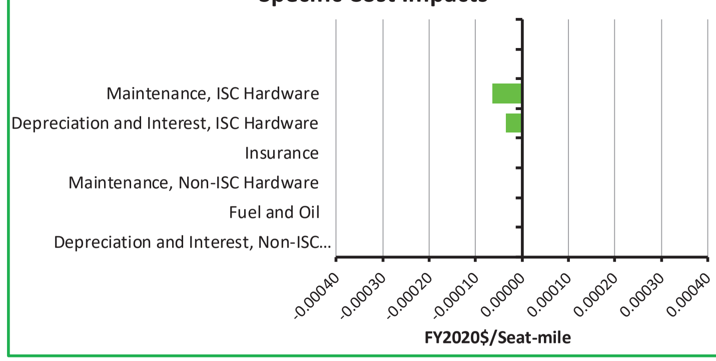
Results

737-800 with ISC center fuselage

Date: 2/9/23 9:42 PM
Baseline Aircraft: NASA 737-800-like, 160 pax, 2022 adj

Operator's Cost (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact (- is good)
Direct Operating Cost per Seat-mile (FY2020$, 50%)	0.0521	0.0520	-0.0001
Total Operating Cost per Seat-mile (FY2020$, 50%)	0.1499	0.1498	-0.0001
Minimum Coach Ticket Price (FY2020$, 50%)	152.5	152.4	-0.1





Comparative Values (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact
Takeoff Weight (lb, + impact is bad)	174,248	174,248	0
Empty Weight (lb, + impact is bad)	84,147	84,147	0
Useable Fuel Weight (lb, + impact is bad)	46,766	46,766	0
Seat-miles (statute) per Gallon (+ impact is good)	78.0	78.0	0.0
Seat-miles per equivalent kWh (+ impact is good)	2.10	2.10	0.00

Technologies Included

- Replace skin-stringer with ISC

Study Parameters	Assumed	Break-even (50%)
Fleet Size	6,600	N/A
Investment Interest Rate	10%	N/A
Fuel Price (FY2020$/gal)	2.03	N/A
Electricity Price (FY2020$/kWh)	0.11	N/A

PTIRS Version: 1.2

Manufacturer's Investment (50% Confidence)	Reference Aircraft	Enhanced Aircraft	Impact (- is good)
Investment Total (FY2020$M, 50%)	270,110	269,067	-1,221
Minimum Unit Price (FY2020$M, 50%)	42.5	42.3	-0.1

Production Rate Impact	
Pobability	Increase, Units/mo.
10%	35.6
50%	20.3
90%	9.4

Inputs

Cost Driver	Units	Observed Low	Observed High	Default Value	Minimum Value	Most Likely Value	Maximum Value
Diameter of fuselage section	feet	0.000	0.000	0.000	12.500	12.500	12.500
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of frame segments	number	0.000	0.000	0.000	8.000	10.000	12.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Min. thickness of chem-milled ISC	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000
Percentage of attachments made with spot welds versus (manual) rivets	percent	0.000	0.000	0.000	0.330	0.500	0.670
Number of attach points (rivets or spot welds) at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of attach points to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of post-formed ISC	inches	0.000	0.000	0.000	0.100	0.125	0.150
Stringer height	inches	0.000	0.000	0.000	0.750	1.000	1.250
Stringer thickness	inches	0.000	0.000	0.000	0.100	0.200	0.300
Length of fuselage section	feet	0.000	0.000	0.000	58.000	63.000	68.000
Portion of circumference where frames attach directly to skin in addition to stringers	percent	0.000	0.000	0.000	0.400	0.500	0.600
percentage of rivets set manually	percent	0.000	0.000	0.000	0.330	0.500	0.670
Cost of locating and performing spot weld ralative to cost of locating, drilling, and setting an automatic rivet	factor	0.000	0.000	0.000	0.100	0.500	0.900
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of circumfrential joints	number	0.000	0.000	0.000	2.000	2.000	2.000
width of circumfrential joints	feet	0.000	0.000	0.000	0.400	0.500	0.600
Rows of rivets per circumfrential joint	number	0.000	0.000	0.000	4.000	4.000	6.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Number of lap joints (and frame segments)	number	0.000	0.000	0.000	8.000	10.000	12.000
width of lap joints	feet	0.000	0.000	0.000	0.300	0.333	0.366
rows of rivets at lap joints	number	0.000	0.000	0.000	3.000	3.000	3.000
Min. thickness of chem-milled skin sheets, inches	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of rivets at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of rivets to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of blank skin sheets	inches	0.000	0.000	0.000	0.050	0.072	0.094
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000

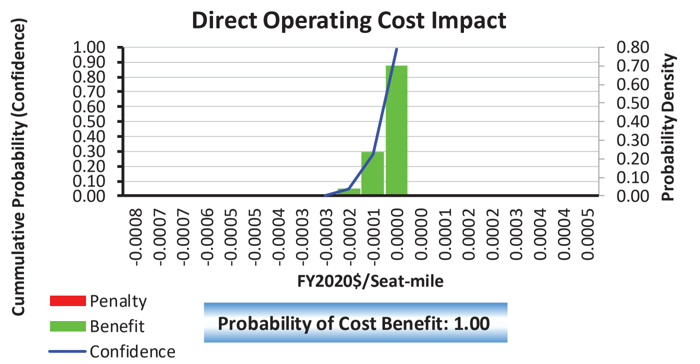
A.10 ISC SECTION LENGTH 15 FT

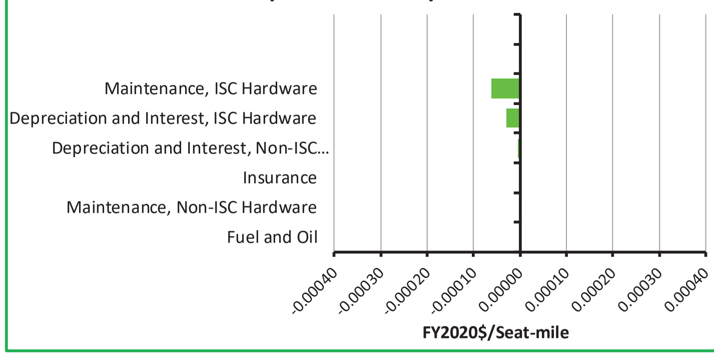
Results

737-800 with ISC center fuselage

Date: 2/10/23 10:18 AM
Baseline Aircraft: NASA 737-800-like, 160 pax, 2022 adj

Operator's Cost (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact (- is good)
Direct Operating Cost per Seat-mile (FY2020$, 50%)	0.0519	0.0518	-0.0001
Total Operating Cost per Seat-mile (FY2020$, 50%)	0.1497	0.1496	-0.0001
Minimum Coach Ticket Price (FY2020$, 50%)	152.3	152.2	-0.1





