Conceptual Design of the Hybrid-Electric Subsonic Single Aft Engine (SUSAN) Electrofan Transport Aircraft

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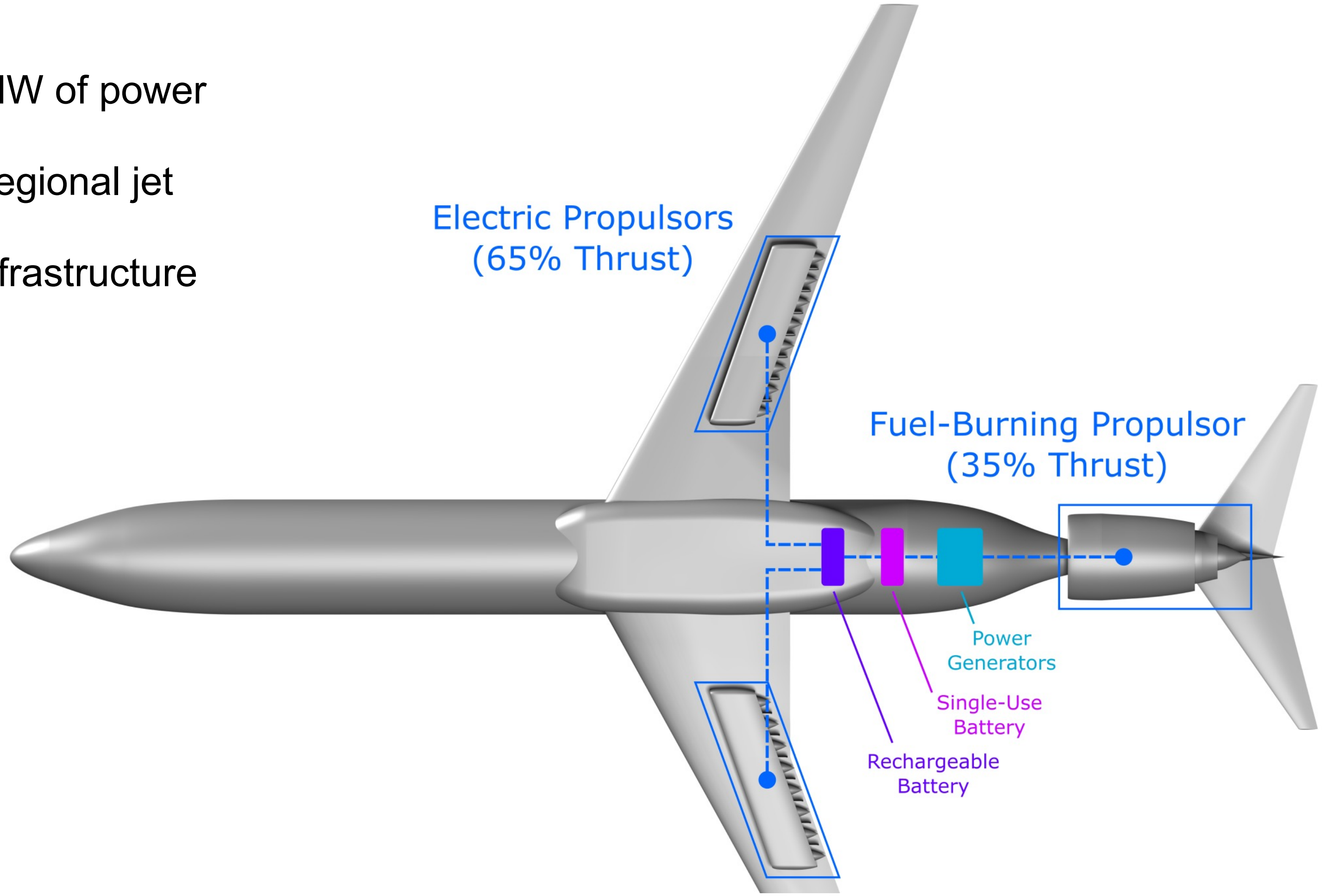
The SUbsonic Single Aft eNgine (SUSAN) Electrofan

- SUSAN Electrofan is a hybrid-electric transport aircraft incorporating advanced **electrified aircraft propulsion (EAP)** and **propulsion-airframe integration (PAI)** technologies to significantly reduce aviation energy usage and emissions within the 2035–2040 time frame
  - High levels of electrification with up to 20 MW of power
  - Retains size, speed, and range of a large regional jet
  - Remains compatible with existing airport infrastructure and operations

Specifications	
Class	Regional
Capacity	180 PAX
Mach	0.785
Altitude	37,000 ft
Design Range	2,500 nmi
Economy Range	750 nmi



Basic schematic of the SUSAN Electrofan's hybrid-electric propulsion system.

System Level Assessment and Trades Included

Objectives:

1. To develop a closed aircraft concept of the SUSAN Electrofan based on current design requirements and assumptions
2. To obtain baseline estimates of relative fuel burn performance compared to year 2020 technology level aircraft based on the Boeing 737 MAX 8 (Boeing 737-8)

The present study includes the following subset of **system level benefits and trades**:

- ✓ Distributed electric propulsion (DEP) … reduces TSFC
- ✓ Boundary layer ingestion (BLI) aft fuselage turbofan … reduces TSFC
- ✓ Turbine Electrified Energy Management (TEEM) … reduces TSFC
- ✓ Advanced turbofan design … reduces TSFC
- ✓ Two turbofan engines to one … reduces weight and drag
- – Electrified aircraft propulsion (EAP) systems* … increases weight
- – Electrical transmission losses … increases TSFC

*Electrified aircraft propulsion (EAP) systems include the power systems, battery systems, and thermal systems.

Design Requirements, Considerations, and Assumptions

- Most of the **top-level aircraft requirements (TLARs)** are based on **Boeing 737-8,** assuming a similar overall sizing*
  - Maximum wing loading, 129.8 lb/ft^2
  - Minimum thrust-to-weight ratio, 0.298
  - Propulsion system thrust requirements
  - Year 2020 technology levels for common aircraft components and subsystems through model calibrations
- Power system sized for a maximum 20 MW
- Assume no propulsion-airframe integration (PAI) effects

Parameter	Boeing 737-8	SUSAN
Maximum payload (lb)	46,000	46,000
Design Mission		
Payload (passengers)	180	180
Range (nmi)	3,100	2,500
Mach, SOC	0.775	0.775
Altitude, SOC (ft)	35,000	35,000
Economy Mission		
Payload (passengers)	180	180
Range (nmi)	1,000	750
Mach, SOC	0.785	0.785
Altitude, SOC (ft)	36,000	37,000

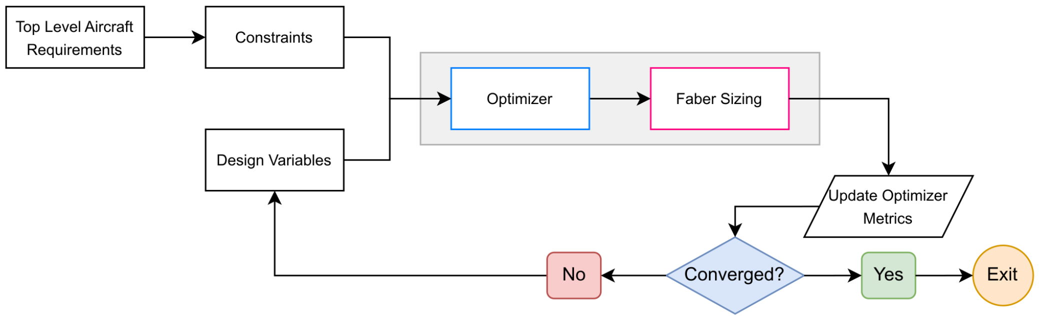
*Assumes system level trades (e.g. lower fuel weight vs. higher fixed weights) result in similar MTOW

