DISTRIBUTED PROPULSION FEASIBILITY STUDIES

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Abstract

This paper describes the research efforts at Cranfield University to ascertain the technical, economical, and environmental feasibility of distributed propulsion.
An analysis of the feasibility of small gas turbine distributed propulsion by means of a techno-economical model is presented. The results indicate that thermal efficiency issues for small engines must be addressed in order for small gas turbine distributed propulsion to become viable. The greatest potential for distributed propulsion might lie in the relaxation of design requirements and airframe and propulsion system integration to reduce weight and cost.

1 Introduction

The predominant configuration of aircraft with podded high-bypass engines seems to provide the best solution for civil transport today. This might not necessarily be the case in the future: The conventional arrangement will benefit only marginally from advances in the fields of micro, nano, and biotechnology or superconductivity, but an alternative platform might derive greater advantage from the infusion of technologies and provide an overall better solution.
Distributed propulsion consists in spreading the thrust of the propulsion system along the span of the aircraft, and could one day become an attractive option. So far, interest on distributed propulsion has focused mainly on its potential for noise reduction [1] – [4], but the impact that distributed propulsion systems could have on the aerospace industry is much greater. The ACARE goals set out by the European aerospace industry [5] illustrate the challenges that must be met in the coming years. Fig. 1 shows how one possible future scenario could be affected by distributed propulsion:
The challenge of quality and affordability could be met through reduced propulsion system life cycle costs and maintenance costs. Lower fuel consumption, the possibility of reduced or even zero emissions and lower perceived noise levels could result in environmentally friendly aircraft. A reduced probability of critical propulsion system failures could make aircraft significantly safer, and simplified maintenance could enhance safety and reduce turnaround time.

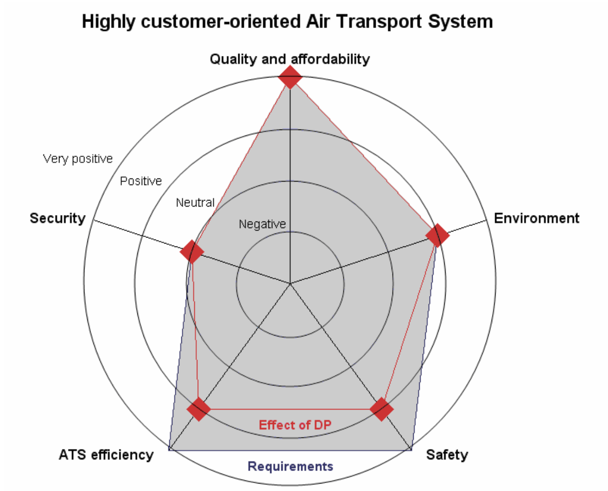

Fig. 1. Distributed propulsion contribution to ACARE

Nevertheless, there are important hurdles that must be overcome for distributed propulsion to become a practical option. Cranfield University is collaborating with industry to determine the viability of distributed propulsion. The initial stage of the project has been devoted to the analysis of small gas turbine distributed propulsion, and is described in this paper.

2 Small gas turbine distributed propulsion

Once we have decided to spread the thrust of the propulsion system, it is necessary to select an arrangement. The simplest options are:

- Spreading the exhaust of the propulsion system units along the wing by means of high aspect ratio nozzles [2], [6]-[10]
- Distributing the propulsion units themselves [11]-[14].

The propulsion units mentioned above might not necessarily be gas turbines. Other options envisaged at the moment are gas-driven fans [15] and electrically driven fans [16], [17]. Hybrid options are also possible. For example, different combinations of engine numbers and high aspect ratio nozzles could be used.

Ultimately, the arrangement chosen will determine the type of benefits accrued from the use of distributed propulsion: arrangements using high aspect ratio nozzles and low specific thrust engines could be used to improve propulsive efficiency, and small distributed engines open the way for mass manufacturing and new business paradigms.

