Aircraft Performance Simulation of 19-Passenger Commuter Aircraft: A Comparison between Normal and Amphibious Category

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ABSTRACT

This article presents calculating flight performance aspects and simulations of flight characteristics during a flight mission of the 19-passenger commuter aircraft, with a focus on the comparison between the normal and amphibious category aircraft. The objective is to analyse the flight characteristics (warm up, takeoff, cruise, descent, landing) and capabilities of both aircraft configurations. The significant difference between the two aircraft lies in the presence of float components in the 19-passenger Amphibious aircraft. The calculation process, both manual and simulation-based, involves utilizing constraint analysis and mission analysis to determine the weight fraction values for each flight phase. The results of the constraint analysis indicate that the amphibious category aircraft has higher values (35% - 80%) compared to the normal category aircraft. Meanwhile, the calculations using aircraft engine design (AEDsys) software reveal nearly identical reductions in weight fraction for each phase, with the amphibious category aircraft having a significant decrease in the final weight fraction of 0.87836. The fuel weight used is 2129 lb or 965.70 kg (8 barrels) with a range of approximately 372 nm or about 690 km and a flight time of approximately 2.4 hours. The drag polar values obtained using Parametric cycle analysis software at an altitude of 3,048 meters (10,000 ft) show that the normal category aircraft has a smaller coefficient drag (C_D) value. Further validation of the findings from this performance simulation study can be conducted through direct experimental validation during flight to be utilized for optimizing aircraft performance.

Keywords: *Aircraft; Amphibious; Engine; Performance; Simulation*

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Nomenclature

AR	Aspect Ratio
b	Span
C_D	Coefficient Drag
C_{DO}	Coefficient Drag at zero
C_L	Coefficient Lift
C_1	Coefficient in Specific Fuel Consumption
C_2	Coefficient in Specific Fuel Consumption
CRIT	Critical
D	Drag
e	Planform efficiency factor
g	Gravity
K_1	Coefficient in Lift-Drag Polar Equation
K_2	Coefficient in Lift-Drag Polar Equation
K'	Inviscid Drag in Coefficient in Lift-Drag Polar Equation
K"	Viscous Drag in Coefficient in Lift-Drag Polar Equation
kT_O	Velocity ratio at takeoff
L	Lift
M	Mach number
R	Rotation
S	Wing area
STD	Standard day
v	Velocity
t	Time
u	Total Drag to Thrust Ratio
W	Weight
T_O	Takeoff
TSFC	Thrust Specific Fuel Consumption
T_{SL}	Thrust Sea level
α	Installed Thrust Lapse
θ	Dimensional Static Temperature
ρ	Density
β	Weight fraction
Π	Mission leg weight fraction

Introduction

Indonesia, as one of the largest archipelagic countries located between 6° north latitude (NL) - 11° south latitude (SL) and 95° east longitude (EL) - 141° east longitude (EL), with a total of 16,766 islands [1] spanning a distance of 81,000 kilometres, requires an efficient transportation system that can effectively connect the small islands. A suggested approach for achieving this involves the development of amphibious aircraft [2]. Amphibious aircraft possess distinct structural characteristics and flight capabilities that offer numerous advantages over traditional aircraft. These aircraft are extensively utilized in various domains, including maritime transportation, search and rescue operations, medical evacuations, and combating forest fires [3]. Thus, the 19-passenger Amphibious aircraft was created as an advanced version of the 19-passenger aircraft as mentioned by Pinindriya et. al [4] as seen in Figure 1, utilizing turboprop engines to provide good short take-off and landing capabilities [5].

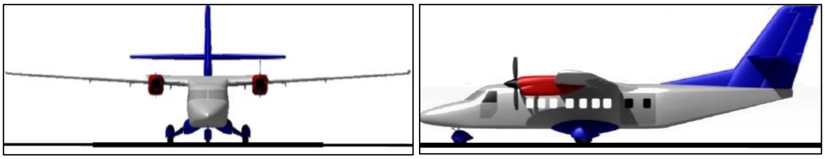

Figure 1: The 19-passenger aircraft [6]