Comparative Values (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact
Takeoff Weight (lb, + impact is bad)	174,248	174,248	0
Empty Weight (lb, + impact is bad)	84,147	84,147	0
Useable Fuel Weight (lb, + impact is bad)	46,766	46,766	0
Seat-miles (statute) per Gallon (+ impact is good)	77.7	77.7	0.0
Seat-miles per equivalent kWh (+ impact is good)	2.10	2.10	0.00

Technologies Included

- Replace skin-stringer with ISC

Study Parameters	Assumed	Break-even (50%)
Fleet Size	6,600	N/A
Investment Interest Rate	10%	N/A
Fuel Price (FY2020$/gal)	2.03	N/A
Electricity Price (FY2020$/kWh)	0.11	N/A

PTIRS
Version: 1.2

Manufacturer's Investment (50% Confidence)	Reference Aircraft	Enhanced Aircraft	Impact (- is good)
Investment Total (FY2020$M, 50%)	267,778	266,606	-1,174
Minimum Unit Price (FY2020$M, 50%)	42.1	42.0	-0.1

Production Rate Impact	
Pobability	Increase, Units/mo.
10%	37.8
50%	22.1
90%	10.8

Inputs

Cost Driver	Units	Observed Low	Observed High	Default Value	Minimum Value	Most Likely Value	Maximum Value
Diameter of fuselage section	feet	0.000	0.000	0.000	12.500	12.500	12.500
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of frame segments	number	0.000	0.000	0.000	8.000	10.000	12.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Min. thickness of chem-milled ISC	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000
Percentage of attachments made with spot welds versus (manual) rivets	percent	0.000	0.000	0.000	0.330	0.500	0.670
Number of attach points (rivets or spot welds) at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of attach points to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of post-formed ISC	inches	0.000	0.000	0.000	0.100	0.125	0.150
Stringer height	inches	0.000	0.000	0.000	0.750	1.000	1.250
Stringer thickness	inches	0.000	0.000	0.000	0.100	0.200	0.300
Length of fuselage section	feet	0.000	0.000	0.000	58.000	63.000	68.000
Portion of circumference where frames attach directly to skin in addition to stringers	percent	0.000	0.000	0.000	0.400	0.500	0.600
percentage of rivets set manually	percent	0.000	0.000	0.000	0.330	0.500	0.670
Cost of locating and performing spot weld ralative to cost of locating, drilling, and setting an automatic rivet	factor	0.000	0.000	0.000	0.100	0.500	0.900
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of circumfrential joints	number	0.000	0.000	0.000	2.000	2.000	2.000
width of circumfrential joints	feet	0.000	0.000	0.000	0.400	0.500	0.600
Rows of rivets per circumfrential joint	number	0.000	0.000	0.000	4.000	4.000	6.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Number of lap joints (and frame segments)	number	0.000	0.000	0.000	8.000	10.000	12.000
width of lap joints	feet	0.000	0.000	0.000	0.300	0.333	0.366
rows of rivets at lap joints	number	0.000	0.000	0.000	3.000	3.000	3.000
Min. thickness of chem-milled skin sheets, inches	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of rivets at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of rivets to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of blank skin sheets	inches	0.000	0.000	0.000	0.050	0.072	0.094
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000

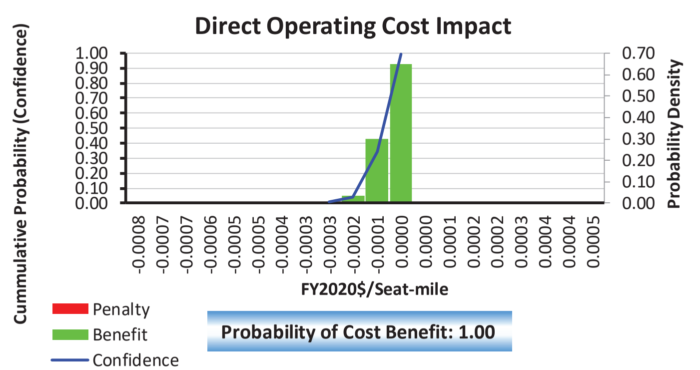
A.11 ISC SECTION LENGTH 20 FT

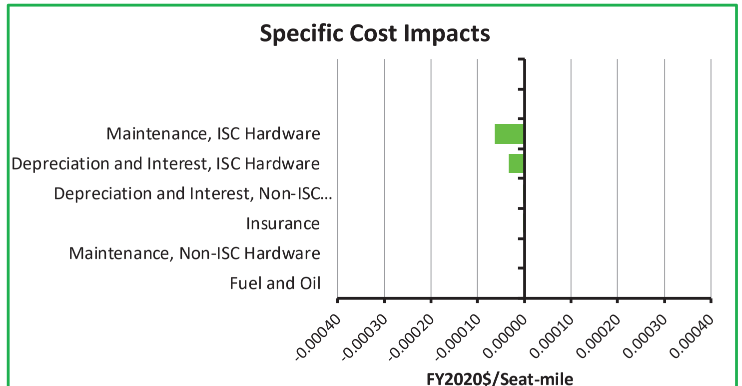
Results

737-800 with ISC center fuselage

Date: 2/10/23 10:28 AM
Baseline Aircraft: NASA 737-800-like, 160 pax, 2022 adj

Operator's Cost (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact (- is good)
Direct Operating Cost per Seat-mile (FY2020$, 50%)	0.0520	0.0519	-0.0001
Total Operating Cost per Seat-mile (FY2020$, 50%)	0.1498	0.1497	-0.0001
Minimum Coach Ticket Price (FY2020$, 50%)	152.4	152.3	-0.1