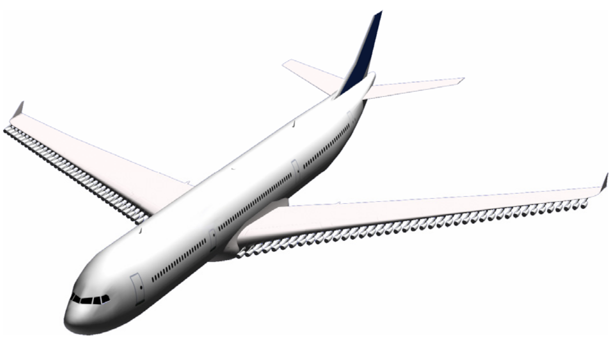

Fig. 2 Small gas turbine distributed propulsion

The first stage of the project considers the simplest distributed propulsion arrangement possible: using large numbers of small gas turbines to provide the thrust required (Fig. 2). In order to determine the feasibility of such an arrangement, the effects of increasing the number of engines must be considered. The following issues were examined:

- Engine performance
- Engine weight
- Engine reliability and safety
- Nacelle weight and drag
- Auxiliary systems scaling
- Wing bending relief
- Fin sizing design requirements
- Climb gradient design requirements
- Economies of scale
- Thrust vectoring and engine operation

These effects will be described in the following section.

2.1. Description of effects

2.1.1. Engine performance

Some of the effects of engine performance scaling on small gas turbine distributed propulsion were described by Lundblah and Grönstedt [12]. A number of scaling effects are detrimental to the performance of small engines: Reynolds numbers can fall below the critical level due to the smaller size of turbomachinery and other components, resulting in early separation and losses. Combustor scaling becomes increasingly difficult due to loading and residence time requirements [18]. For a given level of manufacturing technology, tip clearances will increase relative to blade height as the core becomes smaller. Geometric features such as trailing edge thicknesses become increasingly difficult to manufacture as the scale is reduced, and requirements for turbine cooling flow passages cannot be met, leading to lower permissible turbine entry temperatures, and lower thermal efficiency. Fig. 3 shows SFC trends for current state-of-the art engines.

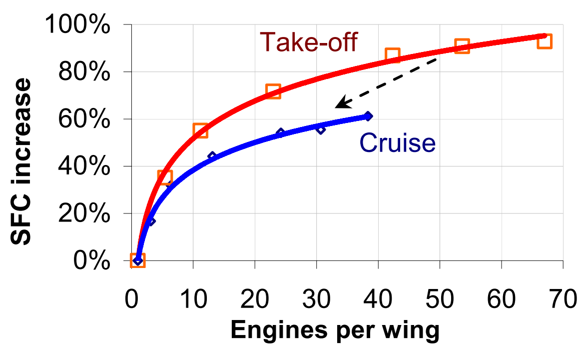

Fig. 3 SFC increase with number of engines

During cruise, flight velocity has a stronger effect on larger, higher-bypass engines. As a result, fewer small engines are needed to supply the required thrust than during take-off. Cruise fuel consumption increases are still on the order of 50 – 60%. The extra 32 engines that would have to be carried during cruise for the 70-engine case imply that it might be advantageous to develop high thrust-to-weight take-off engines to reduce propulsion system weight.

Poor engine performance constitutes the most important limitation to small gas turbine distributed propulsion. A 60% increase in SFC is likely to offset almost any imaginable benefit. The development of alternative technologies or architectures to alleviate the negative effects of reduced scale on performance is therefore critical. Assuming it is possible to find a solution to the performance problem, the effects in the following sections must still be considered.

2.1.2. Engine weight

Theoretically, smaller gas turbines should be lighter than their large counterparts. Assuming constant specific thrust, the force produced by the engines will depend on their frontal area. Since weight depends on density and volume, it will scale down with the third power of the engine dimensions, whereas thrust will decrease with the square. However, the square-cube law does not hold up in practice: auxiliary systems scaling, non-scalable parts, and the inability to use weight-saving technologies at small scale contribute to reversing the square-cube trend, making smaller engines relatively heavier.

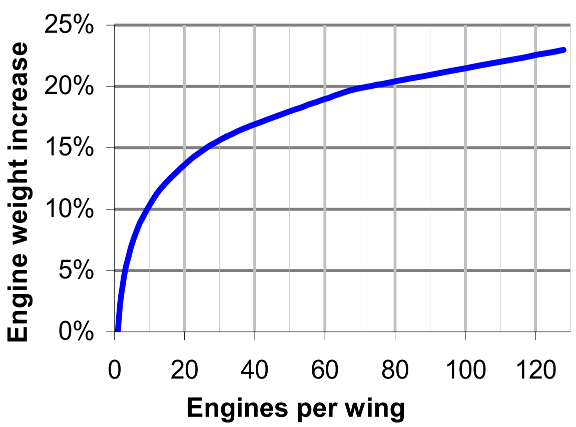

Fig. 4 Engine weight scaling

Fig. 4 shows the net result: larger numbers of gas turbines result in significantly heavier propulsion systems with current technology.