Conceptual Design Environment & Modeling of EAP Systems

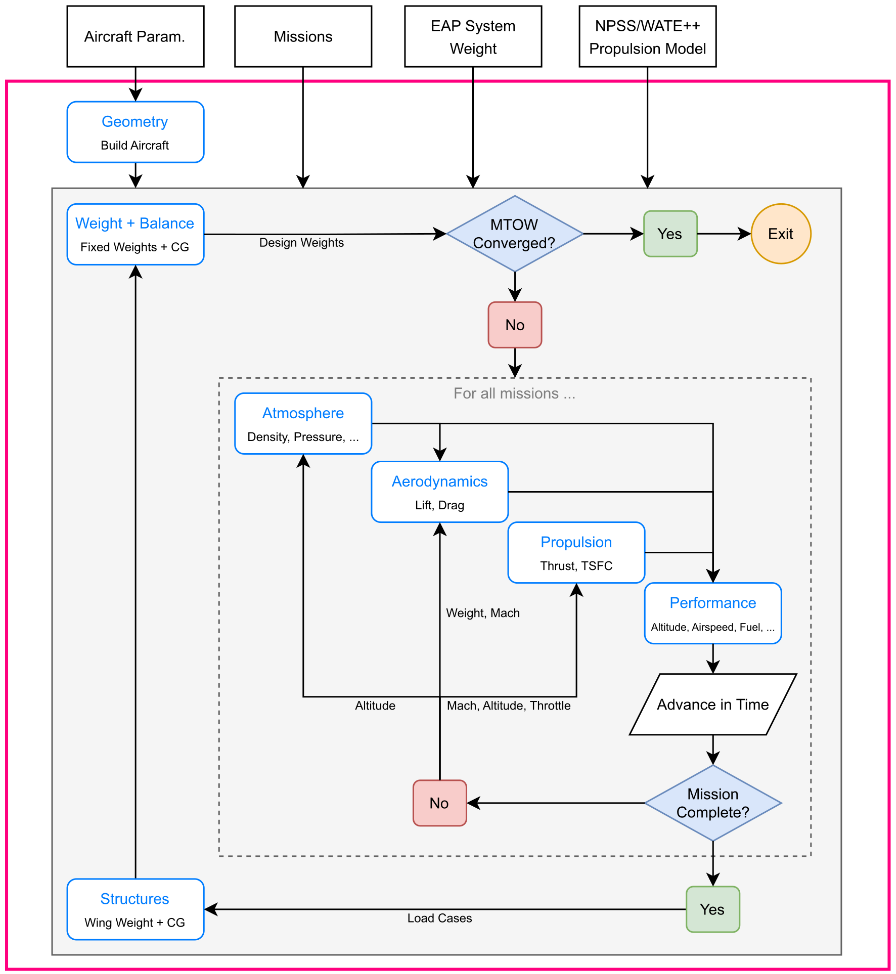
Faber: Conceptual Design Environment

Aircraft systems sizing and analysis through a **Multidisciplinary Design Analysis and Optimization (MDAO)** framework*

- Conceptual level modules for aerodynamics, structures, weight and balance, propulsion, and performance, …
- Gradient-based optimization is used to automate the sizing process, driving a given aircraft design toward a solution that satisfies the top-level aircraft requirements (TLARs)
- Propulsion system model and the EAP system weight are inputs



Faber: Optimization routine



Faber: Aircraft sizing and analysis routine

*Updated from Chau and Zingg, *Journal of Aircraft*, 2022, doi.org/10.2514/1.C036389 and Chau and Zingg, *Journal of Aircraft*, 2023, doi.org/10.2514/1.C037158.

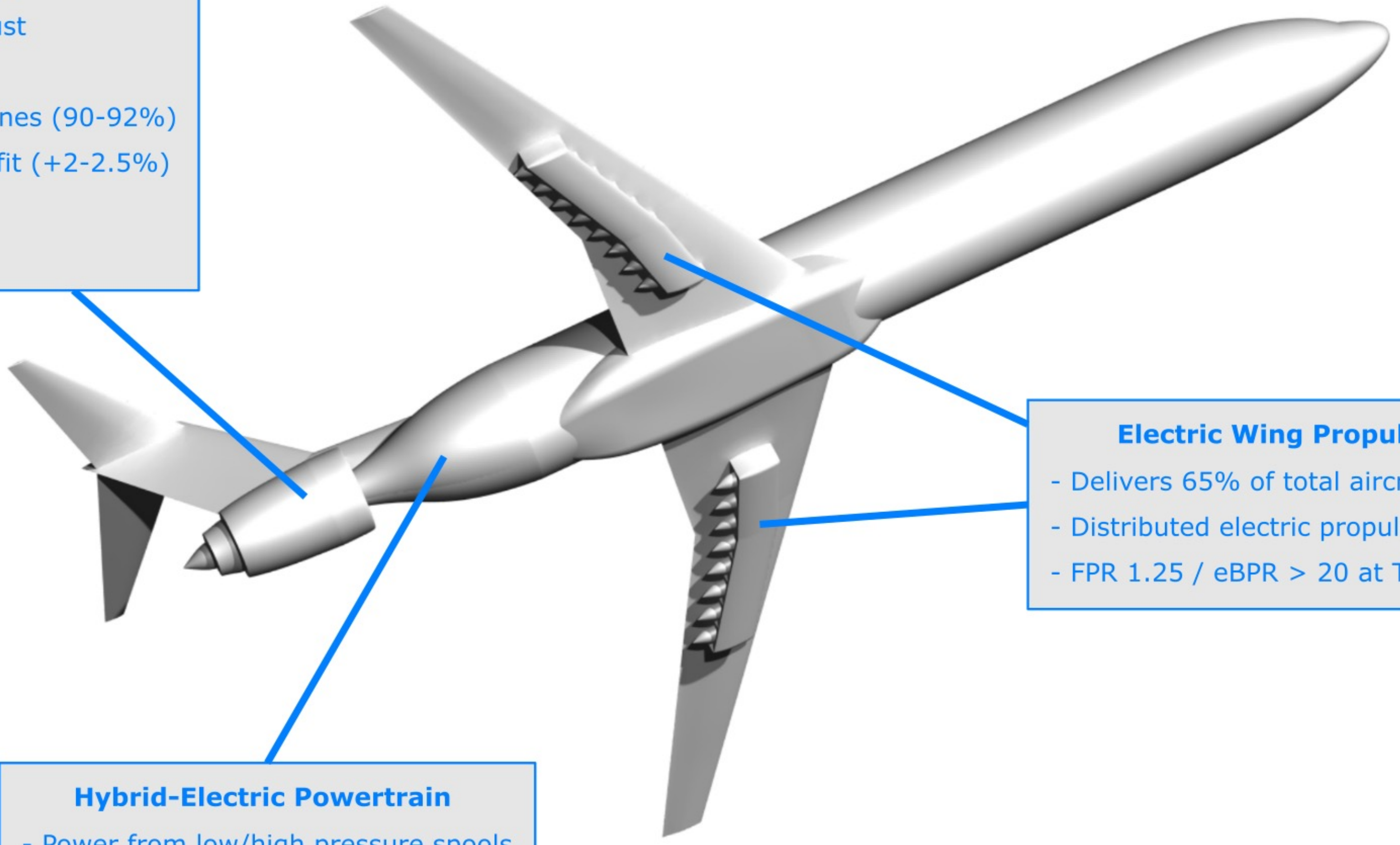
Propulsion System Model (Chapman et al. 2023)

