HYPERX USER'S CONFERENCE

Using HyperX to Define Aerostructure for Sustainable Regional Transport Aircraft

J Donn Hethcock EOS Aircraft
Chris Boshers NIAR ATLAS

Using HyperX to Define Aerostructure for Sustainable Regional Transport Aircraft

- EOS Aircraft Inc is developing a new aircraft
    - sustainable regional transport aircraft
    - Currently operating in “stealth” mode
    - North American based
- Electric – Hybrid Clean Sheet Program
    - Start-Up environment
- All Engineering Leadership Roles Filled
    - US & Canadian job postings

EOS: What has been revealed about our program?

EOS

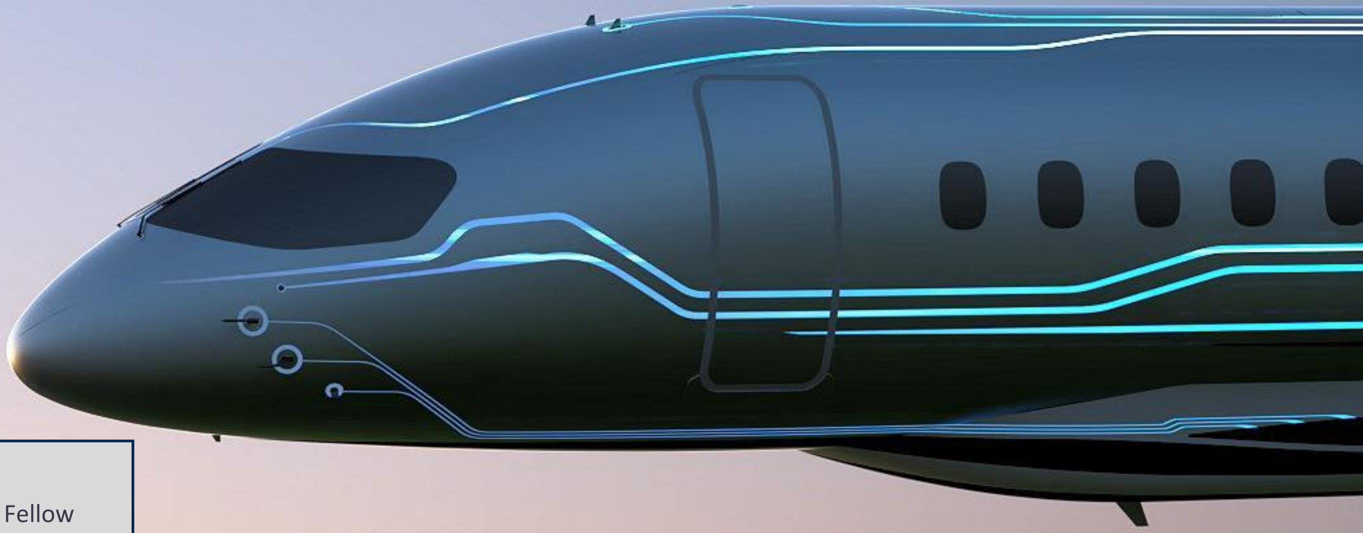
USHERING IN A NEW DAWN OF REGIONAL AVIATION

New Electric-Hybrid Clean Sheet Program

- Next leap in sustainable aviation technology
- Lowest cost of operation compared to any other regional aircraft

About EOS Aircraft Inc.

- Currently operating in stealth mode
- Based in North America
- All engineering leadership roles are filled
- Backed by renowned investors and airlines
- Program launched Q4 2023
- Sizeable engineering team assembled: 60+ and growing



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Beginnings of a Start-Up

- Vision > Design
- Business Driver > Biz Case & Timeline
- Performance > Parametric > Model > Prototype

Another
Luc Van Bavel design

- Technology > Road Map
- Customers & Investors > Understand their needs

Epic Victory Aircraft: Napkin Sketch to 1st Flight in 183 Days

Photo by Sergey Ryabtsev –

EOS

Aircraft Trade Study Metrics

Question: What are the things you most need in a Regional Transport Aircraft?

Customer Segments

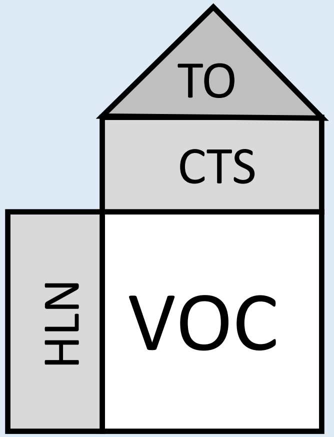
- Passengers who may use Aircraft
- Operators of the Aircraft
- Stakeholders or Investors in EOS Aircraft
- And other segments….