The utilization of engines as the primary power source for airplanes also has a significant impact on both performance efficiency and fuel consumption. Among the engine options available, the turboprop engine stands out as a remarkably compact and lightweight alternative to traditional piston engines [7]. The growing global demand for environmentally and efficient engines for small aircraft transportation has led to an increased interest in employing turboprop engines [8]. Hence, the development of aircraft with minimal environmental impact represents a formidable challenge in the field of modern aviation [9]. Turboprop engines can be described as hybrid engines that combine the thrust of a jet engine with the propulsive force generated by a propeller. They share core engine components similar to other aerospace engines [10]. With these capabilities, the aircraft only requires approximately 368 meters [11] for the minimum runway length needed for takeoff, with the aircraft clearance ready for takeoff [12]. The noticeable difference between these two aircraft is the presence of floats in the 19-passenger Amphibious aircraft as shown in Figure 2, which enable it to float and take off and land on water [13]. Due to its ability to reach inaccessible locations, this type of aircraft significantly contributes to the transportation sector [14]. Additionally, the floats must be able to support the weight of the aircraft and withstand the load during landing [15].

When designing an aircraft, it is essential to calculate and analyse the flight performance at each stage of the flight [16]. This involves utilizing engine cycle and flight performance equations [17] while considering various input data such as Mach number, flight altitude at different mission points, payload, thrust-to-weight ratio, fuel, aspect ratio, aircraft performance, and required engine power. These calculations are typically performed through iterations for each flight path or mission profile [18]. Turboprop-powered aircraft are commonly used for low-subsonic transport purposes. Performance evaluation for such aircraft often focuses on takeoff and landing, climbing, and endurance as primary indicators. Turboprop aircraft are known for their low energy consumption and high efficiency [19]. According to research by Dinc et al. [18], flight scenarios encompass idle flight (0), taxi and takeoff (1), end of takeoff and initial climb- end of climb (2-3), start of cruise-end of cruise (4-5), descent (6), 30-minute hold at 1,500 feet altitude (7), and landing (8).

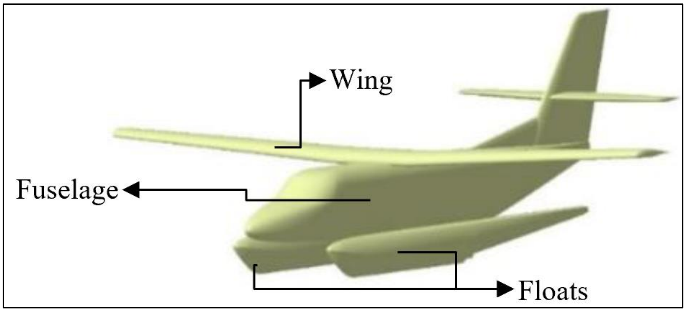

Figure 2: The 19-passenger amphibious aircraft (drawing) [15]

These factors, related to flight performance and mission profiles, including takeoff, climb, cruise, holding, descent, and landing [20], can influence the aircraft's overall flight performance. When considering the addition of floats, which weigh approximately 750-1000 kg, the takeoff distance and time required, as well as hydrodynamic forces generated, are affected. A 10% reduction in weight results in approximately a 17% decrease in distance, while a 10% reduction in thrust increases the takeoff distance by roughly 15% [14].

Small amphibious aircraft, with their smaller and less powerful engines and lower power loads, typically need longer distances for takeoff. According to the research mentioned by Tresnoningrum et al. [16], in the case of the 19-passenger Amphibious aircraft, simulations estimate a takeoff distance of 928 feet or 24 seconds with the float version 1A configuration. The increased distance is due to the presence of floats, which affect the hydrodynamics and require additional lift-off distance. Consequently, during the 24th second of the takeoff, the aircraft has not yet generated enough lift force due to inadequate wing lift.

Previous research conducted on the performance of amphibious aircraft primarily focused on flight performance estimation, takeoff simulations with two floats, hydrodynamic conditions, and a comparison of turboprop engine performance. However, a research gap regarding the increase in MTOW value in amphibious aircraft with floats, which can have an impact on the performance comparison between the standard 19-passenger aircraft and the amphibious version. Therefore, it is necessary to calculate constraints and mission analysis to enable the determination of the weight fraction reduction during each flight phase and to estimate the performance value for each aircraft.

Material and Method

Constraint analysis

The design process constraint analysis shown in Figure 3 begins by calculating or determining the minimum thrust-to-weight ratio (T_{SL}/W_{TO}) and wing loading values during takeoff (W_{TO}/S).