Propulsion system model developed through NPSS[1] and WATE++[2]

- Multiple design point (MDP) method based on rolling takeoff (RTO), top of climb (TOC), and cruise (CRZ)
- Engine deck maps **thrust/TSFC** to **Mach/altitude/throttle**

Aft Fuselage Turbofan

- Delivers 35% of total aircraft thrust
- Geared dual spool architecture
- High efficiency compressors/turbines (90-92%)
- TEEM compressor efficiency benefit (+2-2.5%)
- Boundary layer ingestion (BLI)
- FPR 1.37 / BPR 5.66 at TOC



Electric Wing Propulsors

- Delivers 65% of total aircraft thrust
- Distributed electric propulsion (DEP)
- FPR 1.25 / eBPR > 20 at TOC

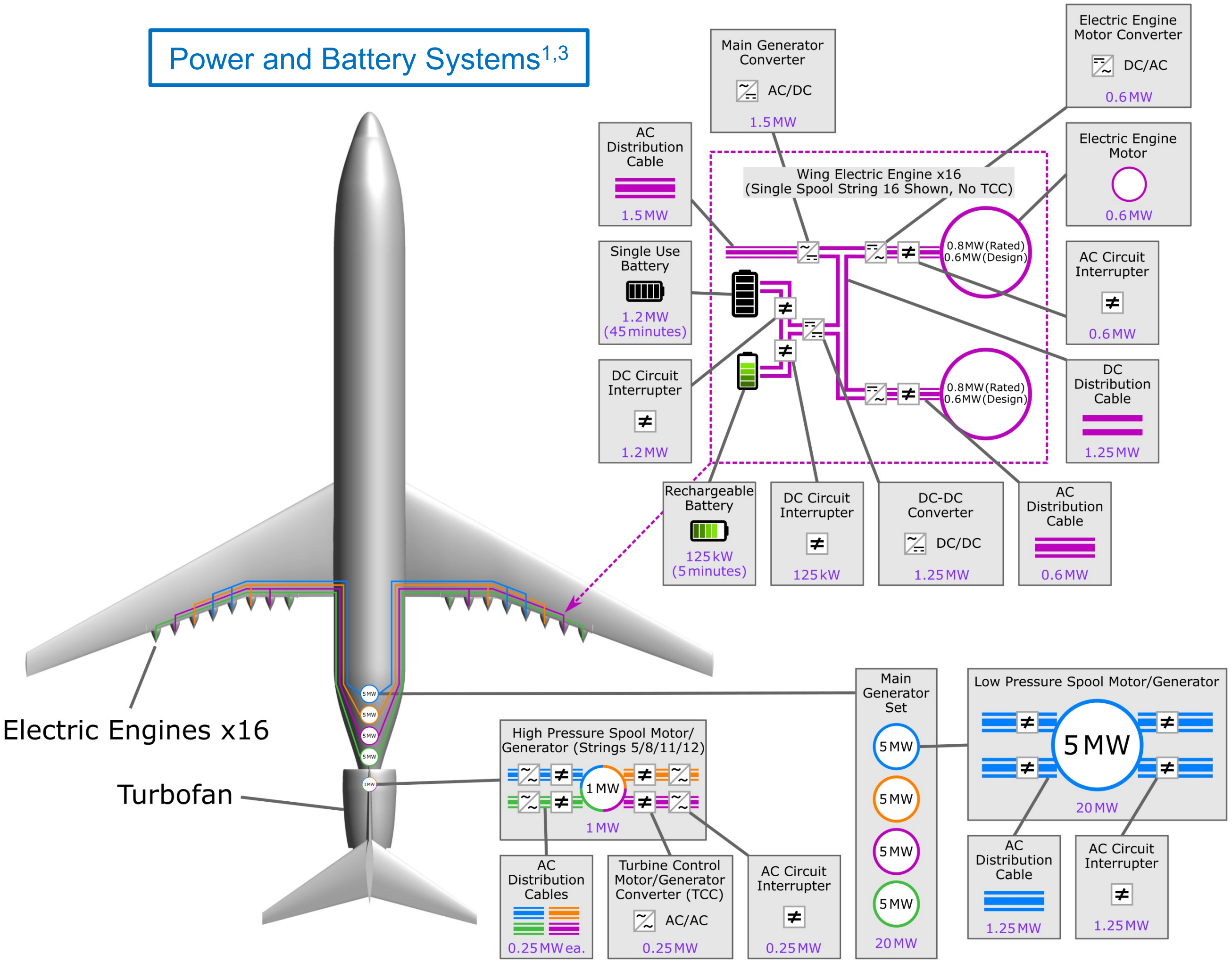
Hybrid-Electric Powertrain

- Power from low/high pressure spools
- Transmission losses

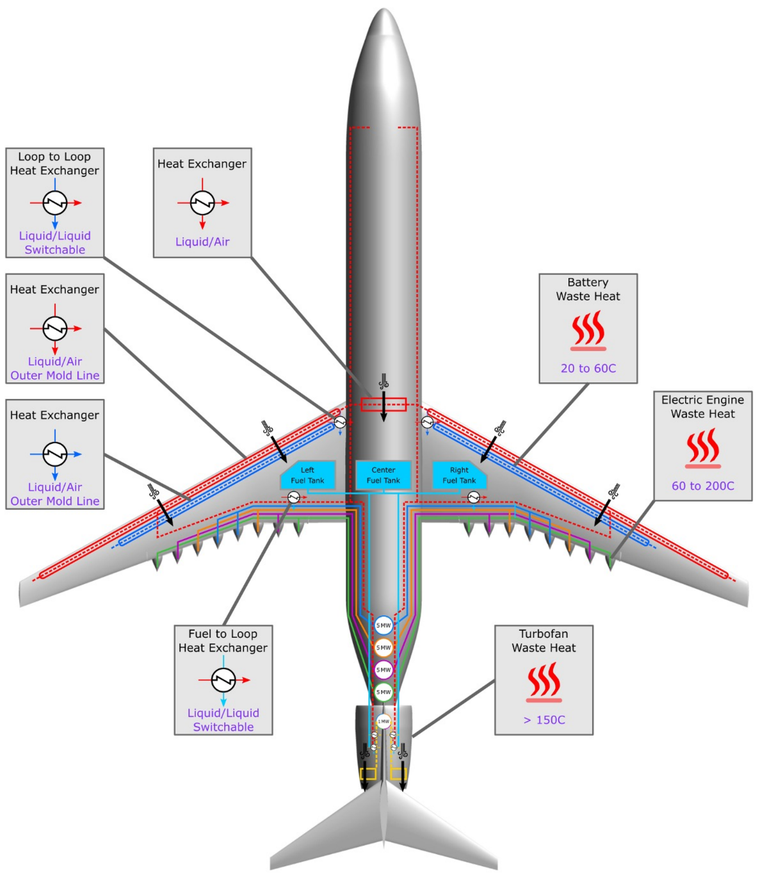
[1]Lytle, 2000, NASA/TM 2000-209915.
[2]Tong and Naylor, 2009, NASA/TM 2009-215656.

Power and Thermal Systems

Power and Battery Systems[1,3]



Thermal Systems[2,3]



Power system sized for 20 MW (LPS), with additional 1 MW (HPS) for TEEM.
Thermal system sized for a maximum heat load of 2.25 MW.

[1] Haglage et al., SciTech 2022, doi.org/10.2514/6.2022-2183.
[2] Heersema and Jansen, SciTech 2022, doi.org/10.2514/6.2022-2302.
[3] Chapman et al., SciTech 2023, doi.org/10.2514/6.2023-1749.