Comparative Values (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact
Takeoff Weight (lb, + impact is bad)	174,248	174,248	0
Empty Weight (lb, + impact is bad)	84,147	84,147	0
Useable Fuel Weight (lb, + impact is bad)	46,766	46,766	0
Seat-miles (statute) per Gallon (+ impact is good)	77.8	77.8	0.0
Seat-miles per equivalent kWh (+ impact is good)	2.10	2.10	0.00

Technologies Included

- Replace skin-stringer with ISC

Study Parameters	Assumed	Break-even (50%)
Fleet Size	6,600	N/A
Investment Interest Rate	10%	N/A
Fuel Price (FY2020$/gal)	2.03	N/A
Electricity Price (FY2020$/kWh)	0.11	N/A

PTIRS Version: 1.2

Manufacturer's Investment (50% Confidence)	Reference Aircraft	Enhanced Aircraft	Impact (- is good)
Investment Total (FY2020$M, 50%)	268,743	267,601	-1,237
Minimum Unit Price (FY2020$M, 50%)	42.1	42.0	-0.1

Production Rate Impact	
Pobability	Increase, Units/mo.
10%	51.1
50%	31.5
90%	18.3

Inputs

Cost Driver	Units	Observed Low	Observed High	Default Value	Minimum Value	Most Likely Value	Maximum Value
Diameter of fuselage section	feet	0.000	0.000	0.000	12.500	12.500	12.500
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of frame segments	number	0.000	0.000	0.000	8.000	10.000	12.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Min. thickness of chem-milled ISC	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000
Percentage of attachments made with spot welds versus (manual) rivets	percent	0.000	0.000	0.000	0.330	0.500	0.670
Number of attach points (rivets or spot welds) at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of attach points to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of post-formed ISC	inches	0.000	0.000	0.000	0.100	0.125	0.150
Stringer height	inches	0.000	0.000	0.000	0.750	1.000	1.250
Stringer thickness	inches	0.000	0.000	0.000	0.100	0.200	0.300
Length of fuselage section	feet	0.000	0.000	0.000	58.000	63.000	68.000
Portion of circumference where frames attach directly to skin in addition to stringers	percent	0.000	0.000	0.000	0.400	0.500	0.600
percentage of rivets set manually	percent	0.000	0.000	0.000	0.330	0.500	0.670
Cost of locating and performing spot weld ralative to cost of locating, drilling, and setting an automatic rivet	factor	0.000	0.000	0.000	0.100	0.500	0.900
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of circumfrential joints	number	0.000	0.000	0.000	2.000	2.000	2.000
width of circumfrential joints	feet	0.000	0.000	0.000	0.400	0.500	0.600
Rows of rivets per circumfrential joint	number	0.000	0.000	0.000	4.000	4.000	6.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Number of lap joints (and frame segments)	number	0.000	0.000	0.000	8.000	10.000	12.000
width of lap joints	feet	0.000	0.000	0.000	0.300	0.333	0.366
rows of rivets at lap joints	number	0.000	0.000	0.000	3.000	3.000	3.000
Min. thickness of chem-milled skin sheets, inches	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of rivets at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of rivets to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of blank skin sheets	inches	0.000	0.000	0.000	0.050	0.072	0.094
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000

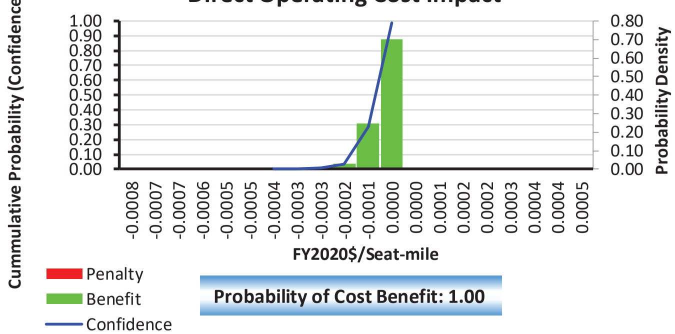
A.12 SPOT WELD V. RIVET COST FACTOR = 0.2

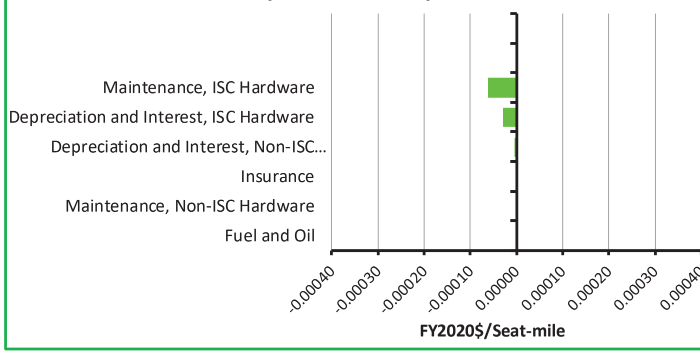
Results

737-800 with ISC center fuselage

Date: 2/10/23 10:40 AM
Baseline Aircraft: NASA 737-800-like, 160 pax, 2022 adj

Operator's Cost (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact (- is good)
Direct Operating Cost per Seat-mile (FY2020$, 50%)	0.0523	0.0522	-0.0001
Total Operating Cost per Seat-mile (FY2020$, 50%)	0.1501	0.1500	-0.0001
Minimum Coach Ticket Price (FY2020$, 50%)	152.7	152.6	-0.1





Comparative Values (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact
Takeoff Weight (lb, + impact is bad)	174,248	174,248	0
Empty Weight (lb, + impact is bad)	84,147	84,147	0
Useable Fuel Weight (lb, + impact is bad)	46,766	46,766	0
Seat-miles (statute) per Gallon (+ impact is good)	77.7	77.7	0.0
Seat-miles per equivalent kWh (+ impact is good)	2.10	2.10	0.00

Technologies Included

- Replace skin-stringer with ISC

Study Parameters	Assumed	Break-even (50%)
Fleet Size	6,600	N/A
Investment Interest Rate	10%	N/A
Fuel Price (FY2020$/gal)	2.03	N/A
Electricity Price (FY2020$/kWh)	0.11	N/A

