AN OPEN-ROTOR DISTRIBUTED PROPULSION AIRCRAFT STUDY

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ABBREVIATIONS

CFD	Computational Fluid Dynamics
CL	Lift Coefficient
OHS	Outboard Horizontal Stabilizer
STOL	short take-off and landing
TSR	Tip to Speed Ratio
USTOL	Ultra short take-off and landing

1. ABSTRACT

THE EU-funded SOAR project[‡] analyzed the high-lift efficiency of an open-fan wing design by systematic variation of fan blade count and angle. The research project built a cross-flow fan propelled wing section and investigated it by means of fluid dynamic simulation and wind tunnel testing. The experimental data resulting from the wind tunnel model were used to generate non-dimensional parameters which were used to scale data for the full-scale SOAR wing section. Preliminary aircraft design studies have been carried out after mission and market analysis, plus an evaluation of direct operating costs.

2. BACKGROUND

The open-fan wing is a unique aircraft whose lift and thrust derives from the distributed propulsion from a rotating horizontal fan mounted on a supporting wing structure. Advantages include enhanced low speed efficiency, ultra-short take-off and landing from difficult and limited terrain, no stall while powered, stable flight and forecasted simple and economical maintenance and construction. A series of successful scaled model test flights have provided proof of concept of the internationally patented technology. The SOAR team, led by DLR, and involving experienced professionals in computational analysis (VKI), academic systems engineering (USAAR), in collaboration with the originator and founder-developer of the open-rotor technology (FANWING), have undertaken a first in-depth European-based investigation into this promising innovation. The two year project predicts a substantial range of environmentally important and sustainable applications, some of which are targeted in detail as part of this initial exploration. Project objectives are to find and evaluate suitable markets and missions for this technology, build and test an open-fan wing wind tunnel model to determine the optimal blade profile and cavity position, and verify the open-fan wing's aerodynamic performance using state-of-the-art aircraft design and computational flow simulation codes.

3. RESEARCH QUESTIONS

The SOAR project comes around 18 years after the initial FanWing experiments were conceived and conducted and the first small scale test models flew. These early experiments revealed the STOL potential of the FanWing. This potential, however, needed to be explored on larger scale along with a potential business case. The critical research questions SOAR is designed to address are as follows:

3.1. Scaling to larger fan diameters

Does the performance of the FanWing scale up? Specifically, does the vortex inside the fan remain at larger diameters? A vortex was found inside one of the earlier test models of the SOAR project in 2014.

It is hypothesized that this vortex contributes to the high maximum lift coefficients between 3 and 15 depending on TSR relative to the maximum lift coefficients between 3 and 5 of a fixed wing aircraft with a flap-slat high lift system.

The higher lift coefficient reduces take-off and landing field and the lowest maneuvering flying speed which are key competitive advantages for the FanWing configurations. A set of wind tunnel tests and unsteady CFD simulations with larger fan diameter were conducted to gain insight into this question.

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3.2. Required operational power

What is the real power input required to operate the FanWing? The power input is a critical technical characteristic that affects economic competitiveness and is needed to validate the FanWing's performance claim of providing a low cost, low speed maneuvering solution that lies between a helicopter and a fixed wing aircraft.

If the power required exceeds that of a helicopter for the same payload, then it would be more economical to continue to use helicopters and fixed wing aircraft in the FanWing's target markets. As with research question 3.1, wind tunnel tests and unsteady CFD simulations were conducted to gain insight into this question.

3.3. Economic competitiveness

How economically competitive is the FanWing in the identified target markets?

Crop Dusting and Firefighting were identified as the most promising existing markets [1]. While they are non-traditional markets for typical aircraft design activities, both markets show a willingness to pay premiums for low speed maneuvering and have an adequate combination between the premiums and production volumes to justify a new aircraft program.

The performance predictions from the wind tunnel and CFD tests are combined with 3-D aircraft configurations designed for each mission to be used as inputs into an economic analysis that evaluates the competitiveness compared to the leading incumbent in each market.