Power and Battery System KPPs (Haglage et al. 2022)

	Weight				Efficiency			
	Nominal	Min	Max	Unit	Nominal	Min	Max	Unit
Electric Machines								
Main Generator	25	15	50	kW/kg	99.0%	98.0%	99.5%	--
Turbine Control Motor/Generator	20	10	30	kW/kg	99.0%	98.0%	99.5%	--
Electric Engine Motor	20	10	30	kW/kg	98.5%	97.0%	99.0%	--
Power Conversion								
Main Generator Converter (AC-DC)	30	20	40	kW/kg	99.0%	97.0%	99.5%	--
Turbine Control Converter (AC-AC)	15	10	20	kW/kg	98.0%	94.0%	99.0%	--
Electric Engine Motor Converter (DC-AC)	20	10	40	kW/kg	99.0%	97.0%	99.5%	--
Battery Converter (DC-DC)	10	6.7	13.3	kW/kg	98.0%	97.0%	99.0%	--
Batteries								
Single-Use Battery	1,500	700	3,000	Wh/kg	90.0%	50.0%	98.0%	--
Rechargeable Battery	500	200	1,000	Wh/kg	97.0%	90.0%	98.0%	--
Cables								
AC Distribution Cable	2	0.5	10	kg/m/MW	0.040%	0.080%	0.020%	loss/m
DC Distribution Cable	2	0.5	10	kg/m/MW	0.040%	0.080%	0.020%	loss/m
Circuit Interrupters								
AC Circuit Interrupter	300	200	600	kW/kg	99.5%	99.7%	99.9%	--
DC Circuit Interrupter	150	100	300	kW/kg	99.5%	99.7%	99.9%	--

- Power systems sized based on power ratings and specific power values
- Battery systems sized based on energy required for ETOPS and specific energy values
- Component efficiency values determine end-to-end transmission efficiency + maximum heat loads for thermal system sizing

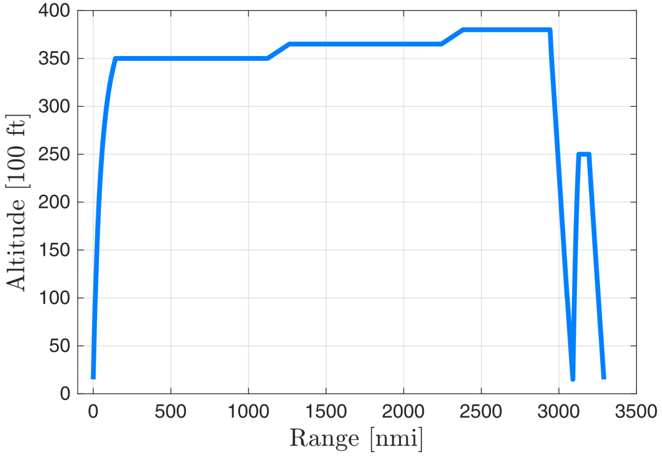
KPPs are projections based on NASA's research in EAP technology and are considered **variable technology levels driven by design requirements / environmental sustainability goals**

Reference Aircraft Based on the Boeing 737 MAX 8

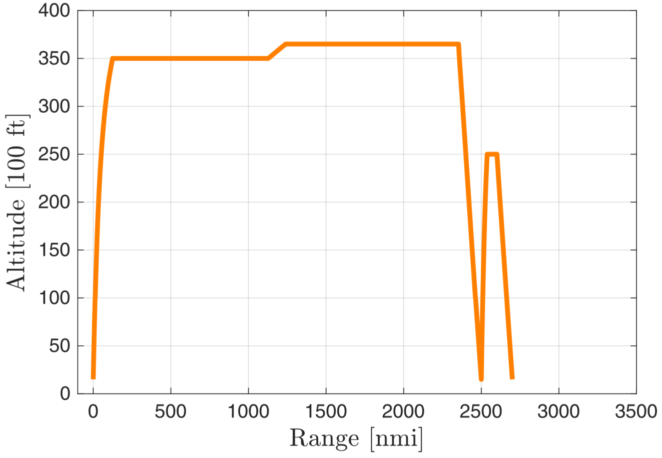
Reference Aircraft Based on the Boeing 737 MAX 8

- **B737-8** is developed as-drawn based on the Boeing 737-8 to represent an in-service year 2020 technology level reference aircraft
- **B737-8R** is a variant sized and optimized for reduced range capabilities, enabling more direct comparisons

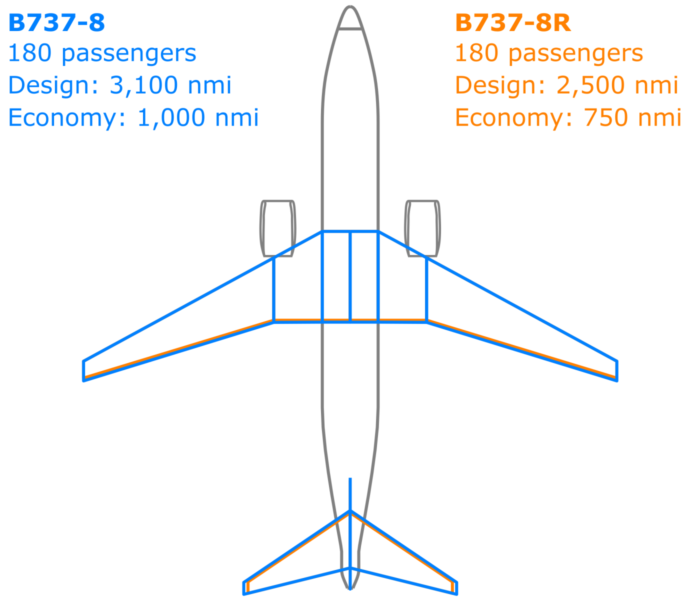
- B737-8 used to **calibrate weight and aerodynamics models** against …
  - Design weight data reported by Boeing
  - Weight, aerodynamics, and mission fuel data from an equivalent FLOPS model[1] of the Boeing 737-8
  - Calibration factors applied to the B737-8R and SUSAN Electrofan; effectively **sets the technology level** of common aircraft components and subsystems
- CFM LEAP-1B engine deck developed via NPSS and WATE++



B737-8: Design mission profile (3,100 nmi)



B737-8R: Design mission profile (2,500 nmi)



Reference aircraft concepts

[1]Thacker and Blaesser, *AIAA Aviation Forum*, 2017, doi.org/10.2514/6.2019-2984.

Conceptual Design Studies of the SUSAN Electrofan

SUSAN: Optimization Problem Formulation

Objective (1):

