Conceptual Exploration of Aircraft Configurations for the SUSAN Electrofan

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This paper presents an aircraft configuration trade space exploration for NASA's SUbsonic Single Aft eNgine (SUSAN) Electrofan, which is a 180 passenger regional class transport aircraft that utilizes electrified aircraft propulsion and advanced propulsion airframe integration technologies to enable reduced fuel consumption and emissions. At its core is a hydrocarbon fuel-consuming aft fuselage propulsor that produces 35% of the total thrust while generating power to drive wing-mounted electric propulsors, which produce the remaining 65% thrust. This power is extracted from the aft fuselage propulsor via a set of generators and is managed with the help of a rechargeable battery, classifying the propulsion system as hybrid electric. Investigated in this work are different aft fuselage propulsor concepts, several wing propulsor configurations, and different types of stability and control strategies that can be accommodated by this hybrid electric system architecture, with an emphasis on aircraft performance. Results obtained using a low-order multidisciplinary design and analysis framework demonstrate that even with a subset of the advanced technologies that are being considered for the SUSAN Electrofan, significant improvements to fuel efficiency can be achieved.

Nomenclature

a	=	Speed of sound
F	=	Fuel fraction
L/D	=	Lift-to-drag ratio
M	=	Mach number
R	=	Range
W	=	Weight

Acronyms

CRPF	=	Counter Rotating Propfan
EAP	=	Electrified Aircraft Propulsion
ICA	=	Initial Cruise Altitude
MFW	=	Maximum Fuel Weight
MRW	=	Maximum Ramp Weight
MZFW	=	Maximum Zero Fuel Weight
OEW	=	Operating Empty Weight
PAI	=	Propulsion Airframe Integration
SLS	=	Sea-Level Static
SOC	=	Start of Cruise
SUSAN	=	SUbsonic Single Aft eNgine

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TOC = Top of Climb
TSFC = Thrust Specific Fuel Consumption

I. Introduction

Increasing demand for air travel has motivated the need for research into greener and more sustainable aircraft technologies. In response, organizations around the world have proposed long terms goals for significantly reducing the environmental impact of the commercial aviation sector. For example, one of the strategic pillars of the International Air Transport Association is to achieve a 50% reduction in fuel consumption and CO_2 emissions by the year 2050, relative to 2005 levels [1]. Another example is from the Flightpath 2050 program, which proposes a 75% reduction in fuel burn and CO_2 emissions per passenger kilometer for aircraft operating in the year 2050, relative to 2000 levels [2]. Aligned with these goals is the vision set forth by NASA's Aeronautics Research Mission Directorate (ARMD), which seeks long-term solutions for reducing commercial aviation fuel burn, emissions, and noise [3].

Toward this end, aircraft concepts utilizing Electrified Aircraft Propulsion (EAP) systems with Propulsion Airframe Integration (PAI) technologies show much promise. For example, NASA's Single-aisle Turboelectric AiRcraft with an Aft Boundary-Layer propulsor (STARC-ABL) offers a 7 and 12% savings in fuel consumption over its economy and design missions, respectively, when compared to an advanced conventional tube-and-wing aircraft with similar technology levels [4]. The turboelectric system architecture consists of two under-wing mounted hydrocarbon fuel-consuming turbofans which produce 1/3 of the total thrust each, while powering an electrically-driven and boundary-layer ingesting aft fuselage propulsor that provides the remaining 1/3 thrust.

Building on the success of the STARC-ABL concept and its contributions to advancing turboelectric aircraft system technology, NASA is now exploring alternative options which involve reducing the number of hydrocarbon fuel-consuming and power-generating engines from two to one. One such concept currently under development is called the SUbsonic Single Aft eNgine (SUSAN) Electrofan [5], which targets a 10 MW class EAP system to further electrify the aircraft and reduce fuel consumption. The system consists of a hydrocarbon fuel-consuming tail-cone thruster whose mechanical shaft power is extracted and converted to electrical power via a set of generators to drive wing-mounted electric propulsors. Power extraction and usage is regulated with the help of a rechargeable battery [6], classifying the propulsion system as hybrid electric. In order to reduce the typical power requirements of the aircraft, the SUSAN Electrofan is developed for a 750 nmi economy mission range and a design mission range of 2,500 nmi, positioning it for the regional jet class.

Through the hybrid electric system architecture of the SUSAN Electrofan, many options remain open regarding the selection of the airframe configuration, as well as the configurations of the fuel-consuming and electrically-driven propulsion systems. This paper presents some of the work that has been done to investigate the system level performance of various concepts, which has focused on providing first-order estimates to help guide the evolution of the aircraft configuration. Although a wide range of different aircraft configurations were explored, this paper presents results for four specific examples. These include both tailed and tailless configurations, three different aft fuselage propulsor concepts, and three different wing-mounted electric propulsor configurations.