2.1.3. Engine reliability and safety

Though small gas turbines may be less reliable than their large counterparts, it is possible in theory to develop—given the incentive—gas turbines with similar reliability levels. If we accept that possibility, we are still faced with a tradeoff: though the probability of an engine failure increases linearly with the number of engines, the probability of a critical propulsion system failure is reduced thanks to system redundancy (see Fig. 5).

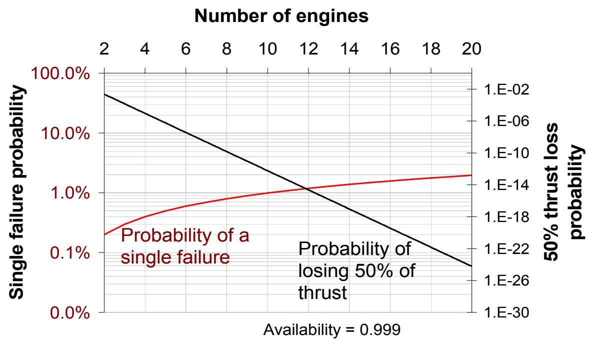

Fig. 5 Engine reliability tradeoff

However, any safety advantage resulting from redundancy could be reduced by the dependence of the engines on less distributed systems. This challenge could create a drive towards some level of distribution not only on the engines themselves, but on auxiliary systems, considering design requirements and scaling issues.

2.1.4. Nacelle weight and drag

The use of podded engines for distributed propulsion configurations represents a considerable hurdle. If nacelle length could be assumed to be proportional to engine diameter, there would be no net increase in nacelle wetted area[1]. However, existing engine data shows that the relationship is not linear, and nacelle length can be correlated to the 0.9th power of the diameter.

Nacelle length scaling and Reynolds number effects alone result in increased friction drag for larger numbers of engines. For a 70-engine case,

[1] For constant specific thrust, engine thrust depends on the square of the diameter, and wetted area depends on the product of the diameter and the length

nacelle friction drag is doubled with respect to a single large nacelle (see Fig. 6). In a mid-sized, long-range subsonic transport, this could amount to a 6.5% increase in total drag.

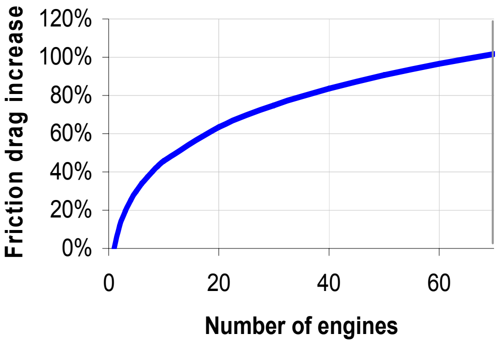

Fig. 6 Nacelle friction drag scaling

Poor auxiliary systems scaling can lead to relatively larger maximum diameters for smaller nacelles, which must accommodate them. Heavier nacelles resulting from higher wetted areas, poor pylon scaling (required for avoiding excessive wave drag between the engine and the wing), and the possibility of shock formation between engines also contribute to make podded configurations undesirable.

2.1.5 Auxiliary systems scaling

The auxiliary systems scaling effect described above can be exemplified by the fuel system: fuel systems are mainly composed of pumps, pipes, and valves. Usually, one main pump is required per engine. Pumps can be characterized by flow rate and operating pressure. The fuel flow rate into the main pumps is proportional to the thrust and SFC of the engine. As we said in section 2.1.1, the SFC of small engines is relatively higher. The amount of piping is likely to increase, as more engines have to be served. In addition, mechanical design limitations contribute towards making fuel systems for distributed propulsion relatively heavier.

For large numbers of engines, it would be possible to form engine clusters fed by a single pump. The result of this, however, would be a reduction of the redundancy benefits from distributed propulsion. Such a reduction could result in a complex tradeoff between fuel systems weight, fin size, and maximum take-off thrust.