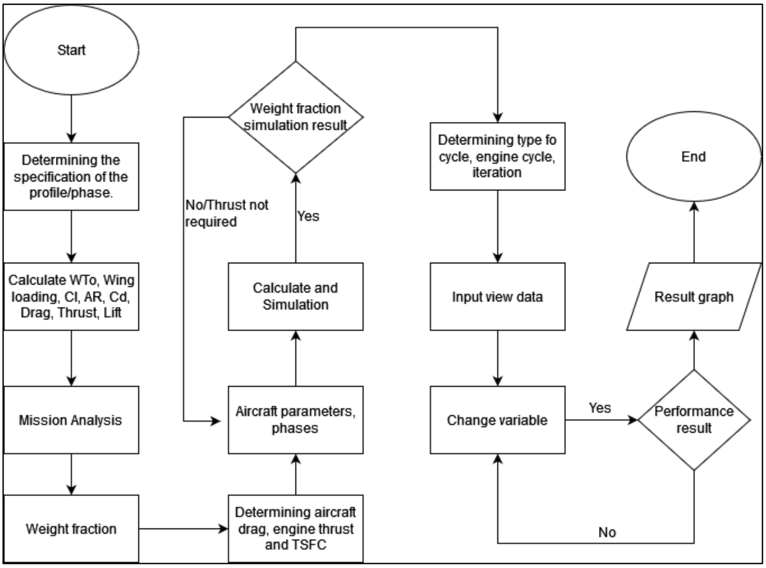

Figure 3: Flow chart process

Weight payload (W_P) is the sum of the passenger, cargo, and crew weight. Weight fuel (W_F) is the initial weight of the fuel that will be gradually consumed during the flight mission. Weight empty (W_E) is the weight of the basic structure of the aircraft plus all permanently installed equipment, such as engines, avionics equipment, landing gear, and passenger seats. Weight Takeoff (W_{TO}) is the sum of W_P, W_F, and W_E [17].

After obtaining the value of W_{TO}, the constraint analysis is calculated as follows:

$$Wing\ Loading = \frac{W_{TO}}{S} \tag{1}$$

Coefficient lift (C_L) can be determined as follows:

$$C_L = \frac{W_{TO}\ g}{½\ \rho\ V2\ S} \tag{2}$$

Aspect ratio (AR) as follows:

$$AR = \frac{b^2}{S} \tag{3}$$

Coefficient drag (C_D):

$$C_{DO} = C_{Dmin} + K''\ C_L\ min2 \tag{4}$$

$$C_D = K1\ C_L^2 + K2\ C_L + C_{DO} \tag{5}$$

Drag:

$$D = ½\ \rho\ V^2\ S\ C_D \tag{6}$$

Calculate the initial thrust value assuming no additional drag (R), so:

$$T = {}^{W}/_{g} + (D + R) \tag{7}$$

Lift:

$$L = ½\ \rho\ V^2\ S\ C_L \tag{8}$$

The initial beta (β) using the formula:

$$\beta = W_{TO}\ Cos\ \theta \tag{9}$$

Fuel reserves are normally stipulated in the mission-specific provisions already in the CASR (Civil Aviation Safety Regulation) governing passenger aircraft transport operations, in calculating the fuel fraction and mission profile like as shown in Figure 4.

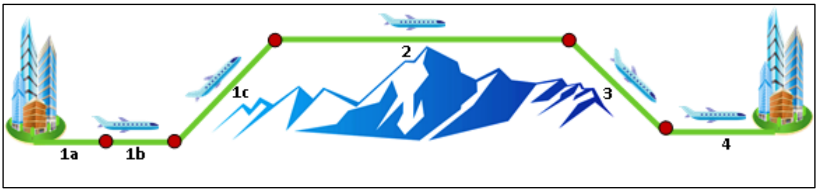

Figure 4: Mission profile

For phase A (warm-Up):

$$\prod_A = 1 - C_1\sqrt{\theta}\,\frac{\alpha}{\beta}\left({T_{SL}}/{W_{TO}}\right)\Delta t \tag{10}$$

where the value of $\beta 1 = \prod A$. For phase B (Takeoff acceleration):

$$\prod_B = exp\left\{\frac{-(C1+C2\,M)\sqrt{\theta}}{g0}\left(\frac{VTO}{1\text{-}u}\right)\right\} \tag{11a}$$

where the value of $\beta 2 = \prod B \times \beta 1$ (11b)