The paper is organized as follows. The design requirements of the SUSAN Electrofan, as well as the assumptions involved in the present study, are included in Section II, while the conceptual design and analysis environment used to size and evaluate each aircraft configuration is presented in Section III. Section IV presents the sizing and analysis results for the four sample configurations, while conclusions and future work are provided in Section V.

II. Design Requirements and Assumptions

The SUSAN Electrofan is a large regional jet aircraft with a wing span of 118 ft, a maximum passenger capacity of 180 PAX, a maximum payload of 46,000 lb, and a nominal cruise Mach number and altitude of 0.785 and 37,000 ft, respectively. It has a design mission range of 2,500 nmi at a 90% load factor of 162 PAX, while the range of its economy mission is 750 nmi at the same load factor. The hybrid electric propulsion system, which consists of a hydrocarbon fuel-consuming aft fuselage propulsor and wing-mounted electric propulsors, is designed to be self-sufficient under nominal operating conditions, namely, electric power is supplied solely from generators attached to the tail-cone thruster. Rechargeable batteries are included, however, to provide the means for augmenting power extraction and usage through an advanced engine control system [6]. Single-use backup batteries are also included to provide sufficient electric power for satisfying an ETOPS-like requirement [7] in the event of an aft engine failure.

In order to help facilitate the exploration of the aircraft configuration trade space, the present study makes use of several simplifying assumptions. For example, first-order estimates of the thrust and power requirements are assumed to develop conceptual models of each propulsion system configuration. Initial estimates are also provided for the weight contributions of the power and thermal management systems, as well as for the rechargeable and backup batteries. These requirements and contributions are assumed to remain fixed for each aircraft configuration. Moreover, since these components and subsystems are assumed to be pre-defined, the sizing and analysis of each aircraft concept does not include trades with the sizing and performance of the propulsion and EAP systems.

Another simplifying assumption is that higher order effects can be excluded. This is because they typically require high-fidelity models and analysis methods such as computational fluid dynamics (CFD), which have not been readily available this early in the design stage. For example, PAI effects such as the aero-propulsive coupling between the fuselage and the tail-cone thruster or the wing and the wing-mounted propulsors are not included. Although the benefit of boundary-layer ingestion and suction are expected to contribute significant improvements to fuel efficiency or to the overall sizing of each aircraft concept, these contributions have not yet been quantified and are the subject of on-going investigations by the SUSAN Electrofan team [8, 9]. Similarly, unconventional structural designs, which are also being considered by the SUSAN Electrofan team, are not included in the present work.

A number of other advanced technologies, which are currently being investigated for the SUSAN Electrofan, are also not included in the present paper. One example includes natural-laminar-flow wing technology, which is expected to provide significant drag reductions. For progress on this front, see Lynde et al. [10]. Differential thrust control is another example, which can enable a downsizing of the control and stability surfaces, thereby reducing aircraft weight and drag. Lastly, alternative fuels are not considered in the present work, since the focus is on aircraft technologies only.

III. Low-Order Multidisciplinary Sizing and Analysis Framework

The sizing and analysis of each aircraft configuration is performed through a conceptual design environment called Faber [11], whose capabilities are currently being incorporated into the Launch Ascent and Vehicle Aerodynamics (LAVA) [12] suite of computational tools. These capabilities include multidisciplinary design and analysis, which is provided through low- and medium-fidelity disciplinary analysis modules for aerodynamics, weight and balance, structures, propulsion, and performance. In order to provide a means for handling hybrid electric aircraft concepts, these disciplinary analysis modules are supplemented by propulsion system models developed through NASA's Numerical Propulsion System Simulation (NPSS) framework [13] and NASA's Weight Analysis of Turbine Engines (WATE++) code [14], as well as first-order estimates for the sizing of the EAP systems. In the following sections, an overview of each of the disciplinary analysis modules is presented. A flow chart of Faber's sizing and analysis routine is shown in Figure 1.