2.1.6. Wing bending relief

From a structural point of view, distributing the engines along the wing could help counteract the lift loads during cruise, providing inertia relief and resulting in a lighter wing [10]. Torenbeek [11] suggests the wing weight savings resulting from placing one and two engines per wing could be 3.5% and 10%, respectively. [19] also provides a method for calculating the reduction in wing box weight afforded by the engines:

$$\left(\frac{\Delta W_{B+S}}{W_{B+S}}\right)_P = -1.5 \times \sum \frac{\eta_p^2}{\eta_{cp}} \times \frac{W_e}{MTOW/2} \qquad (1)$$

where $\Delta W_{B+s}/W_{B+s}$ is the change in bending and shear material, η_p/η_{cp} is the ratio of engine to COP position along the front spar, W_e is the engine weight, and *MTOW* is the take-off weight.

Bending relief benefits are obtained by distributing the load, not by shifting the centre of gravity of the propulsion system outwards. The latter option is limited by landing loads and vertical tail sizing requirements. If we space the engines evenly along the wing, we can see that the maximum wing weight reduction achievable is about 3.5% (Fig. 7):

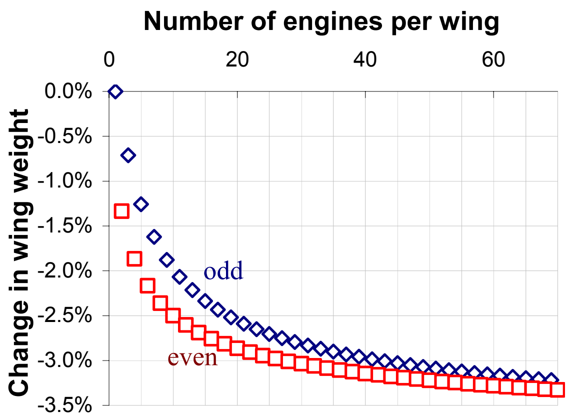

Fig. 7 Wing inertia relief limits

An ongoing study at Cranfield University seeks to determine the optimum wing structural arrangement and placement of the engines considering critical loads, future materials technology, systems layout, and safety issues.

2.1.7 Fin sizing design requirements

Breaking up the thrust of the propulsion system into smaller units can also result in more indirect benefits. One possibility could be the relaxation of the fin sizing requirement: Aircraft fins are sized according to various requirements, including handling, directional, and lateral stability considerations [20]. Usually, the engine-out case presents the largest fin sizing requirement: the aircraft must be able to maintain its heading after the critical engine has failed [21]. Rearranging design equations given in [20], we can obtain an expression for the fin size required:

$$\bar{V}_V \geq \frac{1.35 \times F_N \times \bar{y}_{\max}}{\zeta_{\max} \times \bar{F} \times \left[\left(\frac{c_f}{c} \right)_R^{0.47} + 0.08 \right]} \tag{2}$$

where V_V is the vertical tail volume coefficient (which can give us the vertical tail surface area if all other aircraft parameters remain equal), F_N is the net thrust from the critical engine, y_{max} is the distance of the critical engine to the aircraft centerline, ζ_{max} is the maximum rudder deflection, c_f/c is the mean ratio of rudder chord to fin chord, and F is a form factor.

For the range of engines considered, the fin size could be reduced by more than 90% if we only consider the engine-out case. In practice, however, aircraft stability requirements remain, and the benefit would be considerably reduced unless differential engine thrust was used to provide directional stability and control. This is not possible in practice due to safety regulations, since the aircraft must remain controllable even when there is no fuel left.

2.1.8 Climb gradient design requirements

The maximum thrust requirement for an aircraft is usually given by the requisite of maintaining an appropriate climb gradient in the event of an engine failure. The climb gradient requirements are 2.4% for 2-engined aircraft and 2.7% for 4-engined aircraft [21]. If we assume distributed propulsion configurations could be treated in the same way as 4-engined aircraft, the thrust reduction during take-off can be calculated by balancing the forces during the second climb segment:

$$F_N = \frac{D + L \tan\phi}{N_{engines} - 1} \tag{3}$$

where F_N is the net thrust per engine, D and L are the aircraft drag and lift, respectively, and ϕ is the climb angle. The thrust reduction can now be plotted:

