18. Twin Puffin – Distributed Propulsion Bush Plane

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1. Introduction

Bush planes, aircraft capable of taking off and landing in short distances, play a vital role in supplying communities in remote areas with goods as well keeping them connected with the rest of the world. Current bush planes are mostly based on aircraft designed in the 1940's, the most iconic one being the Piper Cub. Partly due to their age, bush planes are loud and polluting. It is sad and paradoxical that the aircraft flown in the great outdoors damage nature so much.

To combat this, DSE Group 12 designed a bush plane that uses distributed propulsion and is able to reduce both noise and greenhouse gas emissions by more than 50%. The aircraft is a multitalent that bridges the gap between the urban landscape (where it can operate thanks to its low noise) and the great outdoors (where it can operate thanks to its very short take-off and landing distances). It is built for the market and has thus been designed with tourism, transportation, and medical use in mind. Consequently, the aircraft is able to fit up to four people and can carry a stretcher.

2. From Market Analysis to Requirements

A market analysis was performed, both to place the aircraft in a target market and derive the accompanying requirements. This market analysis investigated how the aircraft should be designed in order to be a compelling option for the target customers. Due to the complexity of this endeavour, only preliminary attempts were made to estimate the market. These attempts included an assessment of the current bush plane market, an examination of the prospects for general aviation as a whole, and an analysis of the competition. The analysis revealed a set of requirements that would allow for expansion of the conventional market and use cases.

While the primary objective of the project is to provide a bush-plane type aircraft, the aircraft will also be suitable for performing other roles. For this reason, it is not only compared to other bush planes, but to aircraft in general aviation overall.

To assess the competition for the aircraft, the general aviation market was investigated using FAA reports on general aviation. First, it was estimated that the US has approximately 200 000 active aircraft, of which 12.5% are 'experimental aircraft' including bush planes. Thus, a considerable market exists, and significant demand can be suspected. Secondly, the reports showed that 55% of the active general aviation aircraft are over 40 years old. This hints at a significant number of aircraft becoming obsolete in the upcoming years, either due to their outdated performance or their inability to adhere to new emission regulations.

The number of aircraft produced was also investigated, based on which it was possible to estimate anticipated aircraft sales. As the yearly total number of general aviation aircraft sold is around 1250 units and the sales of a new product lacking recognition can be estimated to be around 5%, it is anticipated that 60 units can be sold per year. This market share is expected to increase, especially if stricter environmental regulations are introduced.

While the reduction in gas emissions provides advantages for upcoming stricter regulations, the reduction in noise emissions opens up completely new markets. The low noise of the aircraft means it can operate in urban environments (which conventional bush planes certainly cannot). This means that the aircraft can bridge the gap between urban centres and the great outdoors.

The market analysis also focused on finding values for the requirements on the usable mass (payload mass + fuel) and number of passengers. This analysis showed that there is slim demand for aircraft with only two seats and that most aircraft sold have a usable mass between 410kg and 500kg. Hence, the requirements were redefined to account for 500kg usable mass and four seats.

Based on the current market and the specific benefits that the distributed propulsion bush plane will offer, three main potential use cases for the project were identified: transportation in remote areas, medical services and tourism in wilderness. In these three use cases, the very short take-off and landing performance, low emissions (gasses and noise) make the aircraft especially competitive.

The market analysis then defined the following set of requirements:

- The aircraft shall have a usable mass of 500kg.
- The aircraft shall be able to fit four seats (or two seats and a stretcher)
- The aircraft shall have a take-off roll of less than 100 m.
- The aircraft shall have a landing roll of less than 100m.
- The aircraft shall have a cruise speed of over 100 kts.
- The aircraft shall have a design range of over 500 Nmi.
- The aircraft needs to be 80% recyclable.
- The aircraft shall reduce CO_2 emissions by 50% with respect to the *Piper Cub* aircraft.
- The aircraft shall reduce the noise pollution by 70% with respect to the *Piper Cub* aircraft.