PTIRS Version: 1.2

Manufacturer's Investment (50% Confidence)	Reference Aircraft	Enhanced Aircraft	Impact (- is good)
Investment Total (FY2020$M, 50%)	270,427	269,255	-1,171
Minimum Unit Price (FY2020$M, 50%)	42.6	42.5	-0.1

Production Rate Impact	
Pobability	Increase, Units/mo.
10%	51.2
50%	40.4
90%	31.0

Inputs

Cost Driver	Units	Observed Low	Observed High	Default Value	Minimum Value	Most Likely Value	Maximum Value
Diameter of fuselage section	feet	0.000	0.000	0.000	12.500	12.500	12.500
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of frame segments	number	0.000	0.000	0.000	8.000	10.000	12.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Min. thickness of chem-milled ISC	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000
Percentage of attachments made with spot welds versus (manual) rivets	percent	0.000	0.000	0.000	0.330	0.500	0.670
Number of attach points (rivets or spot welds) at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of attach points to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of post-formed ISC	inches	0.000	0.000	0.000	0.100	0.125	0.150
Stringer height	inches	0.000	0.000	0.000	0.750	1.000	1.250
Stringer thickness	inches	0.000	0.000	0.000	0.100	0.200	0.300
Length of fuselage section	feet	0.000	0.000	0.000	58.000	63.000	68.000
Portion of circumference where frames attach directly to skin in addition to stringers	percent	0.000	0.000	0.000	0.400	0.500	0.600
percentage of rivets set manually	percent	0.000	0.000	0.000	0.330	0.500	0.670
Cost of locating and performing spot weld ralative to cost of locating, drilling, and setting an automatic rivet	factor	0.000	0.000	0.000	0.040	0.200	0.360
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of circumfrential joints	number	0.000	0.000	0.000	2.000	2.000	2.000
width of circumfrential joints	feet	0.000	0.000	0.000	0.400	0.500	0.600
Rows of rivets per circumfrential joint	number	0.000	0.000	0.000	4.000	4.000	6.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Number of lap joints (and frame segments)	number	0.000	0.000	0.000	8.000	10.000	12.000
width of lap joints	feet	0.000	0.000	0.000	0.300	0.333	0.366
rows of rivets at lap joints	number	0.000	0.000	0.000	3.000	3.000	3.000
Min. thickness of chem-milled skin sheets, inches	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of rivets at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of rivets to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of blank skin sheets	inches	0.000	0.000	0.000	0.050	0.072	0.094
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000

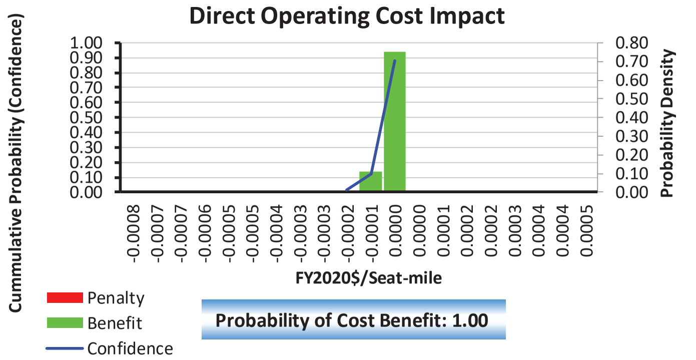
A.13 SPOT WELD V. RIVET COST FACTOR = 0.8

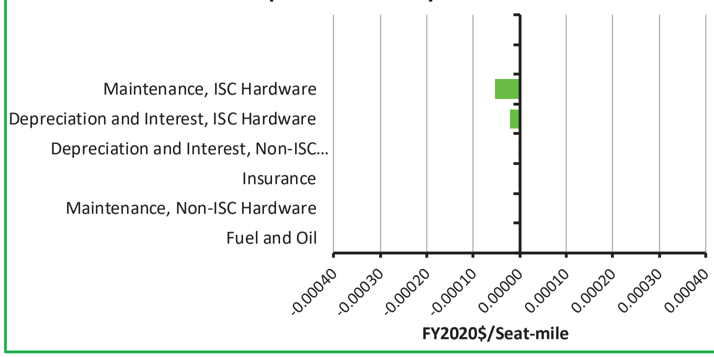
Results

737-800 with ISC center fuselage

Date: 2/10/23 11:10 AM
Baseline Aircraft: NASA 737-800-like, 160 pax, 2022 adj

Operator's Cost (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact (- is good)
Direct Operating Cost per Seat-mile (FY2020$, 50%)	0.0522	0.0522	-0.0001
Total Operating Cost per Seat-mile (FY2020$, 50%)	0.1500	0.1499	-0.0001
Minimum Coach Ticket Price (FY2020$, 50%)	152.7	152.6	-0.1





Comparative Values (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact
Takeoff Weight (lb, + impact is bad)	174,248	174,248	0
Empty Weight (lb, + impact is bad)	84,147	84,147	0
Useable Fuel Weight (lb, + impact is bad)	46,766	46,766	0
Seat-miles (statute) per Gallon (+ impact is good)	78.2	78.2	0.0
Seat-miles per equivalent kWh (+ impact is good)	2.11	2.11	0.00

Technologies Included

- Replace skin-stringer with ISC

Study Parameters	Assumed	Break-even (50%)
Fleet Size	6,600	N/A
Investment Interest Rate	10%	N/A
Fuel Price (FY2020$/gal)	2.03	N/A
Electricity Price (FY2020$/kWh)	0.11	N/A

PTIRS
Version: 1.2

Manufacturer's Investment (50% Confidence)	Reference Aircraft	Enhanced Aircraft	Impact (- is good)
Investment Total (FY2020$M, 50%)	269,798	268,937	-945
Minimum Unit Price (FY2020$M, 50%)	42.4	42.3	-0.1