- **Related to sustainability**
- **Are there are some similar & overlapping needs?**
- **The needs are stated in the voice of the customer (VOC)**
- **VOC high level needs (HLN) are “fuzzy” & not measurable**

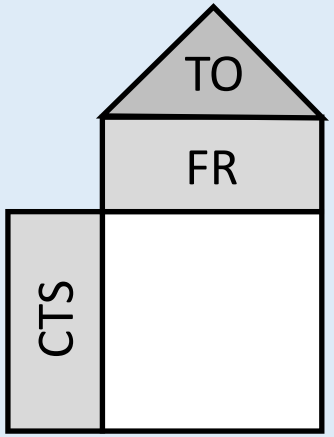
Voice of Regional Airline Customer
Utmost passenger safety
Extra Friendly to the environment
Affordable Service (Tickets)
Service between the right destinations
Comfortable and roomy
Dependable schedule
Voice of Airline Stakeholder
Capacity & Range
Operting Cost
Performance
Cabin Comfort & Amenities
Fleet Compatibility
Sustainability
Reliability & Maintenance
Regulatory Compliance
Voice of EOS Aircraft Investors
Get a Return on Investment
Avoid Circumstance Causing Failure
Increase Propabiity of Success

Quality Function Deployment (QFD)

Tradeoffs (TO)



Voice of Customer (VoC)



Functional Requirements (FR)

Solution Free

High Level Needs (HLN)

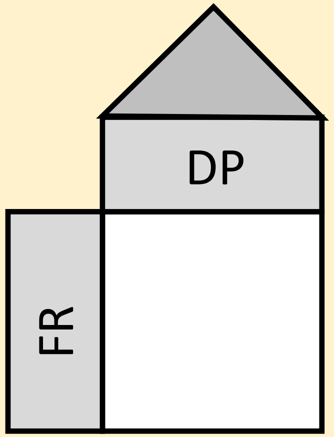
Critical to Satisfaction (CTS)

TRADE STUDIES

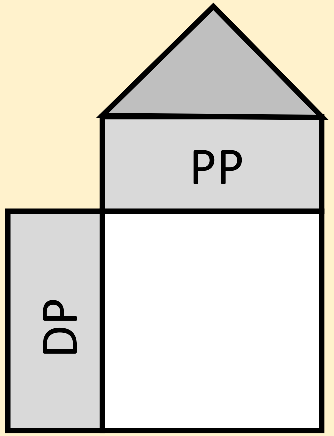
- Brainstorm solutions
- Resolve Contradictions
- Evaluate
- Morph Ideas
- Brainstorm
- Evaluate
- Down select solution

The Big Picture

Solution Control



Design Parameters (DP)



Process Parameters (PP)

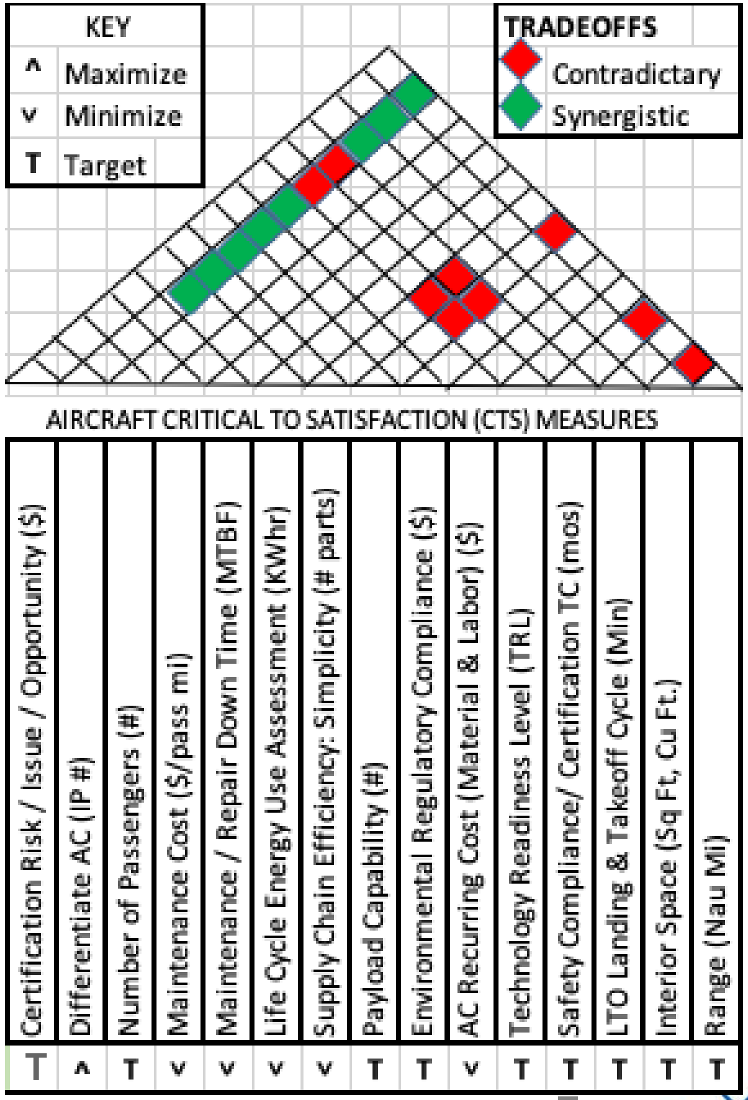
Use QFD to delight customers by providing unexpected solutions