3. Conceptual Analysis

The design process of the aircraft differs from conventional aircraft design processes in three main ways. For one thing, the aircraft characteristics are strongly influenced by the cutting-edge technology of distributed propulsion. Consequently, this meant that the aircraft performance was analysed using a specially designed simulation, rather than the typically used equations. To determine not just a good, but the best aircraft design, an optimisation process was designed and employed.

Distributed propulsion

A major characteristic of this aircraft is the use of distributed propulsion, which leads to lift augmentation. The placement of propellers along the wing leading edge energises the flow over the lifting surfaces behind it, thereby leading to higher lift than could otherwise be achieved at the same flight conditions. The lift augmentation is created mostly by the high-lift engines on the middle of the wing rather than the two wingtip motors. Constrained by the total thrust and the available space on the wing, the number and size of these high-lift engines are optimised to maximise the total lift increase. During take-off and landing, this system provides significant increases in the maximum wing lift coefficient, further improving the aircraft STOL performance.

Simulation

Due to the unconventional nature of the aircraft, standard mathematical equations for aircraft performance analysis are not applicable. To analyse the performance of the aircraft with sufficient accuracy, a discrete two-dimensional simulation of the aircraft was derived and implemented. A state machine was used to control the different physics, available thrust, and controller behaviour during the flight profile. For example, during cruise, there is no normal force, the cruise motors are on, and the controller moves the aircraft to a flight path of zero degrees at the cruise speed. This simulation, amongst other parameters, estimates landing and take-off distances, the energy required during climb, and the power required during cruise. It also verifies that the aircraft is longitudinally controllable during the entire flight.

Optimisation

To ensure that the optimal design would be found, an optimisation process was set up. A tool was designed that takes in high level design parameters, such as wing area and aircraft length, and returns an aircraft design and performance. Based on a statistical analysis of aircraft retail prices, an objective function then estimates the customer value that this aircraft would provide. Depending on the score returned by the objective function, the Nelder-Mead optimisation changes the high-level design inputs to maximise the score. At the end of the optimisation run, the final design maximises the objective function, and thus provides the highest value to the customer.
To find the absolute global maximum, and not a local maximum, the optimisation process was run for multiple initial high-level parameter sets. Afterwards, all aircraft designed during all optimisation processes are compared, and the one with the highest absolute score is selected.

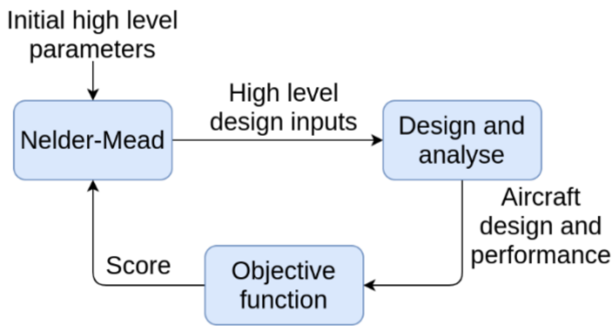


Figure 18.1: High level optimisation structure.

4. Final Design Overview

Inspired by nature, the bush plane is named the *Twin Puffin*, with ‘Twin’ referring to the distinctive twin-boom empennage of the design, and ‘Puffin’ coming from the bird with a stubby display who is a master of short take-off and landing on ocean cliff-sides. The final design of this aircraft is shown in Figure 18.2, together with the main characteristics of the *Twin Puffin*, which are presented in Table 18.1.

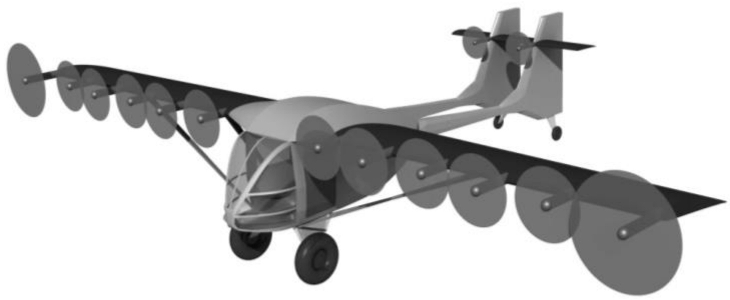


Figure 18.2: Final design of the *Twin Puffin*.