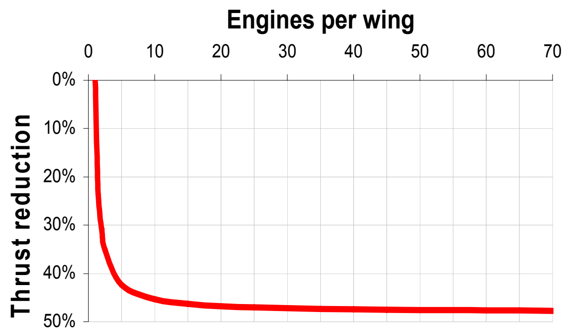

Fig. 8 Climb gradient requirement relaxation

Fig. 8 approaches 50% asymptotically. This is logical, as the thrust loss resulting from an engine failure is 50% for the 2-engine case, and would be negligible for a large number of engines. This could be an important advantage, as it would mean that the same thrust requirements could be met with a proportionally smaller number of engines. As was mentioned in section 2.1.1, the thrust required at cruise is proportionally lower for larger numbers of small engines due to the higher thrust lapse rates for larger, high-bypass engines. Coupled with a lower climb gradient requirement, the actual number of engines on the wing for a particular engine core size could be reduced, resulting in lower propulsion system weight and improved SFC (the difference in throttle settings for different points in the flight envelope could be reduced, improving engine performance).

However, noise is and will continue to be a significant concern for aviation. Many airports today levy noise taxes on aircraft, and often specify a minimum climb gradient that must be maintained in order to clear inhabited areas and reduce the noise impact on the local community. In the case of Brussels National Airport, the minimum climb gradient is 7% [22]. The thrust reduction shown in Fig. 8 would result in engines able to maintain increasingly small climb gradients (the limit case would be 2.7% for a very large number of engines). If we consider the example of Brussels for the all-engines-operational climb gradient requirement, Fig. 9 shows the thrust reduction per engine:

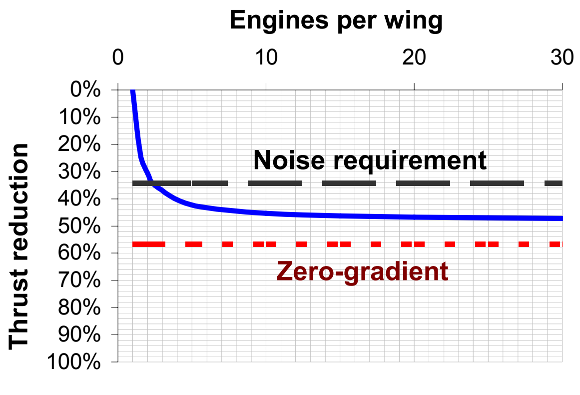

Fig. 9 Effect of noise on gradient

For very small numbers of engines, the engines are still somewhat oversized, and are capable of providing gradients above the noise requirement. For more than 2 engines per wing, however, noise would present the limiting case and cap any thrust reduction benefits. The thrust required to achieve the climb gradient given by noise regulations could be reduced by lowering the weight of the aircraft or reducing drag. Nevertheless, even when we consider this limitation, the relaxation of the climb gradient requirement remains an important advantage.

2.1.9 Economies of scale

The single greatest benefit from small gas turbine distributed propulsion might be the reduced propulsion system cost resulting from economies of scale. [23] suggests savings of 50% in life cycle costs. The requirement for large numbers of engines could drive the industry towards different manufacturing techniques and business paradigms that could result in significantly lower manufacturing and operating costs (see Fig. 10).

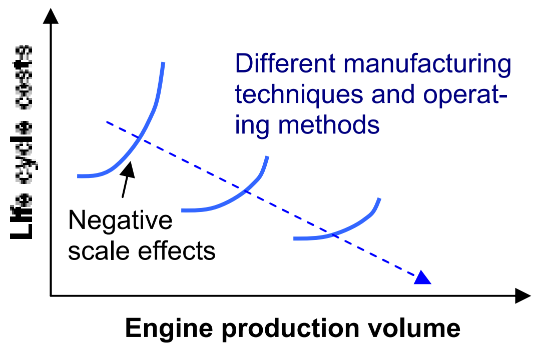

Fig. 10 Effect of manufacturing

If we consider a traditional curve for economies of scale [24], the savings in manufacturing costs could be represented by Fig. 11:

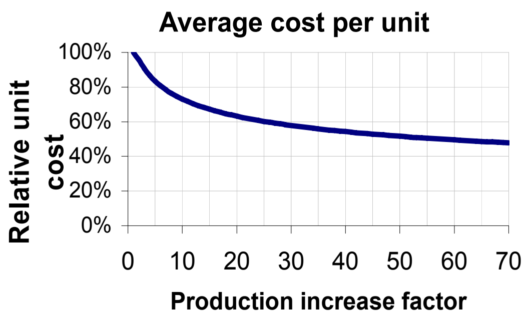

Fig. 11 Economies of scale

The savings suggested by Fig. 11 are relative to the cost of one engine of similar size manufactured in a baseline production volume. If we assume a constant price per pound of thrust, Fig. 11 can be considered to represent the actual manufacturing cost savings when compared to the baseline configuration of two engines. This cost reduction would also extend to the manufacturing costs for nacelles, and maintenance parts costs for the propulsion system.