Trade Study Metrics at Aircraft Level

CTS Metrics for **EOS Aircraft**

No	Critical to Satisfaction (CTS) Metric		UNIT
1	248	Certification Risk / Issue / Opportunity ($)	$
2	190	Number of Passengers (#)	No.
3	185	Maintenance Cost ($/pass mi)	$/Pass*Mi
4	182	Maintenance / Repair Down Time (MTBF)	MTBF
5	181	Differentiate AC (IP #)	No. IP
6	179	Life Cycle Energy Use Assessment (KWhr)	kWhr
7	177	Supply Chain Efficiency: Simplicity (# parts)	No. Parts
8	174	Payload Capability (#)	Lbs
9	165	Environmental Regulatory Compliance ($)	$
10	156	Range (Nau Mi)	Nau Mi.
11	159	AC Recurring Cost (Material & Labor) ($)	$
12	150	Technology Readiness Level (TRL)	No.
13	140	Safety Compliance/ Certification TC (mos)	Mos
14	138	LTO Landing & Takeoff Cycle (Min)	Min
15	128	Interior Space (Sq Ft, Cu Ft.)	Sq./Cu. Ft.

- Tradeoffs >> highlight contradictions between CTS's that can be resolved with innovation



- Establish units & targets from Marketing Rqmts.& Objectives
- Order of Importance derived from HLN / Survey
- Implement 2nd house to determine airframe specific measures

Trade Study Metrics at Aerostructures Level

CTS Metrics for Aerostructures

- Establish units & targets from aerostructures customers
- Next house to determines airframe specific functional requirements

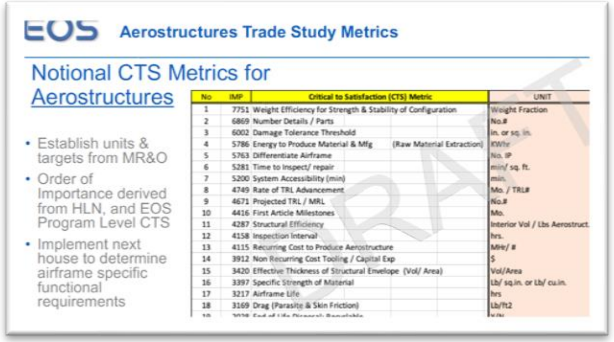
Critical to Satisfaction (CTS) Metric	UNIT
Weight Efficiency for Strength & Stability of Configuration	Weight Fraction
Number Details / Parts	No.#
Damage Tolerance Threshold	in. or sq. in.
Energy to Produce Material & Mfg (Raw Material Extraction)	KWhr
Differentiate Airframe	No. IP
Time to Inspect/ repair	min/ sq. ft.
System Accessibility (min)	min.
Rate of TRL Advancement	Mo. / TRL#
Projected TRL / MRL	No.#
First Article Milestones	Mo.
Structural Efficiency	Interior Vol / Lbs Aerostruct.
Inspection Interval	hrs.
Recurring Cost to Produce Aerostructure	MHr/ #
Non Recurring Cost Tooling / Capital Exp	$
Effective Thickness of Structural Envelope (Vol/ Area)	Vol/Area
Specific Strength of Material	Lb/ sq.in. or Lb/ cu.in.
Airframe Life	hrs
Drag (Parasite & Skin Friction)	Lb/ft2
End of Life Disposal; Recyclable	Y/N

#1 Metric: Weight Efficiency is tied to Sustainability: What is a # of weight worth?

Value of Weight Savings

Purpose:

- **Weight efficiency identified as the #1 Critical to Satisfaction (CTS) metric**
- **Develop cost/weight metric to serve as a means test for incorporation of weight reduction proposals**



No	IMP	Critical to Satisfaction (CTS) Metric	UNIT
1	7751	Weight Efficiency for Strength & Stability of Configuration	Weight Fraction
2	6869	Number Details / Parts	No.#
3	6002	Damage Tolerance Threshold	in. or sq. in.
4	5786	Energy to Produce Material & Mfg (Raw Material Extraction)	KWhr
5	5763	Differentiate Airframe	No. IP
6	5281	Time to Inspect/ repair	min/ sq. ft.
7	5200	System Accessibility (min)	min.
8	4749	Rate of TRL Advancement	Mo. / TRL#
9	4671	Projected TRL / MRL	No.#
10	4416	First Article Milestones	Mo.
11	4287	Structural Efficiency	Interior Vol / Lbs Aerostruct.
12	4158	Inspection Interval	hrs.
13	4115	Recurring Cost to Produce Aerostructure	MHr/ #
14	3912	Non Recurring Cost Tooling / Capital Exp	$
15	3420	Effective Thickness of Structural Envelope (Vol/ Area)	Vol/Area
16	3397	Specific Strength of Material	Lb/ sq.in. or Lb/ cu.in.
17	3217	Airframe Life	hrs
18	3169	Drag (Parasite & Skin Friction)	Lb/ft2