4. Scaled Performance of the FanWing

The demonstrated performance of the FanWing from the SOAR project can be characterized as inconclusive. In the SOAR project, three tests were performed to measure FanWing performance at larger fan diameter than previous tests: an unsteady 2-D CFD test with a diameter of 50cm, a 3-D wind tunnel test in the VKI wind tunnel with a diameter of 50cm, and a bench test with largest diameter 60cm.

The presence of the vortex varied by scale and by test type: the bench test and the unsteady CFD simulation showed a vortex while a stable vortex was not identified in the VKI wind tunnel test.

The presence of the vortex influences the torque and power required to drive the blades as well as the maximum lift and thrust coefficients that determine the minimum cruising speed and take-off field lengths–both critical performance parameters for economic competitiveness.

Figure 1 shows a comparison between the power required at 0 airspeed between the bench tests with a larger fan diameter and the 50cm diameter model tested at VKI. The vortex was shown to be present in the bench test with the larger diameter and the reduced power requirements further support the hypothesis that the vortex can be scaled up to higher diameter and that a lower torque and power requirements may result. However, more work is needed at larger scales that can be demonstrated repeatability to deliver a conclusive answer to this question.

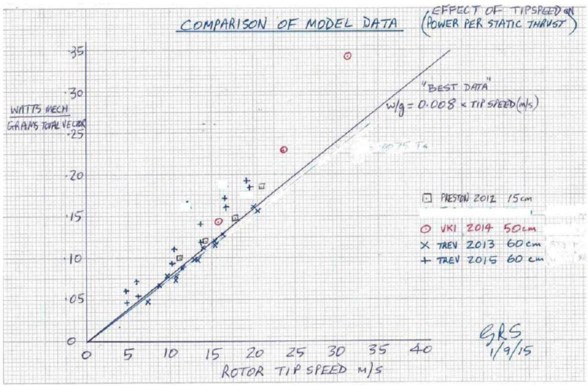

FIG 1: *Power required comparison between wind tunnel tests.*

5. Required Operational Power

The determination of the required operational power is necessary to assess the technical performance, suggested design changes and subsequently economic competitiveness. In this section we will review the torque results from aerodynamic and CFD tests, the aircraft design and mass breakdown, and the resulting estimations of the ratio of installed power to maximum take-off mass in comparison with fixed wing and rotary wing aircraft. Figure 2 shows a comparison of the torque curves corresponding to wind tunnel tests and values obtained from CFD simulations.

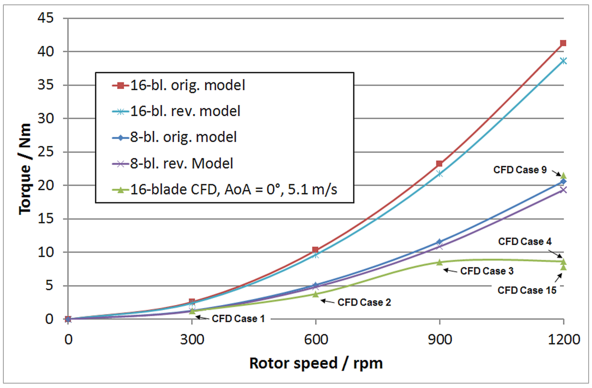

FIG 2: *Torque comparison between unsteady CFD and wind tunnel tests.*

Take-off rotation and performance calculations are taken at 600 RPM case with a TSR of 3 and an angle of attack of 0. The VKI results show a CL of approximately 4.3 at these settings and, a CL of 5.7 at 10 degrees angle of attack. Maximum CL's as high as 10.2 +/- 1,2 were obtained at AOA of 20 and TSR of 5, provided considerable minimum speed margin from the take-off rotation point of TSR 3 and CL of 5.7. While the deviation in torque results between CFD simulations and experiments has not yet been resolved, one possible hypothesis is that the lower torque requirement resulting for CFD corresponds to the well-formed vortex found in the simulations–as opposed to the experiments–and thus could be indicative of the potential to achieve higher efficiency when the vortex is well formed. In scaling the results for performance estimation, the second-highest torque curve corresponding to the wind tunnel tests on the 16-blade rotor was used.