Nevertheless, the validity of these curves is limited to modest production increase factors. To give a better idea of what could be expected, a recent study sponsored by the European Commission [25] concluded that small gas turbine manufacturing costs could experience a 30-fold reduction by switching to castings and other manufacturing techniques suitable for mass production without detrimental effects to performance. The cost of propulsion system maintenance would also decrease due to lower parts costs and more standardized and automated methods.

The current maintenance paradigm could be substituted for simple engine replacements upon failure, and the possibility of using a single engine for the entire aircraft fleet could become attractive for airlines. Different thrust requirements could be met with different numbers of engines, and the development of new engines would cease to be linked to new aircraft, being driven by technological developments to make the product more competitive reduce costs and meet environmental legislation.

These changes cannot be represented by a standard learning curve. A detailed study of the viability of different manufacturing techniques and operating strategies would be necessary to accurately assess the potential advantage.

2.1.10 Thrust vectoring and engine operation

Another possibility brought about by the use of distributed propulsion is the use of thrust vectoring to reduce or eliminate aircraft control surfaces (though the latter is not possible in practice due to safety regulations). Thrust vectoring is not viable for large engines due to safety issues and weight and performance penalties. However, if we have a large number of engines on the wing, safety and weight issues become relatively less important. If we were able to use pitch, roll and yaw thrust vectoring to eliminate the horizontal and vertical tail, we could obtain a considerable reduction in take-off weight:

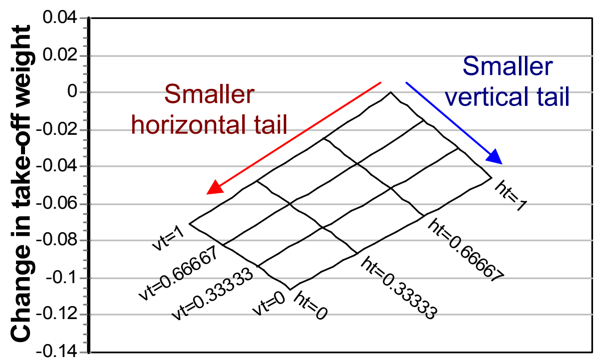

Fig. 12 Example of control surface elimination

The direct benefits obtained by eliminating wing control surfaces would be smaller, but doing so would open up hitherto unavailable space in the wing, making it possible to integrate the propulsion system within the wing with relative ease.

There are reasons why this cannot be achieved with current technology, including engine spool-up times and controllability in low power situations. The weight and performance penalties resulting from the use of thrust vectoring would also reduce the advantage suggested in Fig. 12.

Other possibilities might include shutting down engines when lower thrust levels are required, operating all engines at maximum efficiency, and eliminating engine power off-takes and bleeds by devoting a small number of engines or fuel cells to power production. However, this would have a negative impact on economies of scale.

2.2 Method and results

In order to assess the net effect of implementing a distributed propulsion system, it is useful to establish a baseline. The chosen baseline is a mid-sized, long-range subsonic transport. An aircraft model was created using NASA's aircraft design tool, FLOPS [26]. The model was validated against existing data for similar aircraft, and the effects described above were modeled using various programming tools and spreadsheets, as appropriate. Operating costs and life cycle costs were estimated using the method described in [27], made available within the FLOPS framework.

The range of thrusts investigated in the initial study extends from 75000 lbs down to 1000 lbs per engine to investigate distributed propulsion using small turbofan technology. A series of baseline engines was established using core technology appropriate for each engine size (TET limits and component efficiencies). Baseline engine performance was modeled using TURBOMATCH (Cranfield University's gas turbine performance code) and combined with the aircraft model.

The different models were integrated together and the complete configuration was optimized using Phoenix Model Center.