Approach:

Determine life cycle energy costs for in-service operation

- Determine the energy costs required for representative flights over the expected lifetime of the vehicle
- Include realistic assumptions on segment ranges, load ratios, margin requirements, and energy costs

Calculate lifecycle cost per pound threshold requirement

- Calculate the threshold cost per pound by dividing the total energy cost by the weight of the vehicle + average payload weight
- Calculate the nonrecurring cost per pound by dividing the total nonrecurring cost required to achieve the weight savings by the amount of weight saved
- Amortize lifecycle cost savings to determine cost per weight net present value

Amortize recurring and nonrecurring expenses required to achieve weight savings to a net present value (NPV) and compare to the threshold requirement

- NPV of lifecycle cost savings determined by performing a business case evaluation over the assumed number of production units and fleet operations until A/V retirement

Calculate Energy Cost Per Pound

Approach:

- Rigor needed to establish hurdle for onboarding new technology

Considerations:

- See list of variables & units >>

Assumptions:

- Determine aircraft configuration
- Make assumptions consistent with Marketing Requirements & Objectives (MR&O)
    - assume batteries replaced periodically
- 4% interest rate per year assumed in amortized cost per pound.

Result:

- value of a pound of weight savings **~= $1200/ #**

Will the difference in weight between the material choice justify the extra cost?

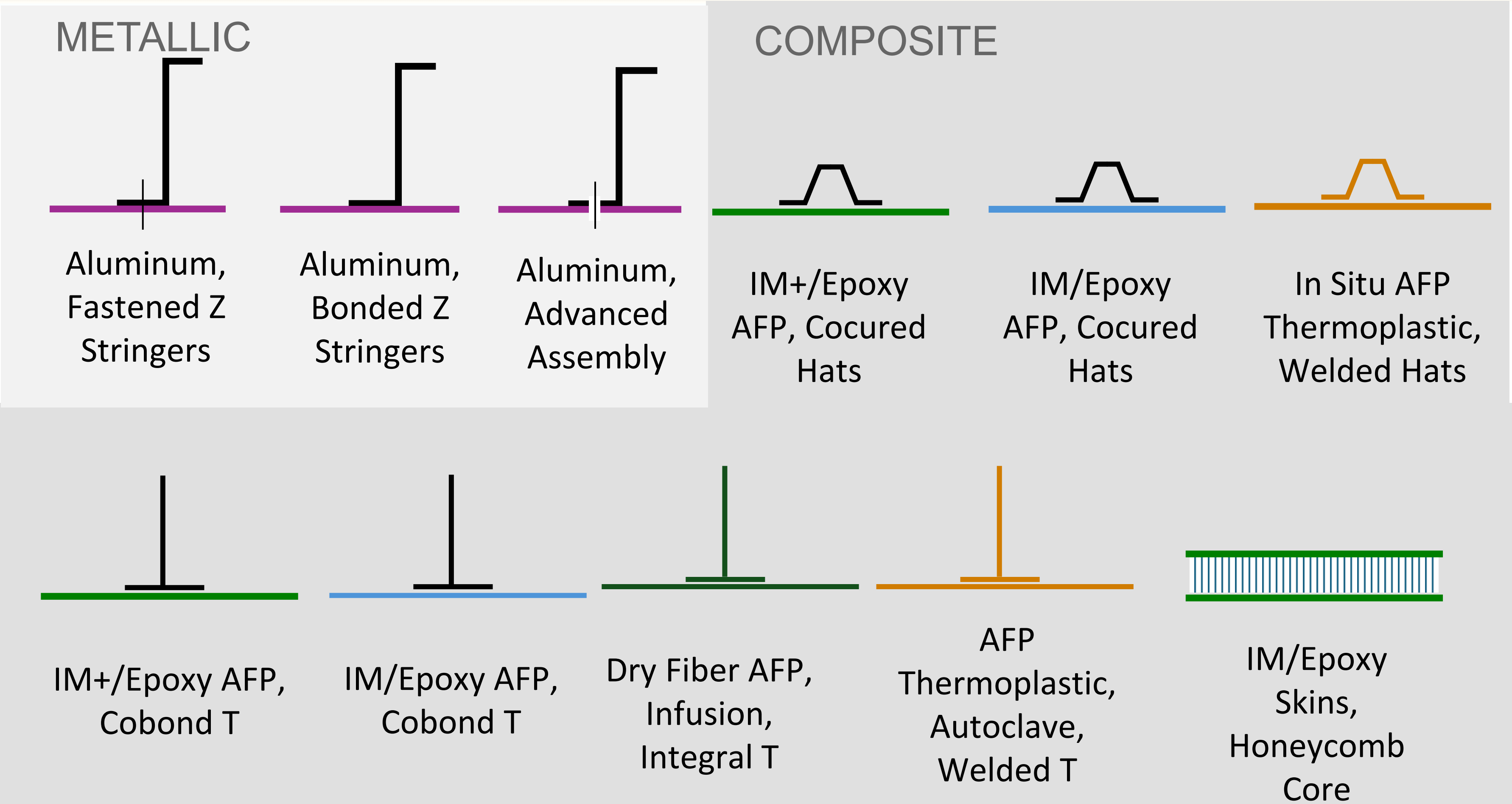
Variable	Units
Mission	nm
Average Diversion Range	%
Fuel Costs	USD/ gal
Electricity Costs	USD /kWh
Battery Cost	USD /kWh
Battery Life	Cycles
Battery Density	Wh/kg
Fuel Used	lbs
Total Fuel Costs	USD
Energy Used	kWh
Total Electric Costs	USD
Total Energy Costs	USD
Payload Fill Level	%
Effective Payload	lbs
Take Off Weight (TOW)	lbs
Vehicle Life Cycles	#
Cost Per Pound	USD/ lb
Amortized Cost / Pound	USD/ lb