The numerical results indicated that the power required for driving the system escalates by increasing rotational speed of the fan. The power required spinning the fan at 75 %, 50 % and 25 % correspond to 74 %, 22 % and 3 % of the nominal power, respectively. The torque exerted by the fan blades was observed to follow a similar trend while the respective values for the torque level are 99 %, 44 % and 14 %. While doubling the cruise speed results in 43 % increase in the power, tripling it only leads 49 % increase from the nominal conditions.

It was observed that the reduction in the fan blade count significantly reduces the power consumed by the SOAR model while maintaining the aerodynamic forces on the model around similar levels. On the other hand, changing the fan blades angle configuration results in a tremendous jump on the torque and the power values, more than 5 times, probably due to a significant increase on the flow field unsteadiness exerted by the reduction in the effective flow area in between the fan blades.

5.1. Aircraft design

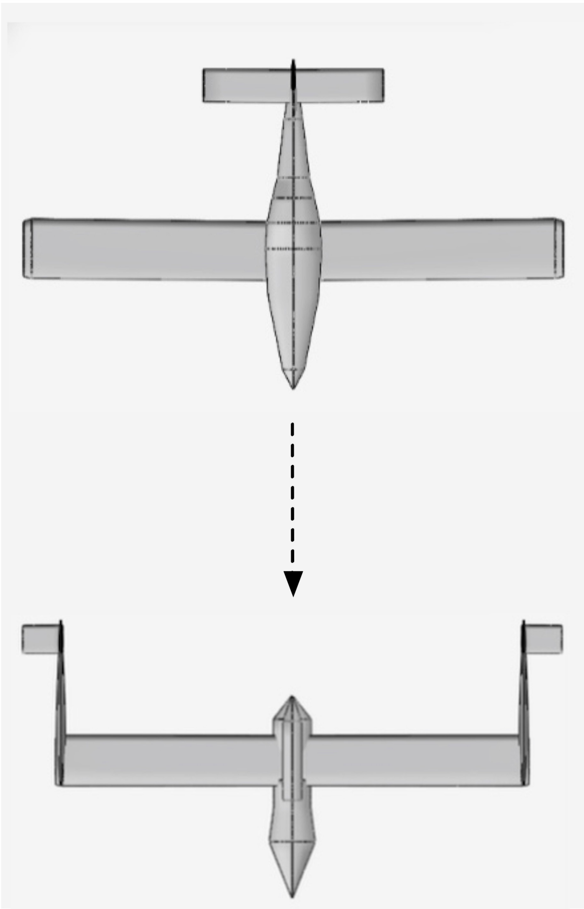

FIG 3: *Conversion of fixed Wing configuration to FanWing configuration.*

In general, the systems and structures in the FanWing should be positioned such that the lateral center of gravity is as close to the fan shaft as possible. Information from the mass breakdown can be used to position the various aerodynamic structures, payload bay, and propulsion items for an ideal center of gravity under the fan shaft. A suggested layout is shown in figure 3.

5.1.1. OHS tails

The OHS twin tail booms should be sized as conventional tail booms but with half the average radius. The equivalent vertical tail area and horizontal tail areas should be maintained. Payload should not be stored in the OHS booms. They do offer free volume but the payload storage there could move the center or gravity outside of a safe range and, introduce roll instabilities if the tails are not evenly loaded. Use of OHS tails increases the rolling and yaw inertia relative to the baseline line aircraft by moving structural mass away from the yaw and pitch axes.