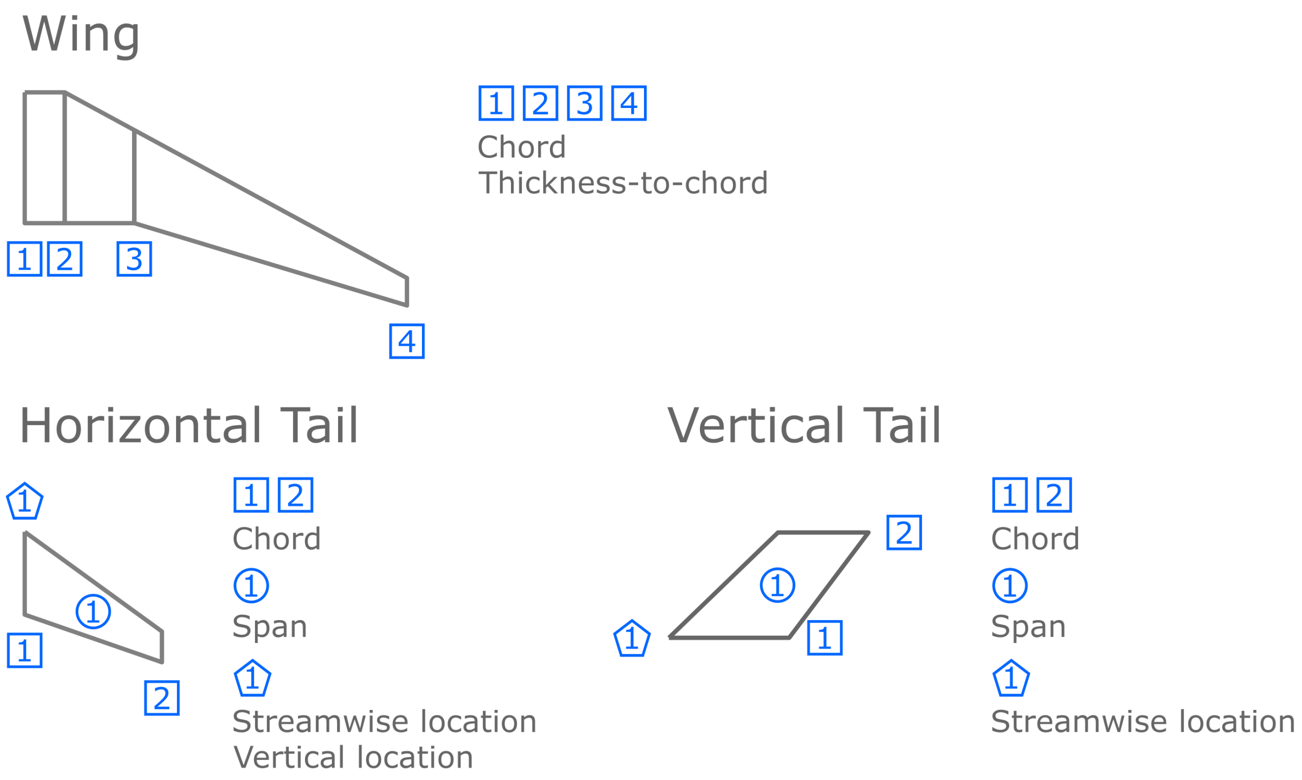
minimize Block fuel burn (1)

Design Variables (27):

w.r.t. Chord (8)
Thickness-to-chord ratio (8)
Horizontal tail chord (2)
Horizontal tail span (1)
Horizontal tail x-location (1)
Horizontal tail z-location (1)
Vertical tail chord (2)
Vertical tail span (1)
Vertical tail x-location (1)

Nonlinear Constraints (5):

s.t. Min. fuel volume (1)
Min. wing volume (1)
Max. wing loading (1)
Min. horizontal tail volume (1)
Min. vertical tail volume (1)

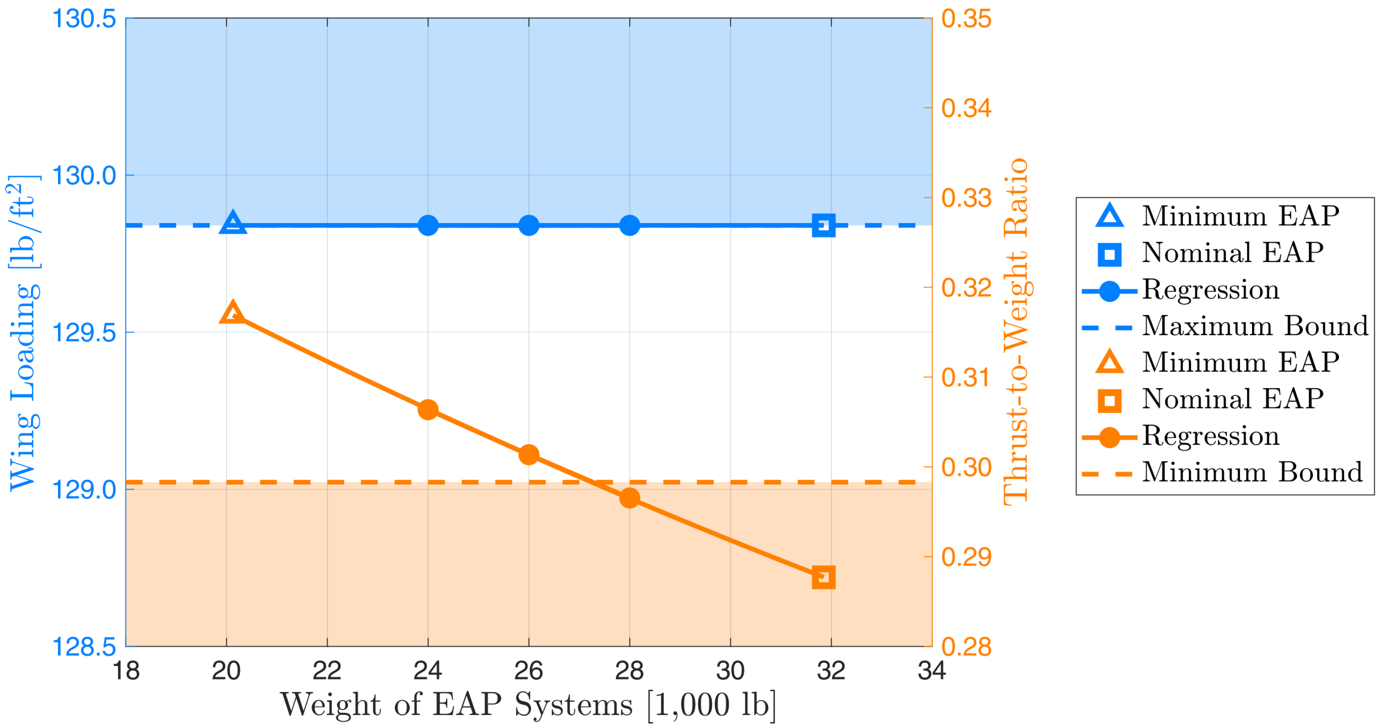


Design variables (DVs) used to define the wing, horizontal tail, and vertical tail sizing and optimization problem.

Optimization is used to drive the aircraft sizing based on top-level aircraft requirements (TLARs) through wing and tail system DVs. A similar optimization problem formulation is used to develop the resized variant of the Boeing 737-8 (B737-8R).

EAP System Weight Sensitivity Study

- **Nominal EAP system weight leads to a heavy aircraft (~197,990 lb MTOW) that exceeds the minimum thrust-to-weight ratio requirement,** despite achieving a net fuel burn benefit
- Since the NPSS engine deck cannot be modified, optimized designs must pass a check external to the automation
- A sweep on the weight of EAP systems is performed (with each point representing an aircraft optimization); bounds are defined by the B737-8 reference aircraft
- Thrust-to-weight ratio constraint is satisfied with an **EAP system weight of 27,230 lb**



EAP weight sensitivity study performed to determine the design point that satisfies all TLARs. Data points are obtained from aircraft design optimizations.