Table 18.1: Main specifications of the *Twin Puffin.*

Parameter	**Value**	**Unit**
Payload Mass	400	kg
Operating empty mass	1201	kg
Maximum take-off mass	1781	kg
Seats	4	-
Wing Area	28.1	m^2
Wing Span	15	m
Aircraft Length	9	m
Cabin Length	4	m
Cabin Width	1.3	m
Cabin Height	1.4	m

Energy Source

In order to reduce noise and emissions without hindering the performance of the aircraft, a diesel-electric hybrid system, consisting of an Internal Combustion Engine (ICE) and batteries, was found to be the most suitable option. To provide sufficient electric energy while achieving the lowest possible environmental impact, the ICE was sized for cruise and will at all times operate at its peak efficiency setting. The batteries will provide all of the required additional power when it is needed (for instance during take-off and climb).

Propulsion

The *Twin Puffin* propulsion system is composed of twelve engines: ten high-lift propellers, and two wing-tip propellers. The former are used during take-off and landing to provide lift augmentation, while the latter are used for efficient operation during climb and cruise.

Structures

The fuselage of the aircraft was designed such that it could fit up to four seats, and also be able to carry a stretcher. The side and front views of the fuselage can be seen in Figure 18.3. One of the key characteristics of the cabin is its transparent cockpit, which allows for better visibility.

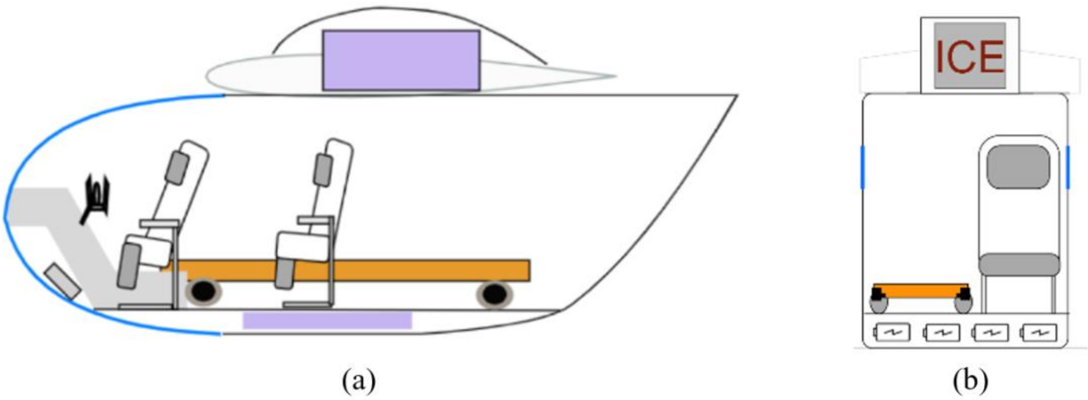


Figure 18.3: Side-view (a) and cross-section (b) of the fuselage.

The material selected for the main structure of the aircraft is flax fibre composite with a bio-epoxy matrix. This choice enhances the sustainability characteristics of the aircraft, as flax absorbs CO_2 while growing, and combined with bio-epoxy, it is easily recyclable.

Aerodynamics

The aerodynamic performance of the *Twin Puffin* is in part enabled by the properties of the selected USA 40-B airfoil, which provides the desired design lift coefficient during cruise and allows for a high clean maximum lift coefficient. The achievable lift coefficient is raised to 2.6 using single slotted flaps and, during landing at sea level, is more than doubled to a value of 5.32 using the leading edge lift augmentation propellers. During landing and at higher altitudes, almost as high lift coefficients are achievable. These lift augmentation effects are seen in Figure 18.5, which shows the lift distribution over the aircraft half-wing for different configurations. The vertical dotted lines indicate the locations of the high lift propellers.
Considering drag, the aircraft benefits from its use of outboard-rotating wing tip engines during cruise. These reduce the strength of the wing tip vortex, thereby increasing the effective aspect ratio by 11% and reducing induced drag. This allows the *Twin Puffin* to fly efficiently at a lift-to-drag ratio of 12.2 during cruise.