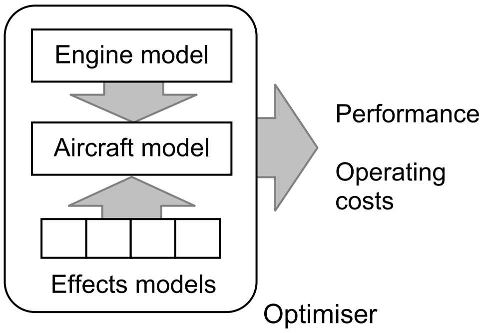

Fig. 13 Model integration

Baselines were established and analyzed for the two limiting cases: a conventional baseline with 2 engines per wing, and a distributed propulsion baseline with 70 engines per wing.

If we begin by considering the SFC effect explained in section 2.1.1, we can immediately see that the increase in take-off weight required to carry enough fuel for an 8000 nm mission would be disproportionately large:

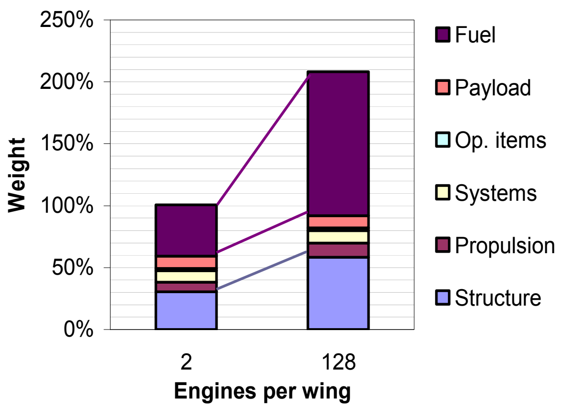

Fig. 14 SFC-based concept comparison

In order to understand how the effect of SFC might have such a large effect on ramp weight, it is useful to refer to the 'snowball effect' [28]. If we look at the Breguet range equation, we can find the fuel fraction required to achieve a given range as a function of technological parameters:

$$W_F = W_P \times \left(1 + \frac{W_E}{W_P}\right) \times \left(1.022 e^{\frac{R}{X}} - 1\right) \qquad (4)$$

where W_F is the fuel weight, W_P is the payload weight, W_E is the zero-fuel weight, R is the range, and X is a technological parameter which combines SFC, aircraft speed, and lift-to-drag ratio.

The increase in SFC can be taken from Fig. 3 as 60%, since the cruise value will dominate the relationship. The extra amount of fuel required to complete the mission will result in a larger wing and added weight. The increase in drag will affect the X parameter, further increasing the amount of fuel required. The airframe structures will need to become heavier to support the fuel weight, increasing W_E and causing yet another rise in the amount of fuel required. The resulting snowball effect drives the aircraft weight inexorably upwards, resulting in an aircraft twice as heavy as the baseline and with 66% higher operating costs per block hour. Both fuel fraction values obtained from the simulations were 5% higher than the value suggested by (4) as fuel reserves were considered in the aircraft model, and the 1.022 factor in (4) only considers take-off and climb in addition to cruise.

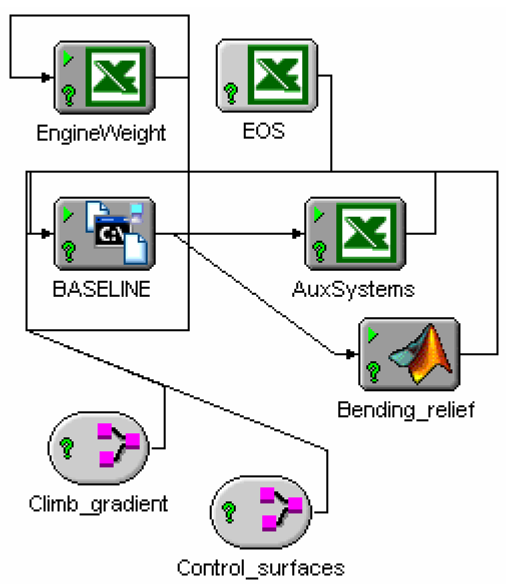

Fig. 15 Phoenix Model Center framework

The picture changes somewhat when we consider all the effects together. Fig. 15 shows a more complex model set up using Phoenix Model Center. This time, the model also considers engine and auxiliary systems weight, bending relief, control surface reduction due to thrust vectoring, climb gradient requirement relaxation, and economies of scale.