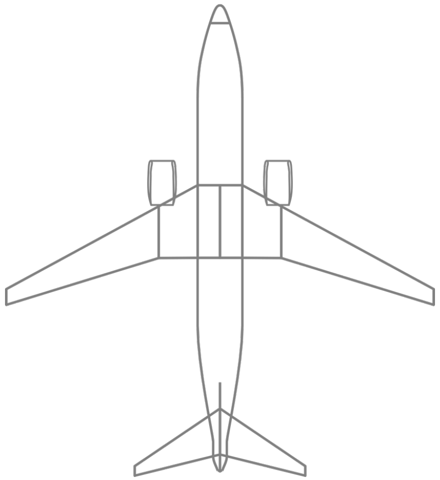
SUSAN vs. B737-8: Performance Comparisons

Compared to the B737-8, the SUSAN Electrofan at the sizing point has …

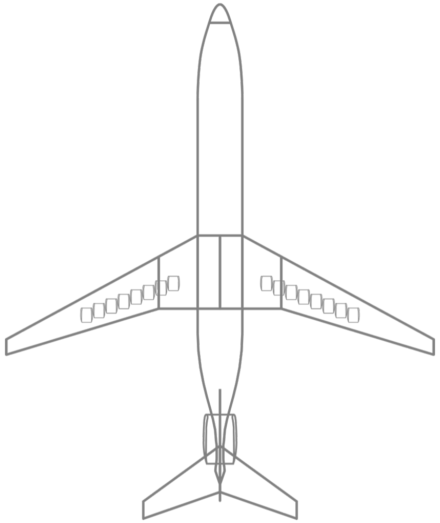
- 13.6% higher weight from EAP systems
- 6.9% higher L/D from higher weight and reduced drag due to thinner wings and embedded mail-slot nacelles
- 21.2% lower TSFC from DEP, BLI, TEEM, and advanced turbofan design

The SUSAN Electrofan provides an **11.1% reduction in block fuel** over the 750 nmi when compared to the B737-8 performing the same mission.

This improves to a **12.5% reduction in block fuel** over the B737-8's 1,000 nmi economy mission.



B737-8: Aircraft concept



SUSAN: Aircraft concept

Parameter	B737-8	SUSAN	Delta [%]
MTOW, lb	181,280	190,890	+5.3
OEW, lb	99,550	120,950	+21.5
MFW, lb	46,160	33,240	-28.0
Economy (750 nmi)			
Mach number (SOC)	0.785	0.785	+0.0
Altitude (SOC), ft	37,000	37,000	+0.0
Weight (SOC), lb	150,640	171,120	+13.6
L/D (SOC)	18.03	19.28	+6.9
TSFC (SOC), lb/lbf/hr	0.5590	0.4404	-21.2
Block fuel, lb	9,130	8,120	-11.1

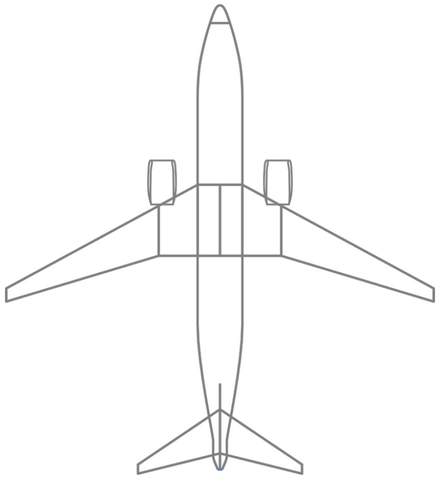
SUSAN vs. B737-8R: Performance Comparisons

Compared to the B737-8R, the SUSAN Electrofan at the sizing point has …

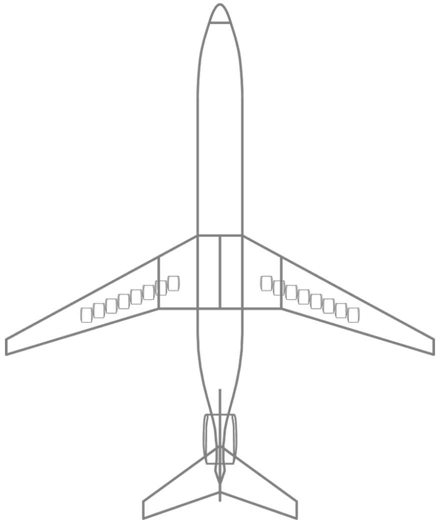
- 17.3% higher weight from EAP systems
- 3.4% higher L/D, reduced advantage due to B737-8R's thinner wings
- 21.2% lower TSFC from DEP, BLI, TEEM, and advanced turbofan design

The SUSAN Electrofan provides an **8.4% reduction in block fuel** over the 750 nmi when compared to the B737-8 performing the same mission.

This improves to a **9.6% reduction in block fuel** over the B737-8's 1,000 nmi economy mission.



B737-8R: Aircraft concept



SUSAN: Aircraft concept

Parameter	B737-8R	SUSAN	Delta [%]
MTOW, lb	173,280	190,890	+10.2
OEW, lb	99,770	120,950	+21.2
MFW, lb	37,160	33,240	-10.5
Economy (750 nmi)			
Mach number (SOC)	0.785	0.785	+0.0
Altitude (SOC), ft	37,000	37,000	+0.0
Weight (SOC), lb	145,880	171,120	+17.3
L/D (SOC)	18.64	19.28	+3.4
TSFC (SOC), lb/lbf/hr	0.5590	0.4404	-21.2
Block fuel, lb	8,860	8,120	-8.4

Summary and Conclusions

- This paper presents a first step toward a systems assessment of the SUSAN Electrofan, incorporating several key system level benefits and high-level interdisciplinary trades related to the electrified aircraft propulsion (EAP) systems
  - Distributed electric propulsion (DEP)
  - Boundary layer ingestion (BLI)
  - Advanced turbofan design with the Turbine Electrified Energy Management (TEEM) system

- Developed a closed concept of the SUSAN Electrofan that satisfies all top-level aircraft requirements (TLARs) based on an EAP system weight of 27,230 lb; this lies between the optimistic and nominal technology level projections

- SUSAN Electrofan provides an **11.1% reduction in block fuel over its 750 nmi economy mission** compared to the **B737-8** operating the same mission

- Compared to the resized **B737-8R**, the SUSAN Electrofan provides an **8.4% reduction in block fuel over its 750 nmi mission**

- These performance estimates represent **baseline estimates** that will be further improved through the incorporation of system level benefits that were not included in the present study; higher fidelity methods will also be used to improve the credibility of these estimates

Acknowledgments

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- Authors gratefully acknowledge technical support and guidance from **SUSAN Electrofan team**; special mentions include:
  - Jeffryes W. Chapman (Glenn) for propulsion system models
  - Timothy P. Dever (Glenn) for power systems support
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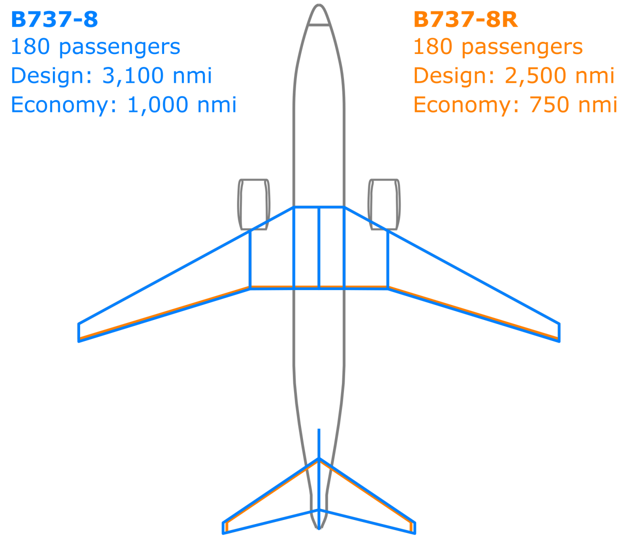
B737-8 vs. B737-8R: Comparison of Weight Schedules in Pounds