For phase C (Takeoff Rotation):

$$\prod_C = 1 - (C_1 + C_2 M)\sqrt{\theta}\,\frac{\alpha}{\beta}\left({T_{SL}}/{W_{TO}}\right) t_R \tag{12a}$$

where the value of $\beta\, 1 - 2 = \prod A \times \prod B \times \prod C$ (12b)

In this phase, the formula used is:

$$\prod_{3\text{-}4} = exp\left\{-\frac{\sqrt{4CDOK1}}{MCRIT}\;\frac{(C1+C2\,MCRIT)\Delta S34}{a\,STD}\right\} \tag{13a}$$

where the value of $\beta 2 - 3 = \prod 3\text{-}4 \times \beta\, 1 - 2$ (13b)

In the descent and landing phase, the value of $\prod 3 - 4 = 1$.

and for the value of $\beta\, 3 - 4 = \prod 3 - 4 \times \beta 2 - 3$ (14)

The equations used in these calculations are theoretical equations, and the purpose of using the AEDsys software is to calculate initial estimates of the constraint analysis and mission analysis values. In this case, the AEDsys software was using to estimate the value of beta (β) for each phase in the mission analysis. The process involves determining the engine type, specifying the number of phases to be analysed, and inputting the aircraft's parameter values. The software then provides the beta values for each phase. The PARA software is utilized to estimate performance parameters, specifically specific thrust and thrust specific fuel consumption. It takes into design limitations such as maximum turbine temperature and achievable component efficiency.

Results and Discussion

Design specification

The initial step that needs to be known in this research is to determine the aircraft profile, and the following in Table 1 are the estimate specifications for the aircraft profile to be designed:

Table 1: The specifications of aircraft

Specification	
Aircraft type	Commuter
Engine	PT6A-42
Passengers	19 people plus 2 crew members with an estimated weight of each passenger at 80 kg
Cruise speed	388,92 kmh
Wing area (*S*)	41.5 m^2
Wing span (*b*)	19.5 m

Constraint analysis

The estimated takeoff weight based on a review of aircraft with similar capabilities and missions. The takeoff weight is a combination of the payload, required fuel, and structural weight. In Table 2, it can be seen that the constraint analysis has a large difference in values (35%-80%) for amphibious aircraft.

Table 2: The constraint analysis values

Constraint analysis	Normal category	Amphibious category
W_{TO}	7030.6817 kg	7937.8665 kg
W/S	169.4202 kg/m^2	191.2935 kg/m^2
C_L	0.23	0.32
C_D	0.027	0.075
AR	9.16	
D	255851.6534 N	717214.5254 N
T	257992.8494 N	7196320.0464 N
L	2220107.4 N	3049625.8653 N

Mission analysis

For the calculation of weight fraction (β) for each phase, the mission profile shown in the Figure 4 will be used. The calculations using Equation (10)-(14) reveal, as depicted in Table 3, that the weight fraction values remain constant during the warming-up phase. However, discernible variations emerge from the takeoff acceleration phase through to landing. To summarize, the flight phase of the amphibious aircraft experiences a more pronounced reduction in weight fraction. The weight fraction (β) values for each phase are detailed in Table 3.

In order to optimize the range of a particular aircraft, as mentioned by Voicu and Fuiorea [21] are conducting a study that focuses on achieving high true airspeed and low fuel consumption. The study will calculate the influence of stock weight on fuel consumption and range during different flight phases.

Table 3: Weight fraction values based on calculations

Phase	Wight fraction (β)	
	Normal category	Amphibious category
Warm Up	0.96001	0.96001
Takeoff acceleration	0.95994	0.95984
Takeoff rotation	0.95632	0.95622
Climb/acceleration	0.94217	0.94217
Subsonic cruise	0.90102	0.90093
Descent and landing	0.90102	0.90093

AEDsys software

Before conducting calculations using the AEDsys software, there are several parameters that need to be adjusted according to the desired calculation design. The goal is to estimate the value of the mission analysis in accordance with the aircraft specifications, so that the obtained weight fraction value can be accurate.