Stability & Control

The empennage of the *Twin Puffin* has been designed such that stability and controllability of the aircraft are ensured at all times. Because of the low stall speed enabled by the lift augmentation, a conventional reasonably-sized horizontal tail is not able to provide full controllability of the aircraft. Hence, two extra propellers were added on the empennage. These blow the tail, augmenting the lift allowing for a smaller horizontal tail area.
To control the aircraft, an augmented autopilot system is used. This system uses conventional rods and wires for the direct control lines between the pilot and control surfaces, but also includes clutched electric motors that allow for a computer-controlled enhancement of the pilot inputs.

5. Design Assessment

Once the design is presented, its performance, cost, and sustainability characteristics can be analysed. Then, its special features can be characterised and it can be compared to the other general aviation aircraft.

Performance

The aircraft performance was estimated using the aforementioned simulation. The take-off distance (at an ISA altitude of 2500ft) is 65 m. The landing distance at the same altitude is 95m, and with a reverse thrust of 900N (20% of landing thrust) it further reduces to 23 m. The aircraft is designed to cruise at 106 knots and, when loaded at its design point, has a range of 1246km. Note that these values go beyond the requirements that were found in the market analysis. This is because the objective function found those performance values that were technically possible and would maximise the predicted aircraft value.

Table 18.2: Performance characteristics of the *Twin Puffin*.

Parameter	Value	Unit
Take-off distance (2500ft)	65	m
Landing distance (2500ft)	95	m
Landing distance with reverse thrust (2500ft)	23	m
Cruise speed	106	kts
Design range	1246	km
Operating cost (800h/year)	150	USD/hr
ICAO noise level	83.6	dBA
CO_2 emissions	232.7	g/pax/km

Cost

For a customer, both the retail price and the operating cost are of great importance. Based on the statistical market analysis, the achievable retail price is estimated around 350K USD. Further estimating the manufacturing and development costs statistically, the breakeven point is found at the 318th aircraft. After 500 aircraft, the total profit is expected to lie at 33M USD. For customers, the operating cost is even more important than the acquisition cost. Private owners flying 200 hours a year will find an operating cost around 440 USD/hr. For flight schools, flying around 800 hour/yr, this hourly cost is reduced to just 150 USD/hr.

Noise

A conservative estimate of the noise level was obtained through the use of empirical formulas that take into consideration the noise levels of the engine exhaust, propellers, and the fuselage. Additionally, it was confirmed that, for all possible aircraft configurations the ICAO noise certification requirements are met. The high reduction in noise over comparable aircraft is due to the decreased propeller diameter as well as the increased number of blades.