A handling experiment in X-Plane found that the horizontal and stabilizers should be increased in area to maintain adequate handling. Although a comprehensive study to find an optimal value was not performed, it was observed that in the 1.000 kg payload model, an increase in distance between the wing quarter chord and the end of the vertical stabilizers of 91 % from 4.7 m to 9.0 m, provided substantially better handling characteristics. The vertical stabilizer area was also increased to hold both ends of the fan and to increase lateral stability. However, the total area of the ohs tails can be reduced aft of the fan if the designer finds adequate handling stability. These modifications to the baseline dimensional layout are shown in Figure 4.

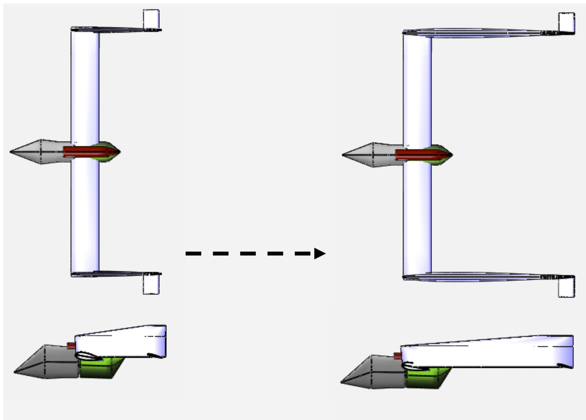

FIG 4: *FanWing configuration layout and OHS changes.*

5.1.2. Configuration layout

The FanWing configuration layout shown in Figure 4 displays color coded sections for each of the critical FanWing structures. The design choices made for each structure after several design iterations are summarized in this section. The resulting mass breakdown for the configuration is described in the following section.

Cockpit placement (gray): The cockpit should, in general, be placed below and in front of the fan. It does not need to be the forward-most major fuselage section but it should allow for adequate clearance below and in front of the wing to reduce cockpit noise and maintain easy accessibility. Fuel Placement: Fuel can be placed in the wing trailing edge, the large wedge like shape that forms the aft section of the wing. Fuel can also be placed in the payload compartment should the designer find it advantageous to use the wing trailing edge for payload placement perhaps in an agriculture application mission.

Payload placement (green): The payload can be placed in a compartment aft of the cockpit, or in the Fan trailing edge should the designer determine that placement to be advantageous. The payload compartment and the aft cockpit section is currently designed to be elliptical but can be made into a rectangular shape. The payload size increased from the baseline aircraft due to being flush with the cockpit and the rear of the engine nacelle. The payload volume roughly doubled in this configuration: specifically from 1.893 m^3 to 3.737 m^3 for the 1.000 kg payload aircraft.

Engine placement (red): The engine should be placed directly above the cockpit and payload sections. The CFD analysis shown in Figure 5 indicates that the stagnation point moves further aft of the wing with TSR and would likely be disrupted with the presence of a structure under the FanWing above a of TSR 1.5.

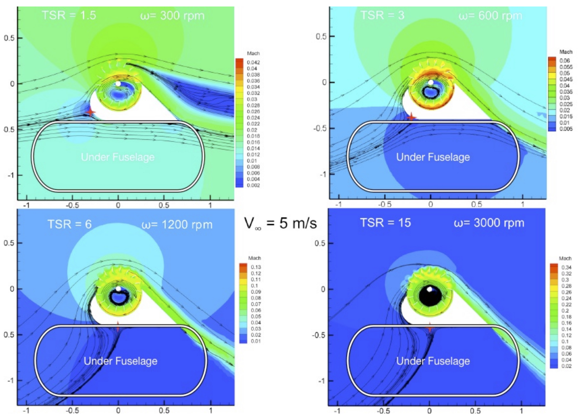

FIG 5: *FanWing CFD flow field analysis at various TSRs.*

Placing the engine above the cockpit keeps weight close to the center of gravity and will not create additional interference effects beyond what is generated by the cockpit/payload section.