A. Aerodynamics

For approximating the total drag of the aircraft, low-order models are used to estimate contributions from profile drag (i.e. skin friction drag, form drag, interference drag, and excrescence drag), induced drag, and wave drag. Profile drag is calculated through the method of Raymer [15], which uses the Prandtl-Schlichting relation for turbulent flow, and includes contributions from the fuselage, wings, horizontal and vertical control and stability surfaces, nacelles, and pylons. For these viscous drag computations, wetted areas are obtained from aircraft geometries modeled in NASA's Open Vehicle Sketch Pad (OpenVSP) [16]. For all other geometric quantities, e.g. the fineness ratios of the fuselage and nacelles, approximations are provided through empirical equations included in the geometry module of Faber. Interference drag penalties are applied as drag penalty factors depending on the aircraft component and its type. As per Raymer [15], a 5% mark-up is applied to the profile drag to approximate excrescence drag. Induced drag is calculated with a vortex lattice method coupled with a Trefftz-plane analysis, while wave drag is approximated by the Korn equation corrected for swept wings [17]. In the present study, elliptical lift distributions are assumed and trim drag is considered negligible.

B. Weight, Balance, and Structures

The weight and balance of each aircraft concept consists of contributions from the weight groups provided in Table 1. For conventional aircraft components, approximations are provided by the statistical correlations of Torenbeek [18], and Kroo and Shevell [19]. This is with the exception of the wing system, for which a semi-empirical approach is employed that combines an equivalent beam model [20] in a finite-element method for calculating the primary or structural weights of the wing system with empirical relations [21] for secondary weights, such as those of the wing ribs,

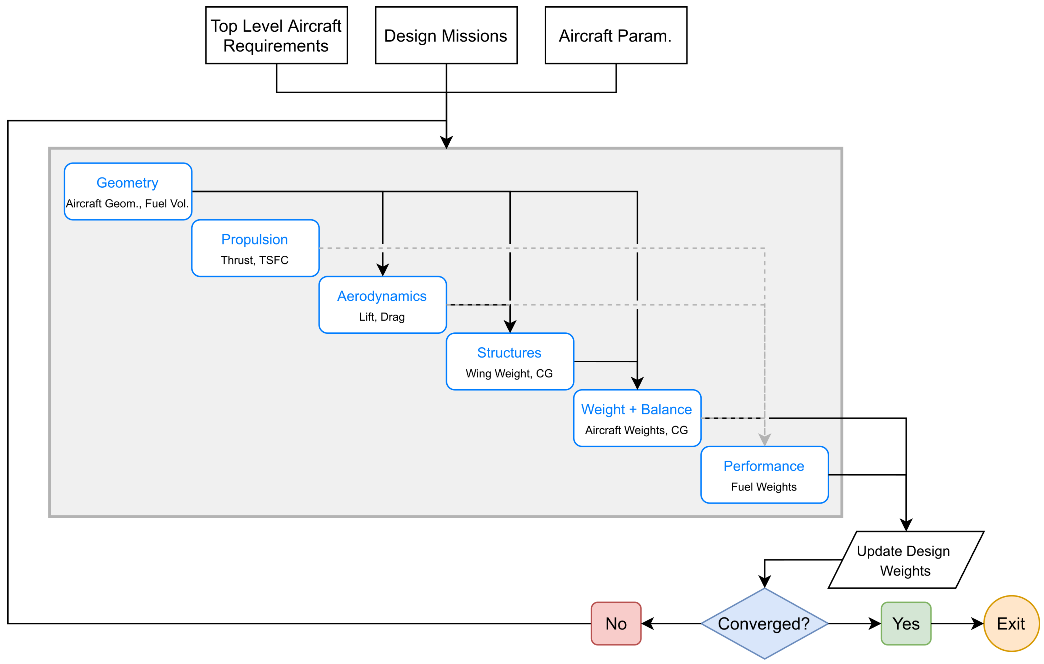

Fig. 1 A flow chart of Faber's sizing and analysis routine.

Table 1 Weight and balance components.

Airframe		**Propulsion**	
Fuselage	Nacelles	Engine	Electric Propulsors
Wing	Landing Gear	Controls	Power and Thermal Systems
Horizontal Surf.		Oil Systems	Batteries
Vertical Surf.		Fuel Systems	
Systems		**Operational**	
Flight Controls	Furnishings	Crew and Provisions	Baggage Containers
Avionics	Safety Equipment	Consumables	Unusable Fuel
Hydraulics	Pressurization	**Payload**	
Electrical		**Fuel**	

minimum gauge structures, (i.e. fixed leading and trailing edges), high-lift devices (i.e. slats, flaps, and spoilers), control systems (i.e. ailerons), support structures, and non-optimum structures. For calculating the primary wing weights, the structures are sized based on a fully-stressed criterion, which according to Gallman, Smith, and Kroo [22] can be comparable at the conceptual design stage to that which can be obtained from a structural optimization routine. Load conditions include $+2.5g$ and $-1.0g$ balanced maneuvers, with inertial relief included.