Production Rate Impact	
Pobability	Increase, Units/mo.
10%	12.3
50%	6.5
90%	2.3

Inputs

Cost Driver	Units	Observed Low	Observed High	Default Value	Minimum Value	Most Likely Value	Maximum Value
Diameter of fuselage section	feet	0.000	0.000	0.000	12.500	12.500	12.500
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of frame segments	number	0.000	0.000	0.000	8.000	10.000	12.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Min. thickness of chem-milled ISC	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000
Percentage of attachments made with spot welds versus (manual) rivets	percent	0.000	0.000	0.000	0.330	0.500	0.670
Number of attach points (rivets or spot welds) at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of attach points to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of post-formed ISC	inches	0.000	0.000	0.000	0.100	0.125	0.150
Stringer height	inches	0.000	0.000	0.000	0.750	1.000	1.250
Stringer thickness	inches	0.000	0.000	0.000	0.100	0.200	0.300
Length of fuselage section	feet	0.000	0.000	0.000	58.000	63.000	68.000
Portion of circumference where frames attach directly to skin in addition to stringers	percent	0.000	0.000	0.000	0.400	0.500	0.600
percentage of rivets set manually	percent	0.000	0.000	0.000	0.330	0.500	0.670
Cost of locating and performing spot weld ralative to cost of locating, drilling, and setting an automatic rivet	factor	0.000	0.000	0.000	0.700	0.800	0.900
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of circumfrential joints	number	0.000	0.000	0.000	2.000	2.000	2.000
width of circumfrential joints	feet	0.000	0.000	0.000	0.400	0.500	0.600
Rows of rivets per circumfrential joint	number	0.000	0.000	0.000	4.000	4.000	6.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Number of lap joints (and frame segments)	number	0.000	0.000	0.000	8.000	10.000	12.000
width of lap joints	feet	0.000	0.000	0.000	0.300	0.333	0.366
rows of rivets at lap joints	number	0.000	0.000	0.000	3.000	3.000	3.000
Min. thickness of chem-milled skin sheets, inches	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of rivets at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of rivets to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of blank skin sheets	inches	0.000	0.000	0.000	0.050	0.072	0.094
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000

A.14 POST-FORMED ISC THICKNESS = 0.072

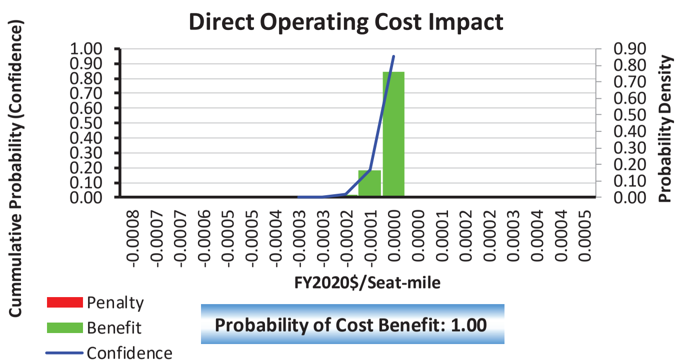
Results

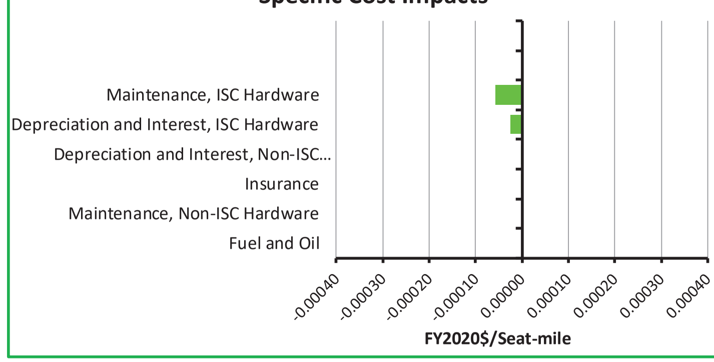
737-800 with ISC center fuselage

Date: 2/10/23 11:23 AM

Baseline Aircraft: NASA 737-800-like, 160 pax, 2022 adj

Operator's Cost (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact (- is good)
Direct Operating Cost per Seat-mile (FY2020$, 50%)	0.0518	0.0517	-0.0001
Total Operating Cost per Seat-mile (FY2020$, 50%)	0.1496	0.1495	-0.0001
Minimum Coach Ticket Price (FY2020$, 50%)	152.2	152.1	-0.1





Comparative Values (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact
Takeoff Weight (lb, + impact is bad)	174,248	174,248	0
Empty Weight (lb, + impact is bad)	84,147	84,147	0
Useable Fuel Weight (lb, + impact is bad)	46,766	46,766	0
Seat-miles (statute) per Gallon (+ impact is good)	78.9	78.9	0.0
Seat-miles per equivalent kWh (+ impact is good)	2.13	2.13	0.00

Technologies Included

- Replace skin-stringer with ISC

Study Parameters	Assumed	Break-even (50%)
Fleet Size	6,600	N/A
Investment Interest Rate	10%	N/A
Fuel Price (FY2020$/gal)	2.03	N/A
Electricity Price (FY2020$/kWh)	0.11	N/A

PTIRS Version: 1.2

Manufacturer's Investment (50% Confidence)	Reference Aircraft	Enhanced Aircraft	Impact (- is good)
Investment Total (FY2020$M, 50%)	268,319	267,254	-1,059
Minimum Unit Price (FY2020$M, 50%)	42.4	42.3	-0.1