5.2. Mass breakdown

The FanWing is a unique aircraft that will require a modification to existing methods to complete a preliminary mass estimate. The unique features of the FanWing that complicate existing mass estimation methods are that it has a unique fan and wing for generating lift and thrust, and, that it uses a twin boom layout with possible aft space for the fuselage and payload carrying sections. It was found that several of mass estimation methods for general aviation were not well suited for the FanWing.

[§]Vehicle sketch pad website: `http://www.openvsp.org`

Instead, we will assume a mass breakdown from Markish [3] and increment the empty weight for the vertical tail component, by a sensitivity factor based on a known change in wetted area, generated from 3-D models made using vehicle sketch pad[§]. The sensitivity was found by incrementing the wetted area by 1 % for the most accurate formula between Raymer and Nicolai for each component then, observing the change in the resulting empty weight. The wing and fuselage weights were then incremented by the resulting changes in gross weight according to their respective sensitivities. Final mass breakdown for the 1.000 kg payload aircraft compared to its baseline competitor aircraft, the A502 are shown below in Figure 6:

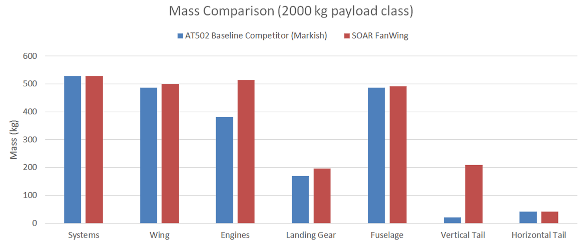

FIG 6: *Mass breakdown comparison for a 2.000 kg payload class aircraft.*

The changes resulted in an 8.8 % increase in overall empty weight due to the vertical tail. When this increase was factored in, the wing mass increased by 2.7 % and the fuselage mass increased by 0.94 %. The engine weight was increased by 35 % to account for the additional power required and the mass of the fan blades. Torsion loads on the wing from fan and stabilizers should be considered in a manufacturing design but the analysis was deemed too detailed to be considered at this preliminary stage. The landing gear weight was then incremented by the changes from the vertical tail, fuselage and wing together. These changes resulted in an overall 17.3 % increase in empty weight from the baseline competitor aircraft and can be used as a preliminary estimate when designing larger or smaller FanWings relative to a fixed wing baseline competitor.

A summary of the overall changes that for creating a generic FanWing from a baseline fixed wing competitor aircraft and the required operating power are described in the table 1 below.

FanWing Design Changes	
Design Category	Change Factor
Payload Volume	2x
Empty Mass	1.17x
Required Operational Power	1.3x

TAB 1: *FanWing power, empty mass, and payload volume change factors from fixed-wing aircraft (multiply by the original value).*

5.3. Power required comparison

The table in the previous section showed that with the necessary design changes to the original FanWing configuration, the payload volume doubles and the power required is approximately 30 % more than an equivalent fixed wing aircraft. In parallel, the power to operate the FanWing has been hypothesized to be between that of a helicopter and of a fixed wing aircraft. The power to take-off mass ratios of various fixed wing aircraft and helicopters are shown in table 2.

Power Required Comparison		
	Power to Maximum take-off Mass Ratio (kw/kg)	Take-off Rotation C_L
V-22 Tiltrotor	0.384	
VH-71 Kestral	0.361	
Sikorsky S-92	0.313	
AW109 Utility Helicopter	0.293	
FW. firefighting	0.231	4.3-5.7
FW. agricultural	0.223	4.3-5.7
Bombardier CL-415 STOL firefighter	0.178	1.45
AT 502 agricultural aircraft	0.172	1.55
Cessna Caravan Utility Aircraft	0.162	1.91

TAB 2: *Comparison of power to mass ratio an take-off lift coefficient of VTOL, FanWing, and fixed-wing aircraft.*