For the weight and balance of each propulsion system, estimates from the NPSS and WATE++ models are used instead. This includes the nacelle and dry engine weight, which are presented in Section III.C. The weight of the EAP systems, which includes the power and thermal management systems, electric propulsors, and batteries, are set based on first-order estimates and are also presented in Section III.C. The methods used for calculating fuel weights are described in Section III.D.

Table 2 TCT weight and performance summary.

Configuration	1	2	3
	Tail-Cone Thruster		
Type	Ducted Turbofan	Open Rotor	Ducted GTF
Dry weight [lb]	8,953	9,264	7,161
Rotor weight [lb]	0	2,350	0
Nacelle weight [lb]	641	489	654
Total pod weight [lb]	9,594	12,103	8,817
	Wing Propulsors		
Type	CRPF	CRPF	Ducted Fan
Total weight [lb]	5,056	5,056	5,040
	System Performance		
Thrust available (SLS) [lb]	72,222	74,433	54,305
Thrust available (TOC) [lb]	11,500	11,500	11,500
Power available (SLS) [hp]	37,166	36,770	26,314
Power available (TOC) [hp]	14,032	13,000	13,469
TSFC (SOC) [lbf/lb/hr]	0.500	0.453	0.440

C. Propulsion and Power

The hybrid electric propulsion system consists of a fuel-consuming tail-cone thruster with a set of generators attached to its shafts to extract and supply power to wing-mounted electric propulsors. This system is designed to provide a top-of-climb (TOC) thrust of 11,500 lb and approximately 54,000 lb at takeoff, with a thrust split of 35:65 between the tail-cone thruster and the wing propulsors, respectively. Preliminary engine decks developed through NPSS and WATE++ provide performance and weight data for three propulsion system configurations that are considered in this work. These include (1) a ducted turbofan tail-cone thruster with 2 or 4 wing-mounted counter-rotating propfans (CRPFs), (2) an open rotor tail-cone thruster with 2 or 4 CRPFs, and (3) a ducted geared turbofan tail-cone thruster with 16 ducted fans distributed across the wings. For the sizing of the wing propulsors, empirical scaling laws are used based on the work of Strack et al. [23] and Khalid et al. [24] for those in a CRPF configuration, while estimates are provided by WATE++ for those in a distributed ducted fan configuration. Table 2 provides a summary of each propulsion system configuration.

The power system is designed to supply up to 26,820 hp (approximately 20 MW) at takeoff and up to 13,410 hp (approximately 10 MW) at TOC, and is assumed to sufficiently power the electric propulsors. For the weight of the power and thermal management systems, which includes generators, inverters, and cables, a fixed weight allowance of 10,000 lb is assumed. The weight of the batteries is taken to be 9,000 lb, which is predominantly backup battery weight. These batteries are sized for an ETOPS-like requirement, and do not support reserve mission capabilities, as preliminary investigations have suggested that this may not be efficient when trading fuel weight for battery weight. Details on the development of the propulsion system concepts can be found in Mirhashemi et al. [25], while more information on the hybrid electric system architecture can be found in Haglage and Jansen [6]. The thermal management systems are described in Heersema [26].

D. Performance

For calculating fuel burn performance, the notional mission profile shown in Figure 2 is considered. The block fuel consists of the fuel spent during takeoff, climb, cruise, descent, and landing. To calculate the block fuel for a given mission, Faber uses the method of fuel fractions, which is given by

$$W_{\text{fuel}} = \frac{1 - \Pi_i F_i}{\Pi_i F_i} (\text{OEW} + W_{\text{payload}}) \tag{1}$$

where F_i is the fuel fraction for mission segment i. For takeoff (including warmup and taxi), climb, and landing, the

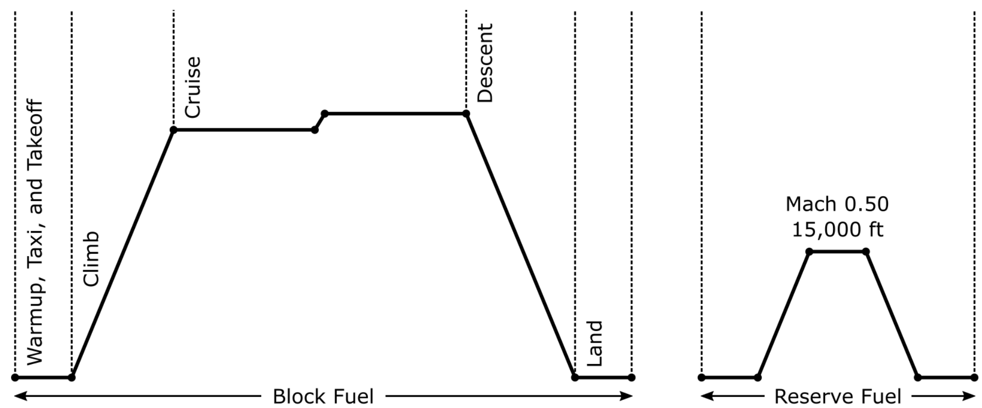

Fig. 2 Simplified mission profile for fuel burn calculations.