Emissions

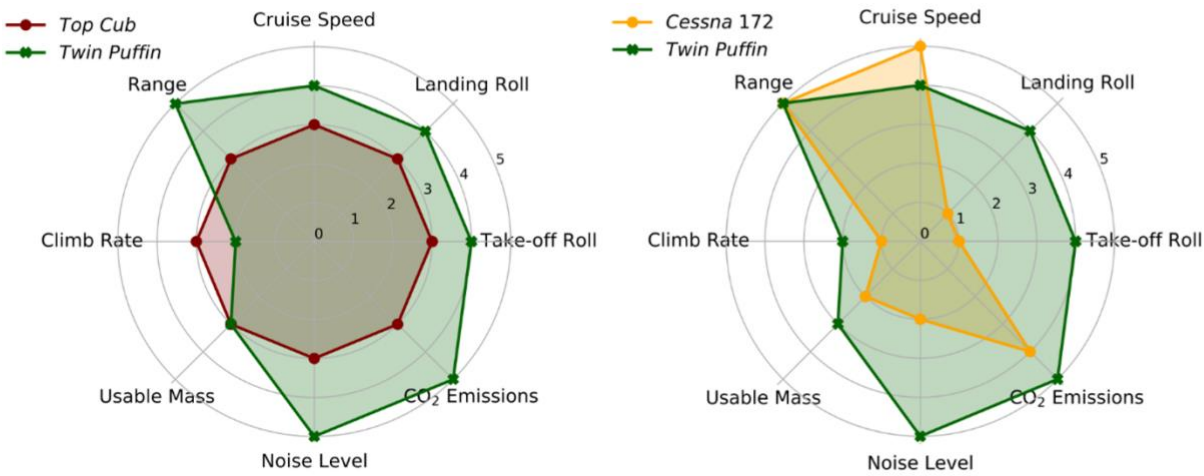
Having a reciprocating diesel combustion engine means there will be greenhouse gas emissions based on fuel consumption. Based on the energy requirements derived from performance characteristics, the fuel mass required was calculated to be 106kg and converted into CO_2 and NO_X emission masses. The *Twin Puffin* produces 56.8 and 0.23 grams per passenger per kilometre of CO_2 and NO_X respectively. This is approximately 75% less than the emissions of the comparable *CubCrafters Top Cub* and is due to the hybrid power source and highly efficient overall design.

Special features

The *Twin Puffin* has a number of special features enabled by the combination of electric motors and augmented autopilot system. For example, when the aircraft is on the ground and the accelerometer measures a pitch angle of less than -10deg, the aircraft turns on reverse thrust, helping to prevent a tip over. The electric motors are also used to produce differential thrust, which allows for more efficient and comfortable flying. The augmented autopilot system furthermore opens up the possibility of remote piloting, which increases the payload mass that can be carried and opens up new markets.

Comparisons with competitors

From the radar charts in Figure 18.6, it can be seen that the *Twin Puffin* outperforms its main competitors in terms of performance. Here the aircraft is compared to the *Cubcrafters Top Cub* and the *Cessna 172 Skyhawk.*



(a) (b)

Figure 18.4: Radar charts showing the comparison between the *Twin Puffin* and (a) the *Top Cub* and (b) the *Cessna 172 Skyhawk.*

6. Conclusion & Recommendations

The aim of the project was to create a market-competitive bush plane that lives up to modern standards of sustainability. This was done by following systems engineering principles and using verified design approaches. The result is the state-of-the-art, high performing *Twin Puffin*, which outperforms the current market and fulfils all stakeholder requirements.

After performing a market analysis, the use cases of the aircraft were determined to be transportation, emergency medical services and tourism. Furthermore, another analysis was done towards markets, such as urban transport, that will open up for quiet STOL aircraft. It can be concluded that the *Twin Puffin's* anticipated market share is bigger than initially expected.

The design process was divided into subsystem design methods, which were then combined in one central iteration and optimization program. The central code optimises the aircraft parameters with respect to a specially defined statistical objective function that takes the aircraft performance parameters as inputs. This optimisation then leads to the final design, which is characterised by its large wings with distributed electric propulsion, as well as by its twin boom empennage that enables easy aft loading.

The final design was assessed in terms of its abilities, its sustainability and its performance relative to the main competitors on the market. The aircraft was found to have a retail price of 350K USD, is expected to generate a total profit of 33M USD, and can be flown for 150 USD/hr when flying 800 hours per year.

In addition to these conclusions, a few recommendations can be made for the continuation of the development program.

- The developed software and models are verified, but not **validated**. To ensure the precision and correctness of the tools, they must be validated.
- A more thorough **market and cost analysis** should be performed in order to increase the confidence in the predicted market for the *Twin Puffin*.
- **Auxiliary systems** should be designed in more detail. So far, the digital aspects of the aircraft have been described, but they should be further designed by specialists.
- The designed aircraft is already a generally certifiable concept, but as the design of subsystems progresses, specific **certification** processes should be taken into account.
- A large part of the aircraft has been designed through software by implementing parametric design tools, which allows for rapid changes in design. This is important as this project considers a large design space. Therefore, **digital engineering** should be continued throughout the project to find the optimal design.