The fixed wing aircraft listed have power to mass ratios between 0.162 for a utility aircraft and 0.178 for a short take-off fire-fighting aircraft. The helicopters ranged between 0.293 for a light utility helicopter helicopter to 0.384 for a military tilt rotor. Therefore, the hypothesis would expect the FanWing aircraft to be able to operate with a power to maximum take-off mass ratio of between 0.178 and 0.293. Both the firefighting and agricultural Fanwings are shown to lie in this range with 30 % power increases from their fixed wing counter parts. The changes to empty mass due to the OHS surfaces will likely compromise range however, the FanWing is designed to operate closer to the place of mission activity with its superior take-off lift coefficients and the resulting shorter take-off field lengths. The doubling of payload volume can also be seen as a further attempt to trade range capability for larger payloads due to the ability to be used in closer proximity to the mission area. The economic competitiveness analysis however is needed to determine the true extent and economic advantages of these design choices and resulting levels of performance.

6. Economic Competitiveness

The resulting economic performance of the FanWing is an attempt to characterize the final economic advantage that can be delivered to the customer. Power requirements are not sufficient to characterize such an advantage–an accurate advantage must also account for changes in the mission, fuel burn, and utilization rate. In many cases, these other factors can far outweigh pure technical performance compromises. In this section, the methodology and results for the 1.000 kg-2.500 kg payload class and the 10.000 kg payload class are included.

6.1. Methodology

Three types of direct operating costs were considered in each selected payload class and corresponding operating market: aircraft ownership costs, fuel costs, and pilot labor costs. Aircraft ownership costs were calculated by using the Raymer Dapca IV method [2], then using Markish model [3] with change factors to find the change in R&D and manufacturing costs. The change factors used in the Markish model are found in Table 3 The costs were then amortized on a per flight basis using a 30 year lease with 8.5 % interest rate and a utilization rate of 5-20 flights per month depending on business model (owner-pilot or business operator). Other direct operating costs such as maintenance costs were not modeled for the purpose of this analysis.

Change Factors for Markish Model	
Design Category	Change Factor
Wing	1.2x
Fuselage	0.9x
Installed Engine	1.1x

TAB 3: *Development and manufacturing effort cost change factors (multiply by the original value).*

Fuel costs were found by first calculating the mission duration, and then using the estimated cruise fuel burn from an aircraft with the same power plant for cruise segments. The same method was used to calculate fuel burn of the competitor aircraft in order to minimize the effect of errors from net fuel burn changes during take-off, taxi, and approach. Climb fuel burn is also not calculated explicit due to the relatively low (5000 ft) cruise altitude for the selected missions. Fuel was assumed to cost € 3 per gallon. Pilot labor costs were considered. Pilots were assumed to cost € 100 per hour of operation. The total pilot cost was then found by multiplying this rate by the duration of the mission for each aircraft. Pilots are typically paid by gross weight and so the assumption was made that the labor rate would not vary between aircraft in the same payload class.

6.2. Results for the 1.000 kg–2.500 kg payload class

The results of the 1.000 kg-2.500 kg are summarized in this section. The results include a description of the target market, competitor aircraft, mission and direct operating cost results.

6.2.1. Target market and competitor aircraft

In the 1.000 kg-2.500 kg payload class scenario, the selected target market is agricultural application. The baseline competitor aircraft for the agricultural application market is the Air Tractor 502 which is used for crop dusting. The Air Tractor 502 is one of the most popular models for crop dusting currently in production. A total of 7800 aircraft, a large volume, have been built for this purpose. Air Tractor prices were not published so its acquisition price was also assessed using the Raymer-Dapca IV evaluation method but with no change factors applied using the Markish model.

6.2.2. Agricultural application mission - 500 kg–2.500 kg payload

The agricultural mission for a business operator consists of 3 mission segments: the departure to the field (50 nautical miles), low altitude application (10 nautical miles), and return to the field (50 nautical miles). The total mission distance is 110 nautical miles or 203.72 km. The business operator is assumed to operate an average of 20 flights per month. The agricultural mission for the owner-operator consists of only a low altitude application phase of 10 nautical miles or 18.52 km. The owner operator was assumed to operate an average of 5 flights per month.