Normal category aircraft

From all the calculations normal category aircraft using AEDsys software, starting from Phase 1a Warm Up to Phase 4-5 Descend and Landing, the summary of calculations is obtained as shown in Table 4.

Based on the calculations for a normal category aircraft using AEDsys software, the final weight fraction obtained is 0.89182, which indicates the reduction in weight equal to the weight of fuel used. In this calculation, the fuel used weighs 1677 lb or 760.67 kg (approximately 6.5 barrels). The aircraft covers 690 km (equivalent to a flight to Surabaya) with a flight time of 8661.2 seconds or 2.4 hours. The aircraft landing weight is 13823 lb, equivalent to 6270 kg. Comparing this value to the aircraft's performance specification of a maximum landing weight of 6940 kg.

Table 4: Summary of results per phase normal category aircraft

Leg	Name	Beta initial	Beta final	Time (sec)	Distance (km)
1	1-2 A	1.00000	0.95497	1200.00	0
2	1-2 B	0.95497	0.94355	110.5	7.0005
3	1-2 C	0.94355	0.94258	30.0	3.796
4	2-3	0.94258	0.93328	356.8	30.6876
5	3-4	0.93328	0.89221	6239.4	613.7157
6	4-5	0.89221	0.89182	634.5	34.8176

Amphibious category aircraft

The calculation results for an amphibious category aircraft using AEDsys software, from phase 1a Warm Up to phase 4-5 Descend and Landing, are summarized in Table 5.

Table 5: Summary of results per phase amphibious category aircraft

Leg	Name	Beta initial	Beta final	Time (sec)	Distance (km)
1	1-2 A	1.00000	0.95497	1200.00	0
2	1-2 B	0.95497	0.95225	29.6	1.7038
3	1-2 C	0.95225	0.95129	30.0	3.4447
4	2-3	0.95129	0.93466	637.6	44.1887
5	3-4	0.93466	0.88256	6079.4	600.5665
6	4-5	0.88256	0.87836	634.5	34.8176

The result of the calculation for the Amphibious aircraft category using the AEDsys software is a final weight fraction of 0.87836. This reduction in weight using the AEDsys software is equal to the weight of fuel used. In this calculation, the weight of fuel used is 2129 lb or 965.70 kg (8 barrels). The rotational behaviour of amphibious aircraft has been projected and analysed. The findings indicate that with full rudder deflection, the rotation radius measures 3159.1 meters. However, when the engine differential and rudder operate simultaneously, the rotation radius is significantly reduced to 1216.8 meters [22]. The aircraft has a flying distance of 684.72 km and a travel time of 8611.1 seconds or 2.4 hours. The aircraft landing weight is 15371 lb, which is equivalent to 6972 kg.

The comparison chart of calculation vs software in the Normal Category Aircraft as shown in Figure 5 indicates a significant difference in the takeoff acceleration phase, with a value difference of 0.0164. This discrepancy arises due to the variation in inputs. However, the trend line for the decrease in the weight fraction is considered to be the same for both manual and software calculations.

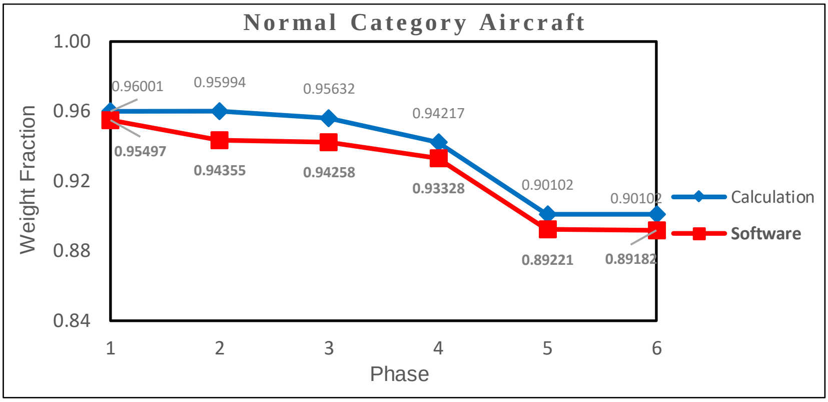

Figure 5: Weight fraction vs phase for normal category aircraft comparison (calculation and software)

In Figure 6, comparison chart illustrates the differences between manual and software calculations for the amphibious category aircraft. Similar to Figure 5, the main distinction in the above graph lies in the descend and landing phase, with the largest difference in value being 0.0226. This discrepancy is due to the software calculation, which takes into account inputs such as initial altitude, initial velocity, initial Mach number, final altitude, final velocity, and final Mach number, resulting in more specific values. In contrast, the manual calculation only considers the initial weight fraction value as an input.