At first, the individual effects were examined to assess their relative importance:

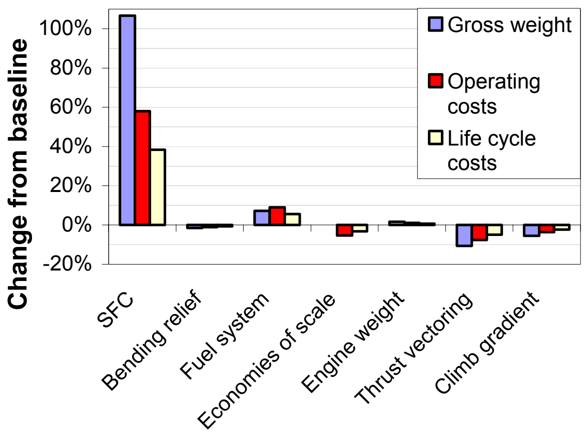

Fig. 16 Individual effects on baseline

We can immediately see from Fig. 16 that the SFC effect is an order of magnitude larger than any of the other effects. Though economies of scale seem to have some impact on operating and life cycle costs, the largest benefits come from the relaxation of design requirements.
The net result obtained by integrating the models becomes:

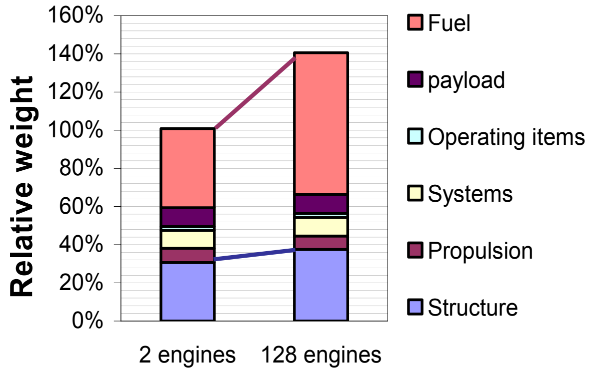

Fig. 17 Weight comparison for 2 and 128 engines

The snowball effect works to our advantage when we consider design requirement effects. If we refer back to (4), we can see that by changing the requirements to which the aircraft is designed, we have altered the ratio of empty weight to payload weight W_E / W_P. As a result, a lighter structure can be used to carry a given amount of fuel. Therefore, despite the large increase in fuel consumption, structural weight remains reasonably low.

Life cycle costs and operating costs for this configuration would increase by 14% and 21% respectively, and airframe acquisition costs would rise by 10%. Even if we use the value suggested in [25], operating costs would be 11% higher than the baseline.

The case for smaller numbers of engines can be assessed by looking at the effects described in section 2: Fuel consumption, which is the dominant parameter in the tradeoffs described, rises steeply as soon as we increase the number of engines from the baseline. Distributed propulsion benefits, on the other hand, increase slowly, and in the case of economies of scale, unsteadily. It becomes clear that unless engine thermal efficiency issues can be dealt with successfully, small gas turbine distributed propulsion is not likely to become viable.

3 Future challenges

Enabling technologies for small gas turbine distributed propulsion should include technologies that can be scaled down favorably. One such example might be the use of recuperated cycles, as low pressure ratios like those found in small gas turbines result in higher thermal efficiency. A crucial challenge in this field is to reduce the weight of heat exchangers. Materials technology might therefore be another crucial enabler, as nano-materials could enable efficient cooling and lighter designs at small scale. The ongoing driven fan studies look at what distributed propulsion technology could look like further ahead into the future. Though there is a higher degree of uncertainty involved, the results suggest that it is only through the introduction of disruptive technologies that distributed propulsion might become a feasible alternative to evolutionary conventional arrangements.

Current work is being focused on a blended wing body transport of similar size to the original baseline. Gas-driven fans, mechanically-driven fans, and electrically driven fan concepts are being studied. These concepts might show higher efficiency and new possibilities for propulsion-airframe integration, even if at the expense of scale economies.

4 Conclusions

The feasibility study presented shows that low thermal efficiency for small engines constitutes the single greatest technical hurdle to the viability of small gas turbine distributed propulsion.
The greatest distributed propulsion benefits stem from propulsion system and airframe integration. Though industry structure today would present an additional barrier to distributed propulsion, environmental and technical trends in aerospace and other fields could eventually provide the drivers for its implementation.

Acknowledgements

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