6.2.3. Direct Operating Cost results – agricultural mission - 1.000 kg-2.500 kg payload

The direct operating results for the 500 kg-2.500 kg payload class can be seen in Figure 7.

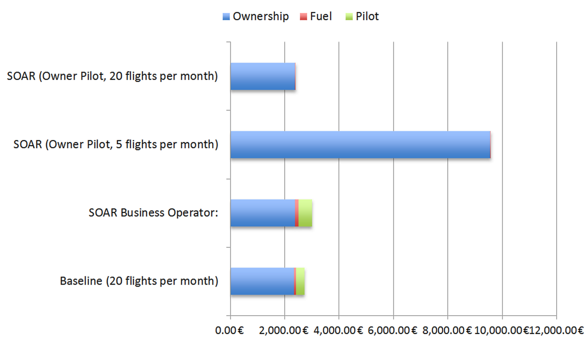

FIG 7: *Direct Operating Cost results for agricultural mission, 1.000 kg-2.500 kg payload class.*

In the business operator role, the FanWing exhibits both higher costs in all three categories. The higher ownership costs result from higher empty weight and power requirements. The higher fuel and pilot costs are the result of a 5-hour mission time vs. a 3-hour mission time for the competitor baseline aircraft with roughly the same fuel burn per hour and a lower cruise speed for the FanWing. The baseline competitor aircraft also is designed for a high speed (30 % faster than the FanWing's maximum speed) chemical application segment, further lowering its mission time.

In the owner pilot operating model, the fuel costs are lower due to the shorter mission distance, however the ownership costs are higher due to having fewer flights per month over which to amortize the costs. The pilot costs are 0 in this case because the owner doesn't hire a pilot and flies the FanWing on his or her own.

Lastly, a scenario in which the FanWing achieves a lower cost in than the baseline aircraft is when the owner pilot needs to fly the same number of times per month (20) as a business operator. The baseline aircraft could not operate in the same way from the owner's field because its take-off field length is prohibitively long, more than 3 times longer than that of the FanWing.

6.3. Results for the 10.000 kg payload class

The results of the 10.000 kg payload class are summarized in this section. The results include a description of the target market, competitor aircraft, mission and direct operating cost results.

6.3.1. Target market & competitor aircraft

In the 10.000 kg payload class scenario, the selected target market is firefighting. The baseline competitor aircraft for the for the firefighting market is the Bombardier CL-415 which has the unique ability to scoop more water and mix it with more fire retardant for additional application after it has dispensed its initial payload . This unique ability gives the CL-415 the ability to be as productive as an aircraft with 3 times the payload but with lower take-off weight, fuel burn and acquisition costs. As a results the CL-415 commands a 100 % premium (2 times the acquisition price) over aircraft with same power-plant and take-off weight that are designed for other applications.

6.3.2. Firefighting mission - 10.000 kg payload

The firefighting mission of 5 mission segments: the departure to the fire (30 nautical miles), 3 segments of a low altitude application and round trip flight to refill the water supply (12 nautical miles), and return to the field (30 nautical miles). The total mission distance is 96 nautical miles or 180 km. The mission time for the FanWing is 1.65 hours compared to 0.78 for the baseline CL 415. The smaller difference in mission time is due in part to the fact that the firefighting baseline competitor is designed for a slow application speed. Unlike the agricultural baseline competitor (AT502) which has a high application speed.

A publicly (government) owned firefighting aircraft operation was considered the only viable operating model for this mission because the application frequency and thus application revenue are highly uncertain. Also in most societies, firefighting is considered a public service while farmland is privately owned and maintained. The government operator was assumed to operate an average of 10 flights per month for either training or live fire application.

6.3.3. Direct Operating Cost results - firefighting - 10.000 kg payload

The direct operating results for the 10.000 kg payload class can be seen below in Figure 8.