Considerations for approach to initial trades

- Weight fraction of battery modules and related systems > 25%
  - Weight remains the biggest limiting factor for battery-powered aircraft.
  - Even at 600 Wh/kg, aviation batteries are **~20 times less energy-dense by weight** than jet fuel.
- Weight saving opportunity for primary aerostructure needed
- Any new approach to primary structure must buy its way on program
  - Make & apply cost ‘rules-of-thumb’
- Apply easy method for relative weight comparison needed between sets of
  - 1) Metallic & 2) Composite configurations
  - Startups typically have limited access to legacy weights databases
- **Starting point**: use initial AC configuration & external lines
  - Set up external load cases and obtain shear / moment diagrams / GFEM
  - Analysis of cross-sections using Hypersizer
- **Follow On:** Explore alternate configurations / design space with multi-discipline approach
  - Update / Morph GFEM

Hypersizer provides initial results for airframe material trade that enables electric-hybrid AC

Wing Airframe Configuration Options



Evaluated these:

- Materials
  - Aluminum
  - Carbon Epoxy
  - Thermoplastic
- Geometry
  - Stiffener shapes
- Manuf. processes
  - AFP
  - Infusion
  - Cocure &
  - Cobond
  - Welding

Utilize stiffening options provided in Hypersizer to evaluate weight of primary loaded structure