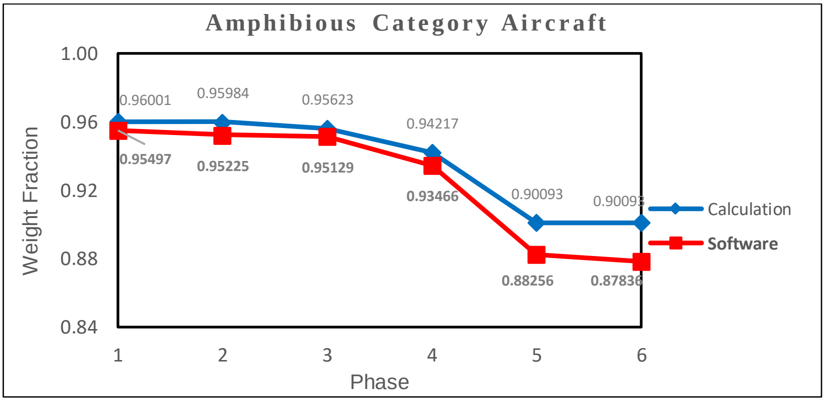

Figure 6: Weight fraction vs phase for amphibious category aircraft comparison (calculation and software)

The reduction in Beta (β) or weight fraction in each phase of an aircraft depends heavily on the aircraft specifications, mission, operations, distance, and flight time. As shown Figure 7, it appears that the amphibious category aircraft exhibits greater weight fraction reduction (final), but in some early phases, the normal category aircraft experiences more significant reductions. These variations can be attributed to the specific characteristics and requirements of each aircraft category, as well as the specific mission profiles and operational considerations.

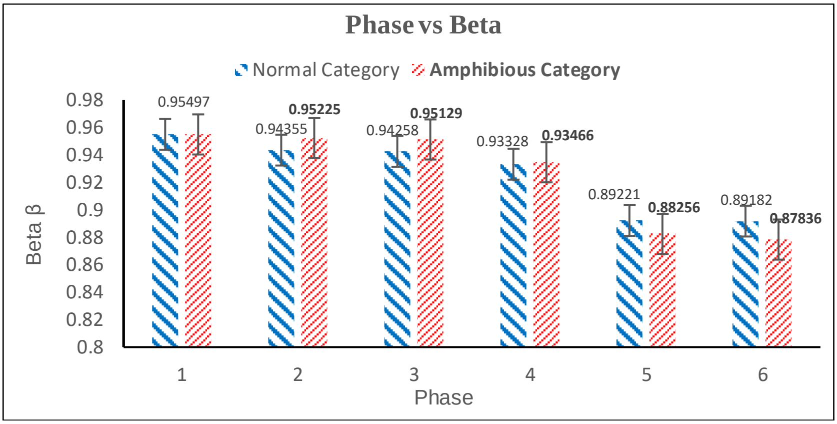

Figure 7: Phase vs Beta comparison between normal and amphibious category aircraft

Flight time using the AEDsys software in Figure 8 is approximately 2.4 hours, with the longest duration being during the cruise phase, taking around 2 hours. The most noticeable difference is observed in the climb/acceleration phase, where it takes the normal category aircraft 5.9 minutes to reach an altitude of 3048 m (10,000 ft), while the amphibious category aircraft requires 10.6 minutes. This difference is attributed to the amphibious aircraft being heavier, having a higher drag coefficient (C_D), and requiring a sufficient Mach number for the climb.

The smaller the drag coefficient (C_D), the more aerodynamic and efficient an aircraft is in overcoming the generated drag force. Figure 9 shows the Drag polar at 3048 meters altitude, where the normal category aircraft has lower CD values (0.0537-0.0559) compared to the amphibious category aircraft (0.102-0.104). This difference occurs due to variations in parameters and aircraft configurations. As a result, at 3048 m (10,000 ft) altitude, the amphibious category aircraft consumes more fuel 413.6308 kg (911.9 lb) compared to the normal category aircraft 288,7569 kg (636.6 lb).