Production Rate Impact	
Pobability	Increase, Units/mo.
10%	33.3
50%	19.0
90%	8.6

Inputs

Cost Driver	Units	Observed Low	Observed High	Default Value	Minimum Value	Most Likely Value	Maximum Value
Diameter of fuselage section	feet	0.000	0.000	0.000	12.500	12.500	12.500
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of frame segments	number	0.000	0.000	0.000	8.000	10.000	12.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Min. thickness of chem-milled ISC	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000
Percentage of attachments made with spot welds versus (manual) rivets	percent	0.000	0.000	0.000	0.330	0.500	0.670
Number of attach points (rivets or spot welds) at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of attach points to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of post-formed ISC	inches	0.000	0.000	0.000	0.058	0.072	0.086
Stringer height	inches	0.000	0.000	0.000	0.750	1.000	1.250
Stringer thickness	inches	0.000	0.000	0.000	0.100	0.200	0.300
Length of fuselage section	feet	0.000	0.000	0.000	58.000	63.000	68.000
Portion of circumference where frames attach directly to skin in addition to stringers	percent	0.000	0.000	0.000	0.400	0.500	0.600
percentage of rivets set manually	percent	0.000	0.000	0.000	0.330	0.500	0.670
Cost of locating and performing spot weld ralative to cost of locating, drilling, and setting an automatic rivet	factor	0.000	0.000	0.000	0.100	0.500	0.900
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of circumfrential joints	number	0.000	0.000	0.000	2.000	2.000	2.000
width of circumfrential joints	feet	0.000	0.000	0.000	0.400	0.500	0.600
Rows of rivets per circumfrential joint	number	0.000	0.000	0.000	4.000	4.000	6.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Number of lap joints (and frame segments)	number	0.000	0.000	0.000	8.000	10.000	12.000
width of lap joints	feet	0.000	0.000	0.000	0.300	0.333	0.366
rows of rivets at lap joints	number	0.000	0.000	0.000	3.000	3.000	3.000
Min. thickness of chem-milled skin sheets, inches	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of rivets at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of rivets to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of blank skin sheets	inches	0.000	0.000	0.000	0.050	0.072	0.094
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000

A.15 POST-FORMED ISC THICKNESS = 0.036

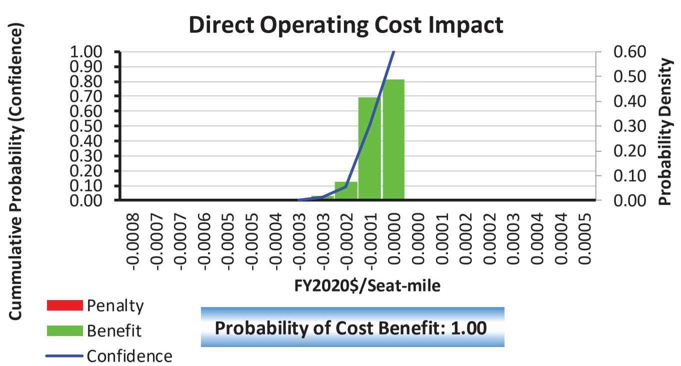
Results

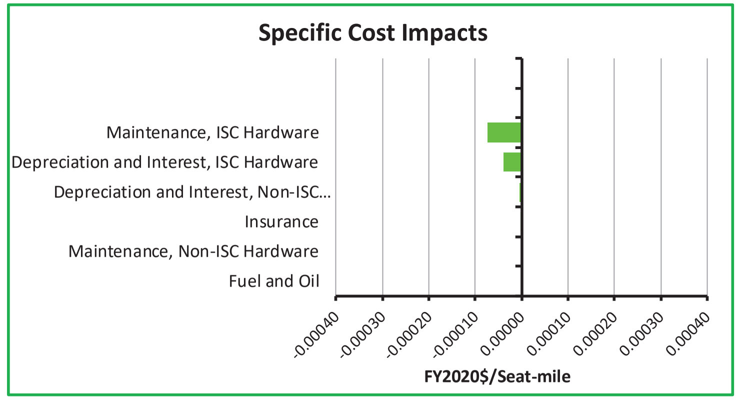
737-800 with ISC center fuselage

Date: 2/10/23 12:04 PM

Baseline Aircraft: NASA 737-800-like, 160 pax, 2022 adj

Operator's Cost (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact (- is good)
Direct Operating Cost per Seat-mile (FY2020$, 50%)	0.0523	0.0522	-0.0001
Total Operating Cost per Seat-mile (FY2020$, 50%)	0.1501	0.1500	-0.0001
Minimum Coach Ticket Price (FY2020$, 50%)	152.7	152.6	-0.1





Comparative Values (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact
Takeoff Weight (lb, + impact is bad)	174,248	174,248	0
Empty Weight (lb, + impact is bad)	84,147	84,147	0
Useable Fuel Weight (lb, + impact is bad)	46,766	46,766	0
Seat-miles (statute) per Gallon (+ impact is good)	77.8	77.8	0.0
Seat-miles per equivalent kWh (+ impact is good)	2.10	2.10	0.00

Technologies Included

- Replace skin-stringer with ISC

Study Parameters	Assumed	Break-even (50%)
Fleet Size	6,600	N/A
Investment Interest Rate	10%	N/A
Fuel Price (FY2020$/gal)	2.03	N/A
Electricity Price (FY2020$/kWh)	0.11	N/A

PTIRS
Version: 1.2

Manufacturer's Investment (50% Confidence)	Reference Aircraft	Enhanced Aircraft	Impact (- is good)
Investment Total (FY2020$M, 50%)	270,462	269,045	-1,440
Minimum Unit Price (FY2020$M, 50%)	42.6	42.4	-0.2

Production Rate Impact	
Pobability	Increase, Units/mo.
10%	45.3
50%	26.0
90%	12.8

Inputs

Cost Driver	Units	Observed Low	Observed High	Default Value	Minimum Value	Most Likely Value	Maximum Value
Diameter of fuselage section	feet	0.000	0.000	0.000	12.500	12.500	12.500
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of frame segments	number	0.000	0.000	0.000	8.000	10.000	12.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Min. thickness of chem-milled ISC	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000
Percentage of attachments made with spot welds versus (manual) rivets	percent	0.000	0.000	0.000	0.330	0.500	0.670
Number of attach points (rivets or spot welds) at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of attach points to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of post-formed ISC	[illegible]	0.000	0.000	0.000	0.100	0.125	0.150
Stringer height	[illegible]	0.000	0.000	0.000	0.750	1.000	1.250
Stringer thickness	[illegible]	0.000	0.000	0.000	0.100	0.200	0.300
Length of fuselage section	feet	0.000	0.000	0.000	58.000	63.000	68.000
Portion of circumference where frames attach directly to skin in addition to stringers	percent	0.000	0.000	0.000	0.400	0.500	0.600
percentage of rivets set manually	percent	0.000	0.000	0.000	0.330	0.500	0.670
Cost of locating and performing spot weld ralative to cost of locating, drilling, and setting an automatic rivet	factor	0.000	0.000	0.000	0.100	0.500	0.900
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of circumfrential joints	number	0.000	0.000	0.000	2.000	2.000	2.000
width of circumfrential joints	feet	0.000	0.000	0.000	0.400	0.500	0.600
Rows of rivets per circumfrential joint	number	0.000	0.000	0.000	4.000	4.000	6.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Number of lap joints (and frame segments)	number	0.000	0.000	0.000	8.000	10.000	12.000
width of lap joints	feet	0.000	0.000	0.000	0.300	0.333	0.366
rows of rivets at lap joints	number	0.000	0.000	0.000	3.000	3.000	3.000
Min. thickness of chem-milled skin sheets, inches	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of rivets at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of rivets to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of blank skin sheets	inches	0.000	0.000	0.000	0.050	0.072	0.094
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000