Wing Airframe Evaluation Matrix

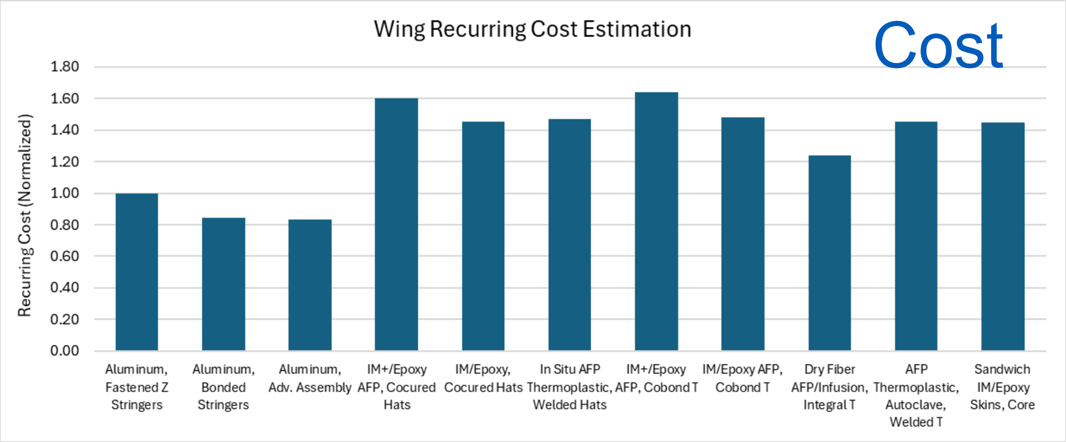
No.	Weighting Factor	Evaluation Metric		Units	Wing: Aluminum, Fastened Z Stringers	Aluminum, Bonded Stringers	Aluminum, Adv. Assembly	IM+/Epoxy AFP, Cocured Hats	IM/Epoxy, Cocured Hats	In Situ AFP Thermoplastic, Welded Hats	IM+/Epoxy AFP, Cobond T	IM/Epoxy AFP, Cobond T	Dry Fiber AFP/Infusion, Integral T	AFP Thermoplastic, Autoclave, Welded T	Sandwich IM/Epoxy Skins, Core
1	7751	Weight Efficiency		lb, Normalized	1.00	1.00	1.03	0.81	0.82	0.81	0.81	0.80	0.81	0.81	0.81
2	5763	Differentiate Airframe	-5=Worst, +5=Best		0	0	0	2	2	3	2	2	2	3	2
3	6869	Number of Details / Parts	# of Parts		713	713	713	683	683	713	683	683	683	713	512
			# of Fasteners		34,443	21,336	34,443	14,282	14,282	14,282	14,282	14,282	14,282	14,282	10,712
			Acreage	ft^2, Normalized	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
4	6002	Damage Tolerance Threshold	-5=Worst, +5=Best		0	0	0	3	3	4	3	3	3	4	5
5	5786	Energy for Materials and Fab		kWh	54932	54970	56803	61651	62913	62050	61661	61398	61546	61598	61598
6	5200	System Accessibility	-5=Worst, +5=Best		3	3	3	1	1	1	3	3	3	3	3
7a	5281	Time to Inspect	-5=Worst, +5=Best		3	0	5	0	0	0	3	3	3	3	3
7b		Time to Repair	-5=Worst, +5=Best		3	0	5	0	0	3	3	3	3	3	-2
8	4671	Projected TRL/MRL			9	9	6	6	9	4	6	9	5	4	4
9	4416	First Article Milestones	-5=Worst, +5=Best		5	5	4	2	2	-3	2	2	0	-3	-3
10	4287	Structural Efficiency	-5=Worst, +5=Best		0	0	0	0	0	0	4	4	4	4	5
11	4158	Inspection Interval	-5=Worst, +5=Best		0	-2	0	2	2	5	5	5	5	5	5
12	4115	Recurring Cost to Produce Aerostructure	Total	$, Normalized to Baseline	1.00	0.84	0.83	1.60	1.46	1.47	1.64	1.48	1.24	1.45	1.45
			Raw Material Cost		0.10	0.10	0.10	0.64	0.50	0.69	0.65	0.49	0.34	0.69	0.49
			Detail Part Fab (Labor)		0.56	0.56	0.63	0.82	0.82	0.72	0.86	0.86	0.76	0.72	0.86
			Assembly (Labor)		0.34	0.19	0.09	0.14	0.14	0.05	0.14	0.14	0.14	0.04	0.10
13	3912	Nonrecurring Cost	Total	$, Normalized to Baseline	1.00	1.02	0.96	3.27	3.27	3.59	3.27	3.27	3.41	3.46	3.34
			Tooling		0.25	0.25	0.16	0.38	0.38	0.51	0.38	0.38	0.62	0.51	0.41
			∆Certification		0.00	0.08	0.05	0.23	0.23	0.29	0.23	0.23	0.23	0.29	0.26
			∆EAC		0.00	0.00	0.00	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
			Capital		0.75	0.68	0.75	2.66	2.66	2.80	2.66	2.66	2.56	2.66	2.66
		∆Lifecycle Energy Cost Reduction/Unit		$/lb	$0	$122,211	-$108,631	$884,841	$884,705	$954,165	$850,791	$1,005,596	$1,190,506	$1,010,228	$1,021,442
14	3420	Effective Thickness of Structural Envelope		in	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
15	4749	Rate of TRL Advancement	-5=Worst, +5=Best		5	5	3	3	4	-3	3	4	1	-3	-1
16	3397	Specific Strength of Material		psi/lb	47000	46968	45452	59390	53349	59007	59380	54665	50816	59441	54552
17	3217	Airframe Life - Inspection/Repair Costs	-5=Worst, +5=Best		0	0	0	3	3	4	3	3	3	4	3
18	3169	Drag (Parasitic and Skin Friction)	-5=Worst, +5=Best		-1	0	-1	2	2	1	2	2	3	1	3
19	2028	End of Life Disposal; Recyclable		Y/N	Y	Y	Y	N	N	Y	N	N	N	Y	N
		Total Score			**97454**	**91661**	**59814**	**120009**	**136102**	**71962**	**174665**	**202407**	**150449**	**111266**	**114047**

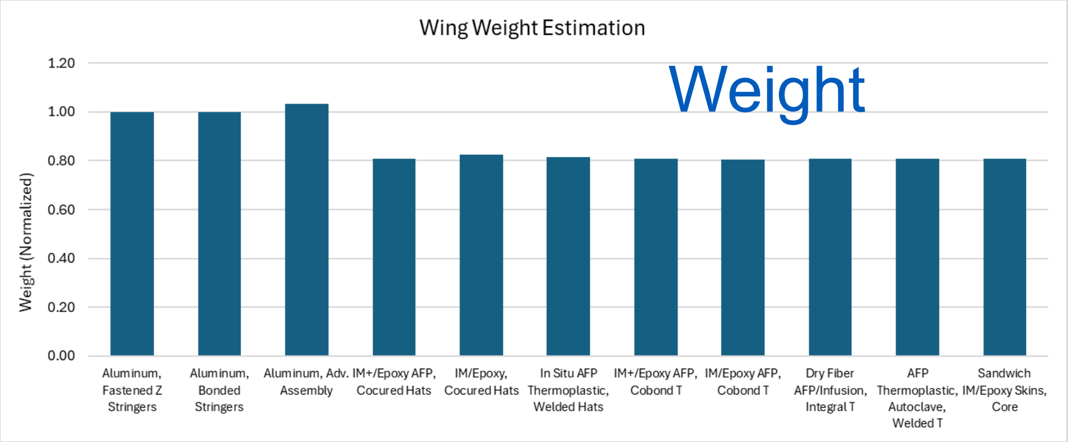
- **Evaluated 10 design concepts against 19 parameters**
- **HYPERX used to evaluate weights-based parameters**