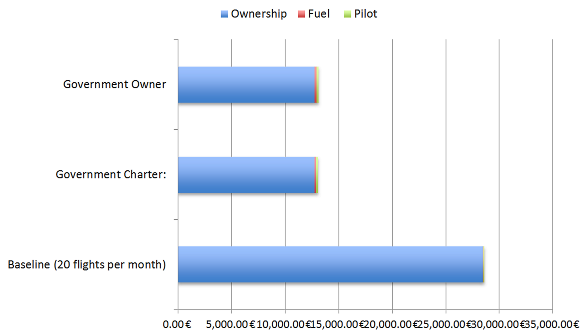

FIG 8: *Direct Operating Cost results, firefighting mission, 10.000 kg payload class.*

In the government operator role, the FanWing exhibits significantly lower overall operating expenses. The lower ownership costs result from the absence of the 100 % price premium that is currently enjoyed by the Bombardier CL-415. The CL-415 does not have any scooping competitors in its payload classes or in smaller or larger payload classes. The acquisition costs dominate the operating costs because of low (10 flights per month) utilization rate. In comparison, an airline might operate an aircraft 100 flights per month. The higher fuel and pilot costs are again the result of a longer mission time. It would not be possible to reliably lower these costs for the FanWing as was possible in the agricultural mission because the location of the fires will be unknown and will vary season to season. Even with higher pilot and fuel costs, the FanWing with scooping capability enjoys a significant operating cost advantage over the CL-415.

6.4. Direct Operating Cost conclusions

The FanWing was shown to have scenarios with lower operating costs than its competitors in both the 500 kg-2.500 kg payload class and the 10.000 kg payload class. In the smaller payload class in the agricultural operation market, the open-fan wing's low take-off distance enables it to be used in owner-pilot model while its competitor aircraft cannot be used in this way. However, the FanWing will only have a cost advantage in this scenario if the owner needs to use the aircraft as often or more often than a business operating chartered agricultural flights. In the 10.000 kg payload class, the FanWing can potentially disrupt the market premiums currently paid by the market by employing scooping capability of the competitor aircraft. The FanWing can further enhance its economic competitiveness by improving its cruising speed or, by further lowering its take-off distance so that the FanWing can be based at more mission sites by owner pilots or be towed there by a service. In a generic market, the Fan Wing needs one of two things to be economically successful: the market must pay a premium for low-speed maneuvering missions and/or the low take-off distance must enable an owner-pilot model in the same market with the owners having a high utilization rate. Alternative fuels or energy sources would not enhance the open-fan wing's competitiveness because the operating costs are highly dominated by aircraft ownership costs, not fuel costs. This is due to the low utilization rates for the selected target markets which is in contrast to an airline model with high utilization rates.

7. Conclusions

The EU SOAR project asked 3 fundamental research questions: would the performance of the FanWing scale up to higher fan-diameter? what is the power required to operate the FanWing? and, is the FanWing economically competitive.

Much progress was made in understanding the scaling of the FanWing but the authors regard the results so far as inconclusive. The vortex was shown to be present and also not present in testing with similar diameter. More wind tunnel and flight testing will be needed to answer this question more definitively.

In the aircraft design phase, changes to the original FanWing configuration were found to be necessary: mainly lengthening the OHS tails, and doubling the payload volume to create a smooth taper between the aft cockpit wall and the trailing edge of the FanWing and engine nacelle. With these changes and the 2-D and 3-D torque data, we estimate a 30 % increase in power requirements over an equivalent fixed wing aircraft with a TSR of 3 at take-off.

Lastly, the FanWing was found to be economically competitive in both of its target markets. In the agricultural application market, high utilization rates combined with basing the FanWing next to the application fields resulted in an economic advantage. In the firefighting market, the built-in premiums in the competitor aircraft price due to the payload-multiplying feature of scooping created a large economic advantage for the FanWing.

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