Input ignored – chem. milling operations simply deleted in this case

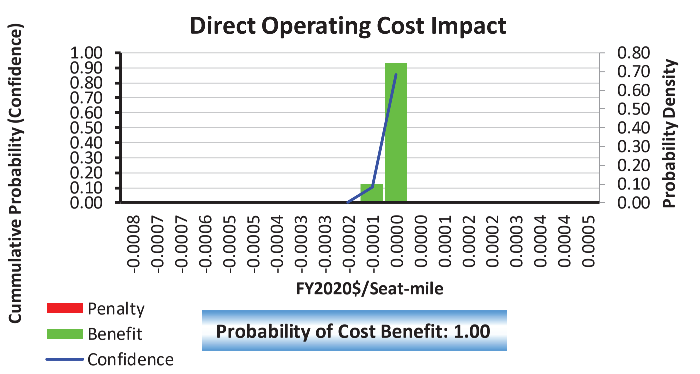
A.16 75% ROBOTIC RIVETING

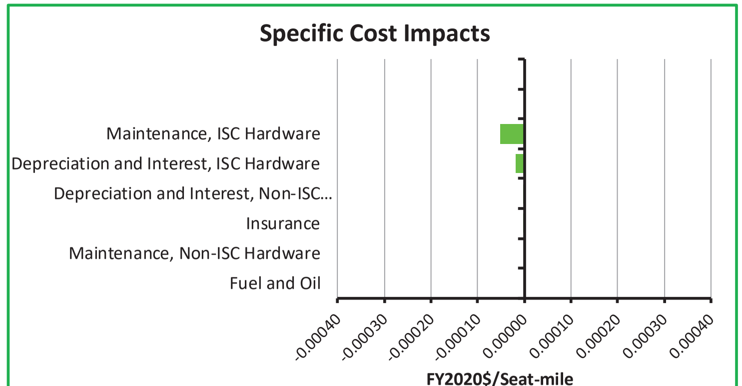
Results

737-800 with ISC center fuselage

Date: 2/10/23 10:08 PM
Baseline Aircraft: NASA 737-800-like, 160 pax, 2022 adj

Operator's Cost (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact (- is good)
Direct Operating Cost per Seat-mile (FY2020$, 50%)	0.0520	0.0519	-0.0001
Total Operating Cost per Seat-mile (FY2020$, 50%)	0.1498	0.1497	-0.0001
Minimum Coach Ticket Price (FY2020$, 50%)	152.4	152.3	-0.1





Comparative Values (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact
Takeoff Weight (lb, + impact is bad)	174,248	174,248	0
Empty Weight (lb, + impact is bad)	84,147	84,147	0
Useable Fuel Weight (lb, + impact is bad)	46,766	46,766	0
Seat-miles (statute) per Gallon (+ impact is good)	78.1	78.1	0.0
Seat-miles per equivalent kWh (+ impact is good)	2.10	2.10	0.00

Technologies Included

- Replace skin-stringer with ISC

Study Parameters	Assumed	Break-even (50%)
Fleet Size	6,600	N/A
Investment Interest Rate	10%	N/A
Fuel Price (FY2020$/gal)	2.03	N/A
Electricity Price (FY2020$/kWh)	0.11	N/A

PTIRS
Version: 1.2

Manufacturer's Investment (50% Confidence)	Reference Aircraft	Enhanced Aircraft	Impact (- is good)
Investment Total (FY2020$M, 50%)	267,977	267,026	-907
Minimum Unit Price (FY2020$M, 50%)	42.2	42.1	-0.1

Production Rate Impact	
Pobability	Increase, Units/mo.
10%	37.0
50%	22.8
90%	13.1

Inputs

Cost Driver	Units	Observed Low	Observed High	Default Value	Minimum Value	Most Likely Value	Maximum Value
Diameter of fuselage section	feet	0.000	0.000	0.000	12.500	12.500	12.500
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of frame segments	number	0.000	0.000	0.000	8.000	10.000	12.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Min. thickness of chem-milled ISC	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000
Percentage of attachments made with spot welds versus (manual) rivets	percent	0.000	0.000	0.000	0.330	0.500	0.670
Number of attach points (rivets or spot welds) at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of attach points to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of post-formed ISC	inches	0.000	0.000	0.000	0.100	0.125	0.150
Stringer height	inches	0.000	0.000	0.000	0.750	1.000	1.250
Stringer thickness	inches	0.000	0.000	0.000	0.100	0.200	0.300
Length of fuselage section	feet	0.000	0.000	0.000	58.000	63.000	68.000
Portion of circumference where frames attach directly to skin in addition to stringers	percent	0.000	0.000	0.000	0.400	0.500	0.600
percentage of rivets set manually	percent	0.000	0.000	0.000	0.200	0.250	0.300
Cost of locating and performing spot weld ralative to cost of locating, drilling, and setting an automatic rivet	factor	0.000	0.000	0.000	0.100	0.500	0.900
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of circumfrential joints	number	0.000	0.000	0.000	2.000	2.000	2.000
width of circumfrential joints	feet	0.000	0.000	0.000	0.400	0.500	0.600
Rows of rivets per circumfrential joint	number	0.000	0.000	0.000	4.000	4.000	6.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Number of lap joints (and frame segments)	number	0.000	0.000	0.000	8.000	10.000	12.000
width of lap joints	feet	0.000	0.000	0.000	0.300	0.333	0.366
rows of rivets at lap joints	number	0.000	0.000	0.000	3.000	3.000	3.000
Min. thickness of chem-milled skin sheets, inches	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of rivets at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of rivets to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of blank skin sheets	inches	0.000	0.000	0.000	0.050	0.072	0.094
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000