Blue – Vendor quote
Green – Determine using HyperX
Brown – Parametrically estimated
Red – WAG

In-depth evaluation necessary to overcome significant resistance over composites

Initial Wing Airframe Results





IM Epoxy AFP

> **Cobonded "T" Stiffened concept recommended**

Cross-sectional method using Hypersizer

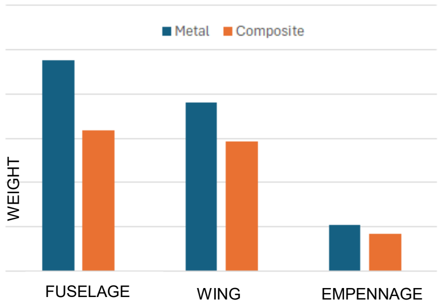
Structural Optimization Tools useful to evaluate trade study alternatives

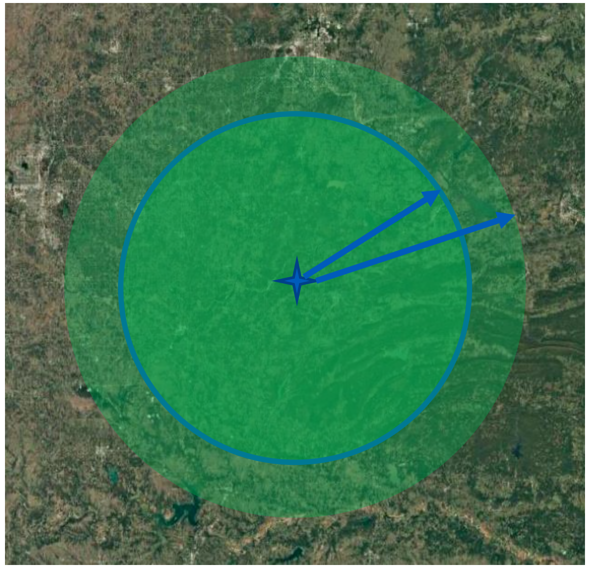
Material Trade Study – Recommendation Summary

Recommendation > Use low-cost graphite/epoxy materials and fabrication methods for primary structure (wing, fuselage, empennage)

Benefits:
- Overall Weight reduction of 27%
- All electric range increase of 20%
- Energy & Carbon tax cost savings of 23%
- Improved corrosion and fatigue resistance

Cons:
- Recurring cost increase of 6.5% / AC
- Additional capital equipment requirements may limit supplier base
- Nonrecurring cost increase
- ∆EAC engineering cost increase





Extended Range

Without compromising Safety or Reliability, structure material selected should prioritize weight efficiency over other considerations (cost and ease of manufacturing, etc.) for weight reductions of 10% or greater compared to other technologies.