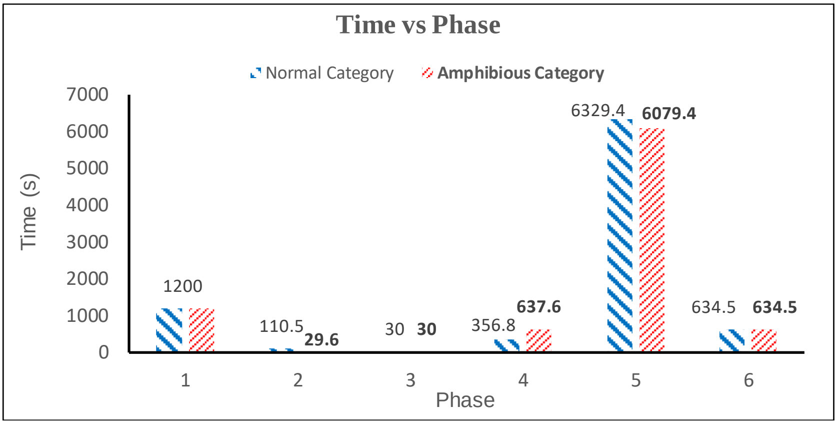

Figure 8: Time vs Phase

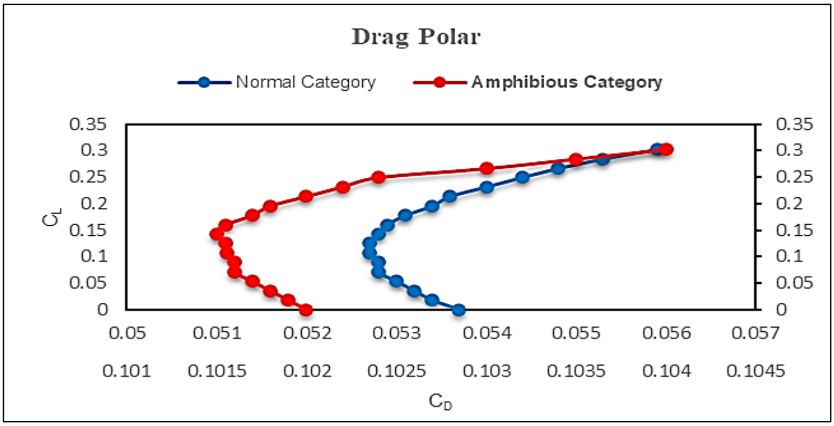

Figure 9: Drag Polar at 3048 m

Parametric cycle analysis

After completing the calculations with the AEDsys software, the next step is to continue the analysis using the Parametric cycle analysis (PARA) software to determine the estimation of Performance Parameters, specifically the values of specific thrust and thrust specific fuel consumption, at the altitude previously used in the AEDsys software.

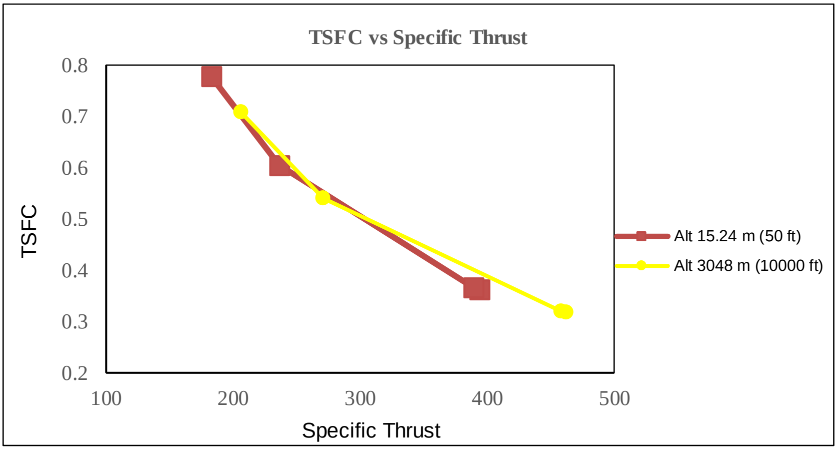

Figure 10: TSFC vs specific thrust at altitude 15.24 m and 3048 m

The larger the specific thrust, the smaller the Thrust Specific Fuel Consumption (TSFC). In Figure 10, altitude of 3048 meters (10,000 ft) the maximum value of TSFC is 0.7 (lbm/hr)/lbf, and the maximum value of specific thrust is 460 lbf/(lbm/sec). By comparing variations in altitude, it can be observed that at lower altitudes, the value of TSFC will be greater compared to higher altitudes, while the value of specific thrust increases with higher altitudes.