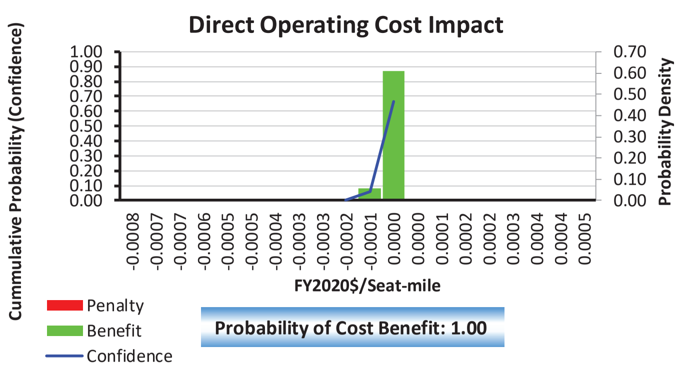
A.17 98% AUTOMATIC RIVETING

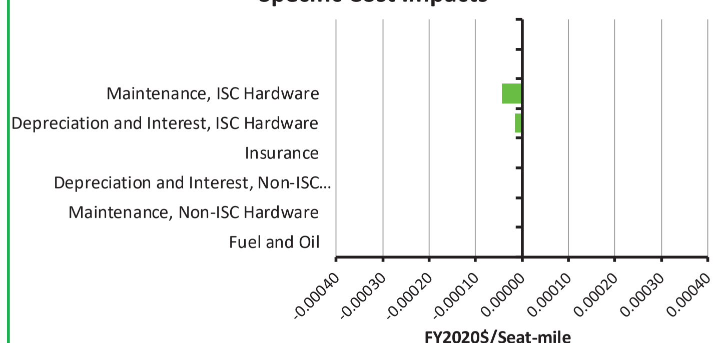
Results

737-800 with ISC center fuselage

Date: 2/10/23 3:50 PM
Baseline Aircraft: NASA 737-800-like, 160 pax, 2022 adj

Operator's Cost (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact (- is good)
Direct Operating Cost per Seat-mile (FY2020$, 50%)	0.0520	0.0519	-0.0001
Total Operating Cost per Seat-mile (FY2020$, 50%)	0.1498	0.1497	-0.0001
Minimum Coach Ticket Price (FY2020$, 50%)	152.4	152.3	-0.1





Comparative Values (50% Confidence)	Baseline Aircraft	Enhanced Aircraft	Impact
Takeoff Weight (lb, + impact is bad)	174,248	174,248	0
Empty Weight (lb, + impact is bad)	84,147	84,147	0
Useable Fuel Weight (lb, + impact is bad)	46,766	46,766	0
Seat-miles (statute) per Gallon (+ impact is good)	78.2	78.2	0.0
Seat-miles per equivalent kWh (+ impact is good)	2.11	2.11	0.00

Technologies Included

- Replace skin-stringer with ISC

Study Parameters	Assumed	Break-even (50%)
Fleet Size	6,600	N/A
Investment Interest Rate	10%	N/A
Fuel Price (FY2020$/gal)	2.03	N/A
Electricity Price (FY2020$/kWh)	0.11	N/A

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Manufacturer's Investment (50% Confidence)	Reference Aircraft	Enhanced Aircraft	Impact (- is good)
Investment Total (FY2020$M, 50%)	269,717	269,073	-761
Minimum Unit Price (FY2020$M, 50%)	42.1	42.1	-0.1

Production Rate Impact	
Pobability	Increase, Units/mo.
10%	39.5
50%	25.4
90%	15.4

Inputs

Cost Driver	Units	Observed Low	Observed High	Default Value	Minimum Value	Most Likely Value	Maximum Value
Diameter of fuselage section	feet	0.000	0.000	0.000	12.500	12.500	12.500
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of frame segments	number	0.000	0.000	0.000	8.000	10.000	12.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Min. thickness of chem-milled ISC	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000
Percentage of attachments made with spot welds versus (manual) rivets	percent	0.000	0.000	0.000	0.330	0.500	0.670
Number of attach points (rivets or spot welds) at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of attach points to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of post-formed ISC	inches	0.000	0.000	0.000	0.100	0.125	0.150
Stringer height	inches	0.000	0.000	0.000	0.750	1.000	1.250
Stringer thickness	inches	0.000	0.000	0.000	0.100	0.200	0.300
Length of fuselage section	feet	0.000	0.000	0.000	58.000	63.000	68.000
Portion of circumference where frames attach directly to skin in addition to stringers	percent	0.000	0.000	0.000	0.400	0.500	0.600
percentage of rivets set manually	percent	0.000	0.000	0.000	0.010	0.020	0.030
Cost of locating and performing spot weld ralative to cost of locating, drilling, and setting an automatic rivet	factor	0.000	0.000	0.000	0.100	0.500	0.900
Number of steps of chem-milling	number	0.000	0.000	0.000	1.000	1.000	3.000
Number of circumfrential joints	number	0.000	0.000	0.000	2.000	2.000	2.000
width of circumfrential joints	feet	0.000	0.000	0.000	0.400	0.500	0.600
Rows of rivets per circumfrential joint	number	0.000	0.000	0.000	4.000	4.000	6.000
average frame spacing	feet	0.000	0.000	0.000	1.567	1.667	1.767
Number of lap joints (and frame segments)	number	0.000	0.000	0.000	8.000	10.000	12.000
width of lap joints	feet	0.000	0.000	0.000	0.300	0.333	0.366
rows of rivets at lap joints	number	0.000	0.000	0.000	3.000	3.000	3.000
Min. thickness of chem-milled skin sheets, inches	inches	0.000	0.000	0.000	0.030	0.036	0.042
Number of rivets at each stringer-to-ring attachment	number	0.000	0.000	0.000	6.000	8.000	10.000
Number of rivets to attach two ring segments together	number	0.000	0.000	0.000	20.000	30.000	40.000
Thickness of blank skin sheets	inches	0.000	0.000	0.000	0.050	0.072	0.094
Number of regular stringers	number	0.000	0.000	0.000	42.000	56.000	50.000