Weight Group	B737-8	B737-8R	Delta
Airframe	50,670	51,270	+600
Fuselage	18,540	18,610	+70
Wing	18,280	19,440	+1,160
Horizontal Tail	1,830	1,660	-170
Vertical Tail	1,220	1,140	-80
Landing Gear	8,830	8,440	-390
Nacelle and Pylon	1,980	1,980	+0
Propulsion	14,810	14,810	+0
Engines	14,470	14,470	+0
Controls	220	220	+0
Oil Systems and Coolant	120	120	+0
Systems	27,720	27,430	-290
Surface Controls	1,600	1,490	-110
Auxiliary Power	1,260	1,260	+0
Avionics and Instruments	2,710	2,570	-140
Hydraulics	1,430	1,430	+0
Electrical	2,690	2,690	+0
Fuel Systems	970	930	-40
Furnishings and Equipment	15,310	15,310	+0
AC and Anti-Icing	1,750	1,750	+0

Weight Group	B737-8	B737-8R	Delta
Operational	6,350	6,260	+510
Crew and Provisions	860	860	-60
Consumables	3,060	3,060	+40
Baggage Containers	1,970	1,970	+570
Unusable Fuel	460	370	-40
OEW	99,550	99,770	+1,770
Payload	39,600	39,600	-
ZFW	139,150	139,370	-
FW	42,130	33,910	-
MTOW	181,280	173,280	-8,000

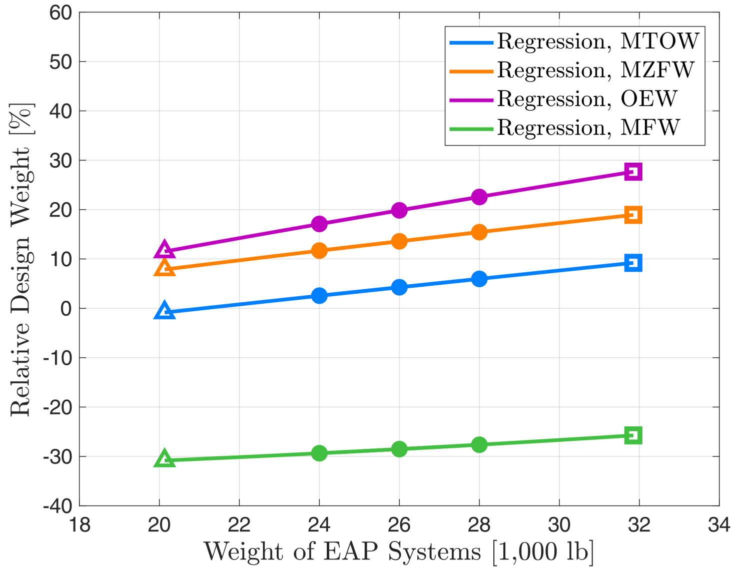


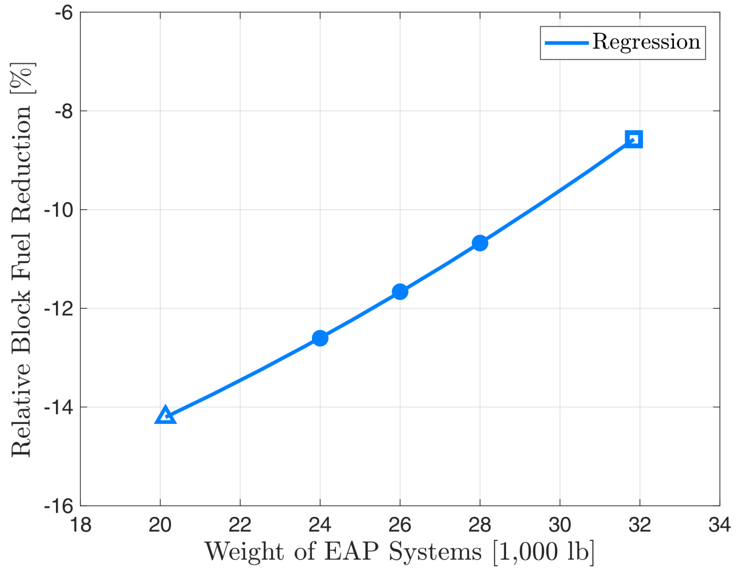
Concepts of the two reference aircraft.

Performance vs. B737-8 and B737-8R Reference Aircraft

SUSAN vs. B737-8

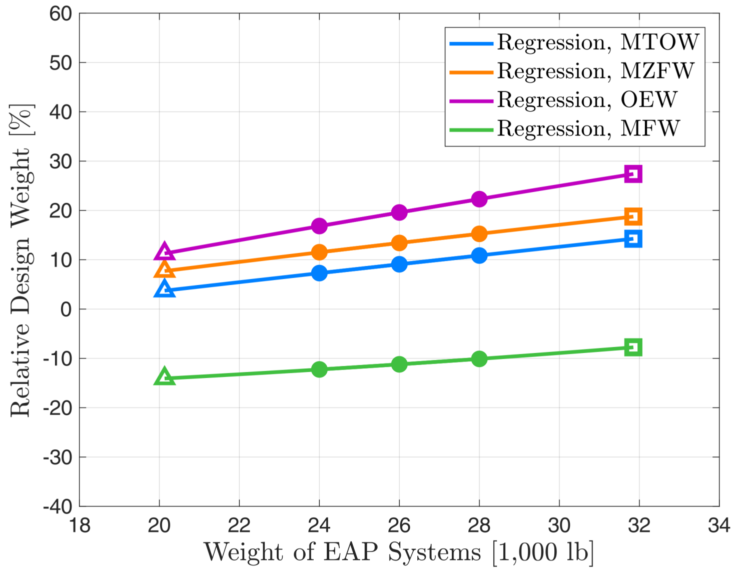
- MTOW change ranges -1 to +9%
- MFW change ranges -31 to -26%
- **Reduction in block fuel (750 nmi) ranges 9–14%**

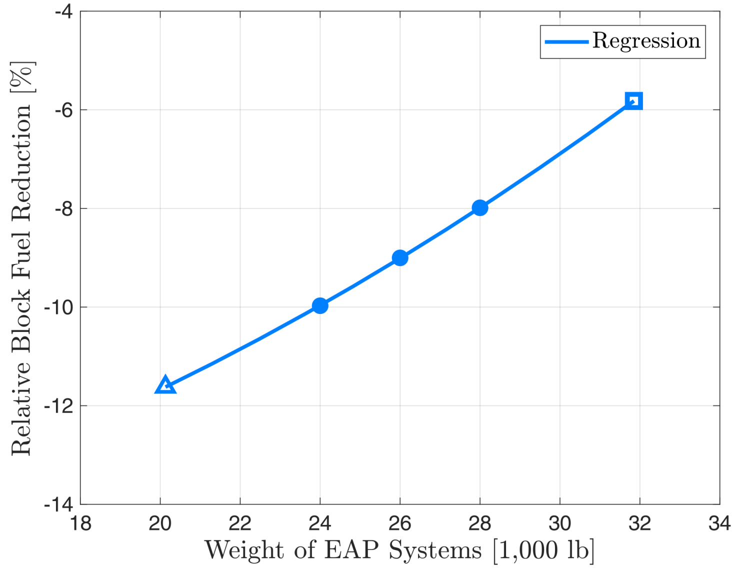




SUSAN vs. B737-8R

- MTOW change ranges -4 to -14%
- MFW change ranges -14 to -8%
- **Reduction in block fuel (750 nmi) ranges 6–12%**