following baseline values are assumed

$$F_{\text{takeoff}} = 0.995 \tag{2}$$

$$F_{\text{climb}} = 1 - 0.013(\text{ICA}/30,000) \tag{3}$$

$$F_{\text{land}} = 0.998 \tag{4}$$

where ICA is the initial cruise altitude (or the change in altitude from one cruise segment to another for step climbs). For the cruise segment(s), the fuel fraction is given by the Breguet range equation

$$F_{\text{cruise}} = \exp\left(-\frac{R \cdot \text{TSFC}}{aM(L/D)}\right) \tag{5}$$

where R is the cruise range, TSFC is the thrust specific fuel consumption, and a, M, and L/D are the speed of sound, Mach number, and lift-to-drag ratio at cruise, respectively. These baseline values are then calibrated against results obtained from FLOPS when analyzing a common baseline SUSAN Electrofan model, for each mission.

In order to account for the range spent climbing, a representative climb profile is analyzed. It consists of three climb segments defined by specified climb angles. The aircraft begins climb at a maximum calibrated airspeed (CAS) of 250 knots from a specified initial climb altitude until 10,000 ft. The aircraft then accelerates at 270 knots CAS until the cruise Mach number is reached, and performs a constant Mach number climb until the ICA. This range is discounted from the cruise segment. As recommended by Torenbeek [18], a first-order approximation for the fuel burn of the descent segment can be obtained by treating it as an extended cruise segment. In particular, the fuel fraction for the descent segment, F_{descent}, is determined by the Breguet range equation, and a reduction in cruise range for the cruise segment calculation is not needed.

Reserve fuel is also included to satisfy a 100 nmi diversion and a 45 minute hold based on FAR Part 121 requirements for regional aircraft. This is done by assuming an equivalent cruise segment at Mach 0.50 and an altitude of 15,000 ft. The total mission fuel is then given by the sum of the block fuel and reserve fuel contributions.

IV. Results

In this section, conceptual sizing and analysis results are presented for four sample aircraft configurations that were considered for the SUSAN Electrofan. The sizing and analysis of a baseline aircraft is also included for performance comparisons. Design considerations for each aircraft concept are presented, and discussions on fuel efficiency, technical feasibility, and certifiability are also included. In this way, this section presents the evolution of the SUSAN Electrofan aircraft configuration so far.

A. Baseline Aircraft

For performance comparisons, the sizing and analysis of a Boeing 737-800-like aircraft is also included, which serves as a year 2005 baseline aircraft in reference to NASA's ARMD 2035 and beyond goals of reducing fuel burn and

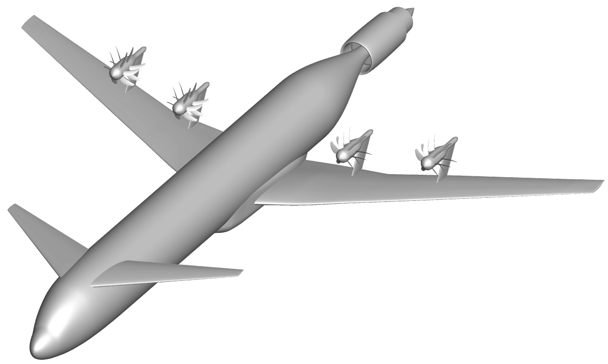

Fig. 3 A conceptual aircraft model of SUSAN V0.

CO_2 emissions [3]. This aircraft is developed for a design range and payload of 2,800 nmi and 160 PAX, respectively, and a maximum payload of 47,000 lb. Its nominal operating conditions include a cruise Mach number of 0.785 and an initial cruise altitude of 36,000 ft. The propulsion systems are based on the CFM56-7B. For fuel burn comparisons, the required block fuel of the baseline aircraft is calculated for the same economy mission range and payload as that of the SUSAN Electrofan.