Material Trade Study – Recommendation Details

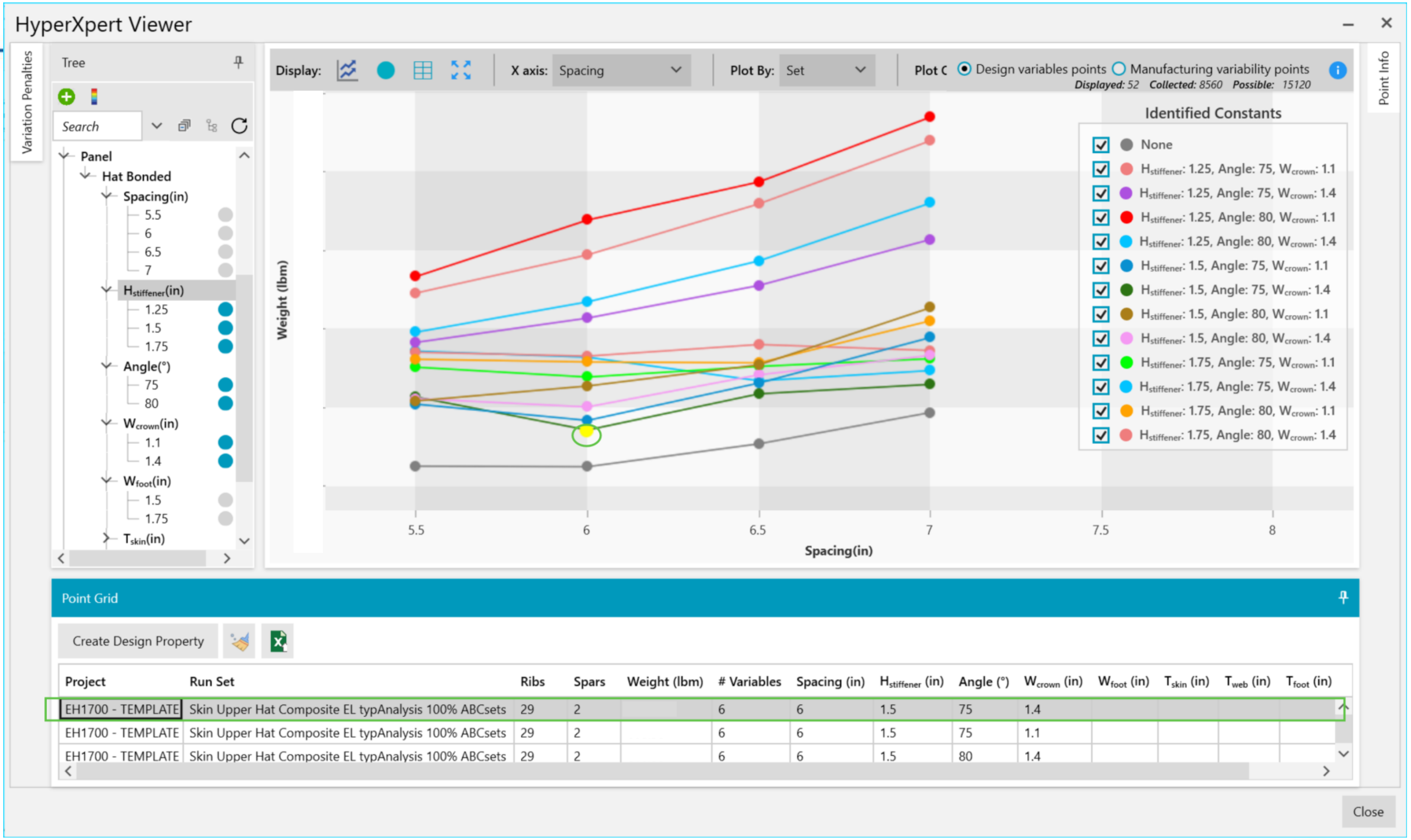
Recommendation Details

- Baseline Material Selection:
  - Tape – primary structural material
  - Compatible fabric – used to locally improve durability, breakout resistance, and producibility
  - Glass fabric needed for galvanic corrosion protection
- Extensive use of automated fiber placement to reduce fabrication cost
  - Minimization of hand layup is essential for cost mitigation
- Use of metallics required for numerous part applications
  - All single load path components
  - All components containing lug or clevis connections
  - Selected components to improve crashworthiness/bird impact resistance
  - **Sufficient conductive area to provide current / grounding return network requirements**
- Weight estimates include provisions for:
  - **Lightning strike**
  - **Minimum gage thickness for any fuel tanks**
  - **Current / grounding return network**

Rigor necessary to overcome partiality toward metallic low-cost approach

Follow-On Use of HYPERX

- Evaluated wing skin configuration with up to 9 parameters
  - Stiffener Height
  - Web Angle
  - Crown Width
- Green circle point: uniform *6” stringer spacing*
- Each color curve represents a different constant dimension for listed parameters



HyperXpert used to refine parameters and take producibility into account early

Expediting Wing Conceptual Design Using 21st Century Methods using Multi-Disciplined Analysis & Optimization (MDAO) Tools

Rapidly & Inexpensively Iterate

Study Inputs

- Vehicle Con-Ops
- Constraints Definition
- Wing Optimization Parameters

Begin optimization on initial assumptions

1st Order MDAO Tool

- ight Optimization System (FLOPS) Weights
- Non-CFD Drag Buildup
- Aircraft Performance & Mission Simulation

Selection of viable configs

Concept Study

- OML Definition & GFEM Loads
- CFD Analysis
- Aircraft Performance & Mission Simulation

HYPERX Structural Sizing & Weights

# of Evaluations	1000's	10's	1's
Iteration Time	Days	Weeks	Mo

Role of Optimization Tools to address AC trade studies

LUC VAN BAVEL
Aircraft Designer

- Transition from parametric to sizing based weights
  Significant no. of unique systems not accounted for in legacy aircraft
- Adapt other accelerated methods ("Model to Margins" automation)
  - Rapid mass properties tools/ aero models & methods
  - Update external loads NIAR & Beyer Flight Sciences
- Morph Global FEM shell model to represent study configurations
- HYPERX used to determine weight deltas for a number of TRADE Studies:
  - Wing Parameters; Planform area; span; taper; sweep; depth/ chord; twist
  - Wing Attachment; Integrated, Independent, Hybrid,
  - Location of high mass items; Inertial relief from moving items to wing
  - Main Landing Gear Configs: Location; Stowed position
- Use of HYPERX for library of common structural configurations
- Structural optimization tools useful to evaluate trade study alternatives

HyperX is practical enough to use for rapid iterations of AC configurations

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Takeaways

Luc Van Bavel
Freedom AC

- Establish needs from each customer segment
- Use systematic approach to affinitize/ set up requirements that are solution free
- Weight efficiency is the primary driver for sustainable aerostructure
- Use MDAO tools to explore design space to establish configuration & lines
  - Include 1st order drag & propulsive efficiency parameters
- Structural optimization tools are useful in early conceptual phases of program
  - Material selection
  - Weight comparisons & cost basis
  - Maturity of configuration
- Composite application must be tailored for weight and manufacturing costs

The use of HYPERX drives early material decision & configuration trades