SUSAN vs. B737-8 / B737-8R: Weight Breakdowns

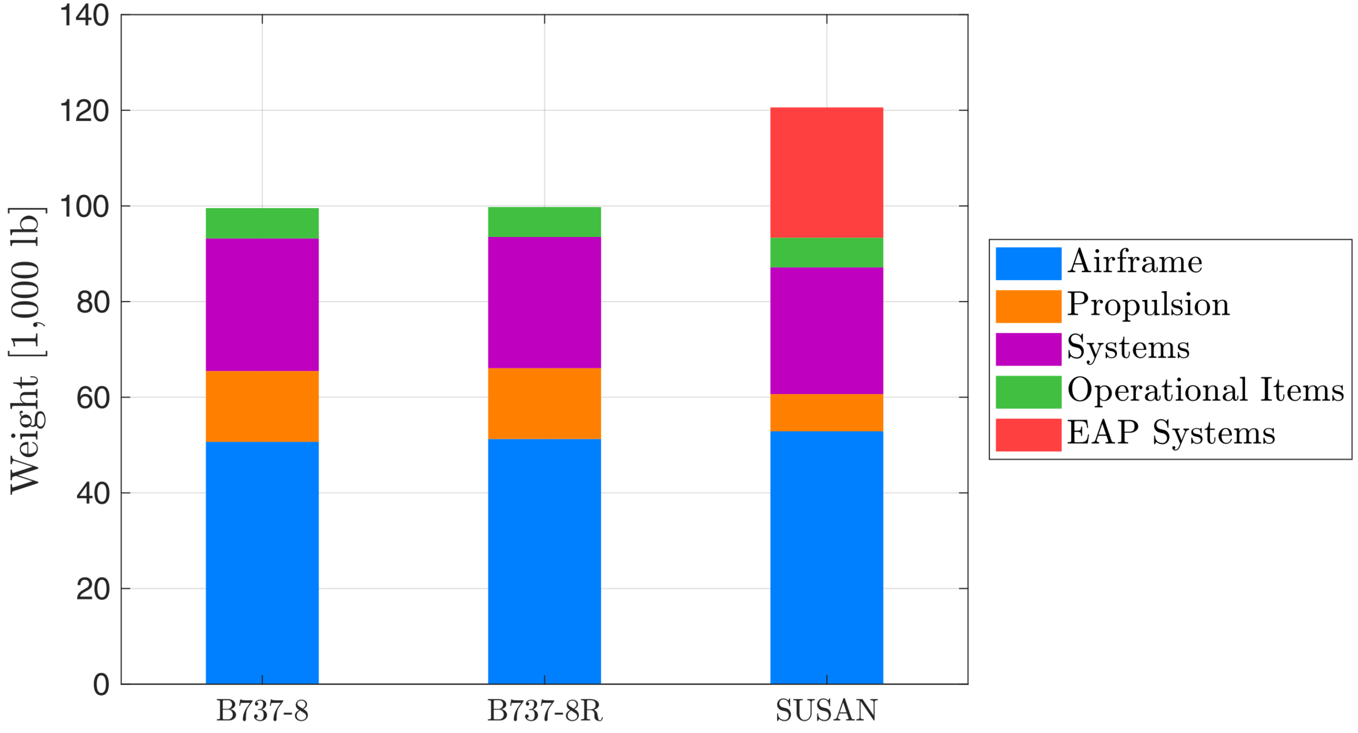
Compared to the B737-8 / B737-8R, the SUSAN Electrofan at the sizing point trades a **decrease** in …

- Weight from one turbofan engine
- Weight from pylons
- Weight from auxiliary power unit

For an **increase** in …

- Weight from the EAP systems (27,230 lb)

Accounting for weight changes due to changes in design weights (e.g. increase in MTOW, decrease in MFW), the **net change in OEW** is approximately **21,000 lb**.



Comparison of Aircraft Concepts (vs. B737-8)

Compared to the B737-8, the SUSAN Electrofan at the design point has a …

- 5.3% higher MTOW
- 5.3% higher wing area, increased with MTOW; the maximum wing loading constraint is active
- 21.5% higher OEW, trading the weight of one turbofan engine for EAP system weight
- 9.0% higher L/D due to drag reductions from embedded mail-slot nacelle, thinner wings, …
- 21.5% lower TSFC from DEP, BLI, TEEM, and advanced turbofan design

The net result is an **11.1% block fuel reduction** over the **750 nmi** economy mission relative to the B737-8.

This improves to a **12.5% block fuel reduction** when comparing performance over the **1,000 nmi** economy mission of the B737-8.

Parameter	B737-8	SUSAN v4	Delta [%]
MAC (reference) [ft]	13.79	14.64	+6.2
Wing area (gross, ref.) [ft^2]	1,396	1,470	+5.3
Wing span [ft]	117.83	117.83	+0.0
Wing sweep (LE) [deg]	28.5	28.5	+0.0
Horizontal tail area [ft^2]	360	409	+13.6
Vertical tail area [ft^2]	278	280	+0.7
Wing loading [lb/ft^2]	129.84	129.84	+0.0
Thrust-to-weight ratio	0.2984	0.2984	+0.0
MTOW [lb]	181,280	190,890	+5.3
MZFW [lb]	145,550	166,950	+14.7
OEW [lb]	99,550	120,950	+21.5
MFW [lb]	46,160	33,240	-28.0
Design payload [lb]	39,600	39,600	+0.0
Design range [nm]	3,100	2,500	-19.4
Mach number (SOC)	0.775	0.775	+0.0
Altitude (SOC) [ft]	35,000	35,000	+0.0
CL (SOC)	0.61	0.61	+0.2
L/D (SOC)	18.0	19.7	+9.0
TSFC (SOC) [lb/lbf/hr]	0.5570	0.4370	-21.5
Block fuel (750 nmi) [lb]	9,130	8,120	-11.1
Block fuel (1,000 nmi) [lb]	11,900	10,410	-12.5

Comparison of Aircraft Concepts (vs. B737-8R)

Compared to the B737-8R, the SUSAN Electrofan at the design point has a …

- 10.2% higher MTOW
- 10.2% higher wing area, increased with MTOW; the maximum wing loading constraint is active
- 21.2% higher OEW, trading the weight of one turbofan engine for EAP system weight
- 1.5% higher L/D
- 21.5% lower TSFC from DEP, BLI, TEEM, and advanced turbofan design

The net result is an **8.4% block fuel reduction** over the **750 nmi** economy mission relative to the B737-8.

This improves to a **9.6% block fuel reduction** when comparing performance over the **1,000 nmi** economy mission of the B737-8.

Parameter	B737-8R	SUSAN v4	Delta [%]
MAC (reference) [ft]	13.42	14.64	+9.1
Wing area (gross, ref.) [ft^2]	1,335	1,470	+10.2
Wing span [ft]	117.83	117.83	+0.0
Wing sweep (LE) [deg]	28.5	28.5	+0.0
Horizontal tail area [ft^2]	332	409	+23.2
Vertical tail area [ft^2]	262	280	+6.8
Wing loading [lb/ft^2]	129.84	129.84	+0.0
Thrust-to-weight ratio	0.2984	0.2984	+0.0
MTOW [lb]	173,280	190,890	+10.2
MZFW [lb]	145,770	166,950	+14.5
OEW [lb]	99,770	120,950	+21.2
MFW [lb]	37,160	33,240	-10.5
Design payload [lb]	39,600	39,600	+0.0
Design range [nm]	2,500	2,500	+0.0
Mach number (SOC)	0.775	0.775	+0.0
Altitude (SOC) [ft]	35,000	35,000	+0.0
CL (SOC)	0.61	0.61	+0.5
L/D (SOC)	19.4	19.7	+1.5
TSFC (SOC) [lb/lbf/hr]	0.5570	0.4370	-21.5
Block fuel (750 nmi) [lb]	8,860	8,120	-8.4
Block fuel (1,000 nmi) [lb]	11,510	10,410	-9.6