B. The SUSAN Electrofan Variant 0

The first variant of the SUSAN Electrofan is shown in Figure 3. It includes a ducted turbofan propulsor in a tailless arrangement with the intention of minimizing the inlet distortion experienced by the tail-cone thruster and maximizing its potential for boundary-layer ingestion. Longitudinal control authority is provided by canards, which are sized based on the horizontal tail volume ratio of the Boeing 737-800-like aircraft. Although the present study assumes no trim drag, a trim drag advantage over an equivalent conventional or T-tail configuration is not anticipated since the main wing must be made independently statically stable about the lateral axis. This is normally achieved through a forward shift in the center of gravity, which can result in a higher trim drag penalty that offsets the benefits of the lifting control surface.

For directional control and stability, SUSAN V0 also features four wing-mounted electric propulsors with CRPFs that are mounted atop vertical fins. In principle, these propulsors can provide a means for differential thrust control and active thrust vectoring in order to help trim the aircraft, while the vertical fins provide a small contribution to directional stability. Since the aft fuselage propulsor is aligned with the centerline of the aircraft, additional vertical stabilizer surface may not be necessary given the reduced adverse yawing moments experienced during an equivalent one-engine-inoperative scenario where one or more wing propulsors are no longer active. This comes at the cost, however, of added control system complexity, especially when combined with the canard configuration. Furthermore, in the event of a complete failure of the electric propulsors, the aircraft has little to no means for directional stability and control. These factors can prove challenging to overcome when considering certification requirements for transport category aircraft.

Nonetheless, assuming that the feasibility and certifiability of this SUSAN Electrofan variant can be demonstrated, which is beyond the scope of the present paper, it provides a 17.2% reduction in block fuel over the economy mission when compared to the baseline aircraft. This advantage comes primarily from the 19.5% lower TSFC despite the 13.0% higher weight at the start of cruise due to the contributions of the EAP systems. In terms of aerodynamic performance, the SUSAN V0 and baseline aircraft each have similar quantities of start of cruise drag. A summary of the conceptual sizing and analysis results is provided in Table 3.

Table 3 SUSAN V0: Conceptual sizing and analysis results.

Parameter	Baseline	SUSAN V0	Δ [%]
MRW [lb]	175,020	181,210	+3.5
OEW [lb]	92,810	113,794	+22.6
MZFW [lb]	139,810	159,790	+14.3
MFW [lb]	43,980	34,280	−22.1
Weight [lb]	141,850	160,290	+13.0
Drag [lb]	8,738	8,750	+0.1
TSFC [lb/lbf/hr]	0.621	0.500	−19.5
Block fuel (750 nmi) [lb]	10,680	8,843	−17.2

Weight, Drag, and TSFC are defined with respect to the start of cruise.

C. The SUSAN Electrofan Variant 1

The next variant of the SUSAN Electrofan concept is shown in Figure 4 and features the open rotor tail-cone thruster, which offers improved fuel efficiency at the cost of noise. Studies done by General Electric [24], however, suggest that a 15-17 EPNdB margin to ICAO Chapter 4 noise levels can be achieved with this technology. A moderate penalty in weight is also paid due to the weight of the rotors, as presented in Section III.C. Given concerns over the feasibility and certifiability of the tailless configuration, SUSAN V1 returns to a tailed configuration, accepting the trade off with inlet distortion. Two front-of-wing CRPFs are used in place of the four over-wing CRPFs since the active control systems are no longer required. This leads to a small reduction in weight and drag due in part to the elimination of the vertical fins.

A T-tail configuration is selected, which was found to be the most efficient in terms of weight and drag for a given set of volume ratios. This is because the vertical tail allows the horizontal tail to be extended past the rotor blades of the aft fuselage propulsor, which results in a larger moment arm. Since tail strike is a major concern for the SUSAN Electrofan, which necessitates an aftward shift of the wings, landing gear, and hence, the center of gravity, this design consideration is of particular importance for maintaining reasonably sized tail surfaces. One concern, however, is the possibility of a rotor blade-off event, which can cause damage to the empennage. Although not considered in the present study, this risk can be mitigated by strengthening the rotor blades or by adding shielding to the empennage, but each is expected to come at the cost of added weight.

Another concern of the open rotor tail-cone thruster is the large diameter of its rotor blades, which are especially vulnerable during ground rotation. To protect them against tail strike, a ventral fin is installed to act as a tail skid while providing additional vertical stabilizer surface. Together, the vertical tail and ventral fin also act as flow straighteners for reducing the inlet distortion metric.

Based on the results included in Table 4, this variant of the SUSAN Electrofan concept provides a 23.7% reduction in economy mission block fuel when compared to the baseline aircraft. This is primarily due to the 27.1% lower TSFC of the open rotor tail-cone thruster, but a small savings in nacelle drag also contributes to a 5.1% savings in cruise drag. As with the previous variant, a net gain in fuel efficiency is still achieved despite an 11.9% higher aircraft weight at the start of cruise.