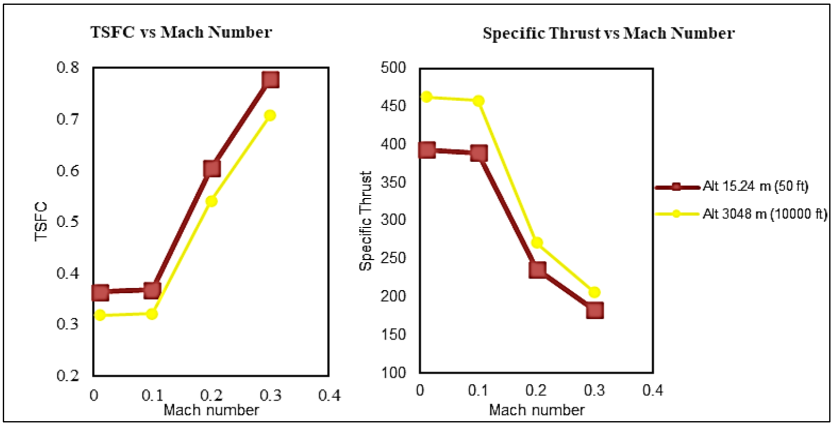

Figure 11: Specific thrust vs Mach number at altitude 15.24 m and 3048 m

The performance exhibited by the aircraft through the TSFC and specific thrust vs Mach number comparison shown in Figure 11 is as follows:

- As an aircraft's Mach number increases, its specific fuel consumption (TSFC) also increases. This means that the aircraft requires more fuel to fly at higher speeds.
- At lower Mach numbers, the aircraft's specific thrust is higher, meaning that it produces more thrust for a given mass flow rate. Conversely, at higher Mach numbers, the aircraft's specific thrust is lower, meaning that it produces less thrust for a given mass flow rate.

Conclusion

Flight characteristics primarily depend on four parameters: payload, range, wing loading, and power loading [23], where the results of the constraint analysis indicate that amphibious category aircraft has higher values (35%-80%) compared to normal category aircraft.

Overall, the weight fraction reduction values for each phase are almost the same. The fuel system plays a critical role in aircraft operations, as it is responsible for providing the appropriate amount of fuel to the aircraft engine in various operational scenarios, including both flight and ground operations. It is regarded as one of the essential and intricate components of an aircraft [24]. However, in the case of amphibious aircraft, both manual calculations (0.90093) and AEDsys software calculations (0.87836) show a greater reduction in the final weight fraction. The fuel weight used is 2129 lb or 965.70 kg (equivalent to 8 barrels) with a range of approximately 372 nm or about 690 km and a flight time of approximately 2.4 hours. Examining the aircraft's performance specifications, the maximum landing weight is 6940 kg. However, the calculated aircraft landing weight using the software is 15371 lb, which equals 6972 kg, exceeding the maximum landing weight by 32 kg.

The drag polar at an altitude of 10,000 ft differs for normal category aircraft and amphibious category aircraft. The normal category aircraft has a smaller CD value (ranging from 0.0537 to 0.0559) compared to the amphibious category aircraft (ranging from 0.102 to 0.104). The maximum values for TSFC and Specific Thrust are 0.7 (lbm/hr)/lbf and 460 lbf/(lbm/sec), respectively. An increase in Mach number leads to an increase in TSFC value. To validate the findings from this performance simulation study, further experimental validation during actual flight is recommended. This would provide a basis for optimizing the aircraft's performance.

Author contributions

H: conceptualization, methodology, data, formal analysis, software, visualization, writing–original draft, writing–review and editing. MA: supervision, conceptualization, methodology, writing–review and editing.

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Conflict of Interests

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