D. The SUSAN Electrofan Variant 2

Given the sizing restrictions imposed by the rotor blades of the open rotor propulsor, the third variant of the SUSAN Electrofan concept returns to the ducted turbofan tail-cone thruster. Through an innovative structural design developed by the Structures team, which integrates the primary load paths of the empennage and the aft fuselage propulsor, the T-tail can be moved further aft, thereby extending the moment arms of the horizontal and vertical tails and reducing their surface areas. Without the rotor blades of the open rotor tail-cone thruster constraining the wing location due to ground rotation requirements, the wing can be shifted forward, further increasing the tail moment arm and reducing the sizing of the horizontal and vertical tails. The ventral fin is also no longer required. This concept is shown in Figure 5.

A summary of the results for SUSAN V2 is provided in Table 6. Compared to the previous variant of the SUSAN Electrofan, SUSAN V2 benefits from a reduction in weight and drag due to the downsizing of the tail surfaces and the elimination of the ventral fin, while also benefiting from a moderate weight reduction returning to the ducted turbofan

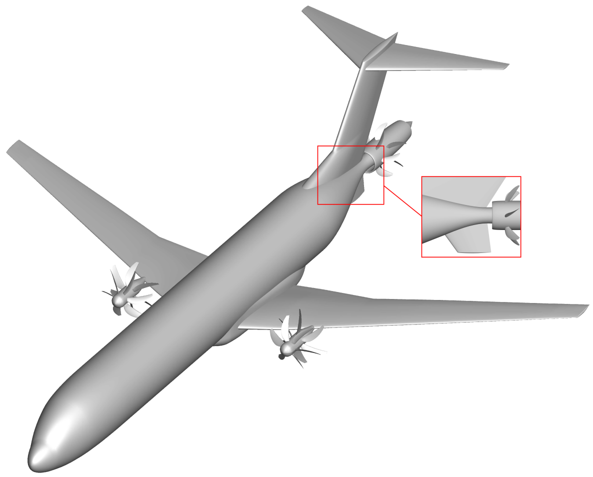

Fig. 4 A conceptual aircraft model of SUSAN V1. The inset highlights the ventral fin.

Table 4 SUSAN V1: Conceptual sizing and analysis results.

Parameter	Baseline	SUSAN V1	Δ [%]
MRW [lb]	175,020	178,505	+2.0
OEW [lb]	92,810	113,588	+22.4
MZFW [lb]	139,810	159,588	+14.1
MFW [lb]	43,980	29,922	−32.0
Weight [lb]	141,850	158,730	+11.9
Drag [lb]	8,738	8,290	−5.1
TSFC [lb/lbf/hr]	0.621	0.453	−27.1
Block fuel (750 nmi) [lb]	10,680	8,149	−23.7

Weight, Drag, and TSFC are defined with respect to the start of cruise.

propulsor. The TSFC advantage is not as large as that of the open rotor configuration, however, resulting in a block fuel advantage of −20.5% when compared to the baseline aircraft over the economy mission.

E. The SUSAN Electrofan Variant 3

The fourth and current variant of the SUSAN Electrofan is shown in Figure 6 and utilizes an updated ducted turbofan propulsor, which includes a gearbox to improve propulsive efficiency at the cost of added weight. An overall reduction in propulsion system weight is achieved, however, with a much larger diameter design, which was the result of investigations performed by the Aerodynamics and Propulsion teams [8, 9] that indicated a greater capture area was required to accommodate boundary-layer ingestion. This increase in size translates to a more favorable lapse rate in the conceptual models that allows the top-of-climb thrust to be maintained with a downsizing of the thrust capabilities at takeoff. Sixteen ducted fan electric propulsors are also distributed over the span of the wing in an under-wing mail-slot nacelle configuration, which contribute to an overall reduction in the TSFC of the propulsion system.

Table 6 presents the performance data for SUSAN V3. These results indicate that SUSAN V3 offers a 26.8% reduction in economy mission block fuel relative to the baseline aircraft. This is largely due to the 29.1% lower TSFC of the propulsion system and the weight savings achieved from the downsizing of the propulsion system. As with SUSAN V2, an overall savings in drag is also realized, which is due in part to the smaller wings of the SUSAN Electrofan.

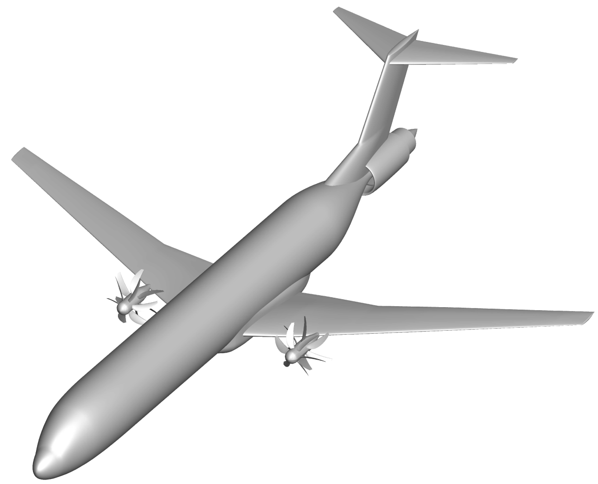

Fig. 5 A conceptual aircraft model of SUSAN V2.

Table 5 SUSAN V2: Conceptual sizing and analysis results.

Parameter	Baseline	SUSAN V2	Δ [%]
MRW [lb]	175,020	178,280	+1.9
OEW [lb]	92,810	111,960	+20.6
MZFW [lb]	139,810	157,960	+13.0
MFW [lb]	43,980	32,350	−26.4
Weight [lb]	141,850	157,880	+11.3
Drag [lb]	8,738	8,190	−6.3
TSFC [lb/lbf/hr]	0.621	0.500	−19.5
Block fuel (750 nmi) [lb]	10,680	8,486	−20.5

Weight, Drag, and TSFC are defined with respect to the start of cruise.

Table 6 Conceptual analysis results for SUSAN V3.

Parameter	Baseline	SUSAN V3	Δ [%]
MRW [lb]	175,020	173,260	−1.0
OEW [lb]	92,810	109,260	+17.7
MZFW [lb]	139,810	155,260	+11.1
MFW [lb]	43,980	28,370	−35.5
Weight [lb]	141,850	153,960	+8.5
Drag [lb]	8,738	8,080	−7.5
TSFC [lb/lbf/hr]	0.621	0.440	−29.1
Block fuel (750 nmi) [lb]	10,680	7,813	−26.8

Weight, Drag, and TSFC are defined with respect to the start of cruise.

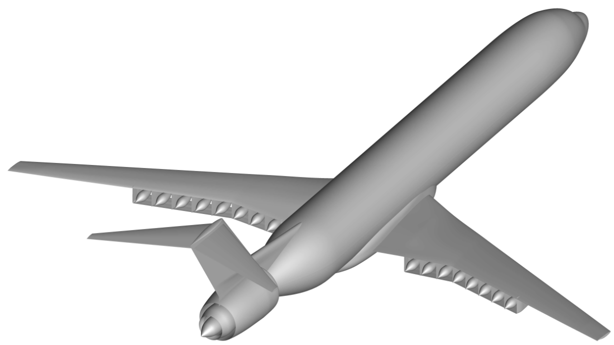

Fig. 6 A conceptual aircraft model of SUSAN V3.

V. Conclusions and Future Work

Increasing technology readiness levels associated with electrified aircraft technologies are opening a number of possibilities for new aircraft concepts that utilize hybrid electric propulsion systems. One such concept is the SUSAN Electrofan, which features a single hydrocarbon fuel-burning engine that not only provides 35% of the total thrust, but also generates and feeds power to wing-mounted electric propulsors that provide the remaining 65% thrust. Although EAP systems can come with high weight penalties associated with their power systems, thermal management systems, and batteries, current projections suggest that a net positive fuel burn advantage can be achieved. In this work, several different aircraft configurations were investigated for the SUSAN Electrofan concept, with results indicating a fuel burn reduction of 17.2-26.8% over a 750 nmi economy mission when compared to a 2005 baseline aircraft, assuming the required power densities can be achieved by the 2035-2040 time-frame.

Current efforts are focused on investigating the design challenges associated with the tail-cone thruster integration, through the application of CFD and aerodynamic shape optimization, with an emphasis on quantifying the impact of boundary-layer ingestion and inlet distortion. Work is also being done to investigate various distributed propulsion configurations for the wing-mounted electric propulsors, with considerations toward under-wing, over-wing, and trailing-edge configurations. Progress on these fronts are presented in Machado et al. [8] and Lee et al. [9]. Other efforts are focused on investigating the applicability of natural-laminar-flow wing technology [10], which has the potential to significantly reduce the viscous drag of the aircraft. Future work will incorporate the impact of these higher-order effects and advanced technologies on the system level sizing and analysis of the SUSAN Electrofan transport aircraft.

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