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Distributed Propulsion featuring Boundary Layer Ingestion Engines for the Blended Wing Body Subsonic Transport

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The blended wing body aircraft is one of the promising contenders for the next generation large transport aircraft. This aircraft is particularly suitable for the use of boundary layer ingestion engines. Results published in literature suggest that it might be beneficial to have a large number of these engines (distributed propulsion). A conceptual design study is therefore performed to determine the potential benefits of boundary layer ingestion engines for a conventional number of engines increasing to a large number of engines. A gasturbine performance tool is combined with a weight prediction tool and a mission analysis tool to analyze aircraft-engine combinations. A genetic algorithm is used to find engine specifications that result in minimum fuel consumption for a given configuration (e.g. 8 engines). Results show that the potential of distributed propulsion systems relies heavily on a weak dominance of beneficial effects over negative effects of similar magnitude. From a performance point of view it is better to abandon the distributed propulsion concept and to focus on a small number of large boundary layer ingestion engines instead since they do not suffer high internal losses. A propulsion system with three boundary layer ingestion engines is shown to have a 5% performance improvement in terms of fuel consumption over a conventional strut mounted propulsion system.

Nomenclature

c_p	=	ratio of specific heats at constant pressure
D_A	=	airframe drag
D_{ing}	=	ingested drag [N]
D_{ing}/T	=	ingested drag as fraction of thrust (or airframe drag in steady flight) [-]
F_N	=	net (installed) thrust [N]
FHV	=	Fuel (lower) Heating Value [J/kg]
h_{BL}	=	last stage high pressure compressor (HPC) blade height [mm]
P_i	=	inlet propulsive power [J/s]
P_j	=	jet propulsive power [J/s]
Re	=	Reynolds number [-]
T_N	=	net propulsive force [N]
T_{metal}	=	maximum allowable metal temperature [K]
T_3	=	high pressure compressor (HPC) inlet temperature [K]
T_4	=	combustor outlet temperature [K]
T_{48}	=	low pressure turbine (LPT) inlet temperature [K]
V_i	=	equivalent intake velocity [m/s]
V_0	=	inlet velocity [m/s]
W^*	=	normalized mass flow [-]
W_0	=	inlet mass flow [kg/s]
W_{25}	=	high pressure compressor inlet mass flow [kg/s]

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W_{bleed}	=	overboard bleed mass flow [kg/s]
W_{fuel}	=	fuel mass flow [kg/s]
WT_{fuel}	=	fuel weight [kg]
WT_{empty}	=	aircraft empty weight [kg]
$WT_{take\text{-}off}$	=	aircraft take-off weight [kg]
η_c	=	compressor polytrophic efficiency [-]
η_p	=	propulsive efficiency [-]
η_t	=	turbine polytrophic efficiency [-]
η_{th}	=	thermal efficiency [-]
$\pi_{0\text{-}1}$	=	free stream total pressure recovery [-]
$\pi_{1\text{-}2}$	=	combined inlet/S-duct total pressure recovery [-]
π_{HPT}	=	high pressure turbine (HPT) total pressure ratio [-]
π_{IPT}	=	intermediate pressure turbine (IPT) total pressure ratio [-]

I. Introduction

Today's vision on the future of air transport reflects the need to combine cost-effectiveness with improvements in safety and reductions in environmental impact[1,2]. Aircraft manufacturers therefore aim on radical new concepts like the blended wing body (BWB) aircraft as contender for the next generation large transport aircraft[3]. The BWB aircraft concept offers some opportunities in the application of new propulsion concepts that show potential to meet these semi-opposing requirements. A radical new propulsion concept called boundary layer ingestion (BLI) is one of the candidates for application with BWB aircraft. With BLI part of the low momentum airframe boundary layer (i.e. part of the viscous aircraft drag) is fed through the engine and is reenergized, resulting in a lower energy waste and a higher propulsive efficiency. Since BWB aircraft have a fairly high percentage of viscous drag (typically over 50%) and since they allow engine placement close to the trailing edge they enable embedded engines to pick up large amounts of aircraft boundary layer which makes BWB aircraft more than suitable for a BLI propulsion system and vice-versa. Campbell et al.[4] presented the design and analysis of a BWB with three BLI engines. Their analysis was carried out based on wind tunnel testing and CFD simulations. They indicate a performance improvement but no actual numbers are given. The main advantages of a BLI propulsion system compared to a conventional propulsion system applied to a BWB configuration are; (1) reduced ram drag, (2) reduced wetted area, (3) lower structural weight and (4) smaller pitching moment due to the lower position of the thrust vector. These advantages come at the cost of a more complex aerodynamic design with respect to the surface integration. Also, embedded engines require an S-duct to guide the flow in the engine.

The use of many small BLI engines arranged along the trailing edge, a distributed propulsion system, is often suggested to ingest a sufficient amount of aircraft boundary layer[5, 6] since for small engines the boundary layer forms a larger fraction of inlet flow compared to larger engines. But when considering small BLI engines a new bottleneck arises: scale effects. Scale effects represent decreasing engine performance with decreasing engine size. Smaller engines have increased pressure and heat losses due to a decreased Reynolds number and a relative increase of leakage flow. So, the question arises if the potentially higher integration efficiency associated with BLI, weighs against the higher specific fuel consumption of smaller engines. Besides this primary effect, introducing a larger number of engines also has an impact on the structural complexity, the design of the flight control surfaces, maintenance and safety. In terms of safety, one-engine-out situations will be far less critical, especially when one considers the relatively poor directional stability of the BWB configuration.

Figure 1. Artist impression of a BWB featuring distributed propulsion with boundary layer ingestion.

This paper describes the results of a quantitative assessment of distributed propulsion systems using embedded, boundary layer ingestion engines applied to blended wing body aircraft. The goal of the research is to determine in the conceptual design phase if the combination of boundary layer ingestion and distributed propulsion is effective in application with BWB aircraft and

if so, to determine which configuration is most effective in terms of fuel consumption savings. This research was conducted as master thesis research at Delft University of Technology. An artist impression of the BWB configuration featuring boundary layer ingestion combined with distributed propulsion is given in Fig. 1. The BWB aircraft developed in the European MOB-project is adopted as template for the generic BWB aircraft used in this study. This aircraft was the result of a multidisciplinary design optimization performed by a consortium of companies, research institutes and universities[7].

The structure of this paper is as follows. First, the overall approach of the research is described, including the assumptions made. The modeling of the BLI (distributed) propulsion system in terms of gas turbine performance, weight prediction, scale effects and mission analysis, is treated in Section III. A numerical optimization using genetic algorithms is performed to design the various propulsion systems analyzed in this study. This is presented in Section IV, followed by the results. Finally conclusions and recommendations are made.

II. Overall Approach

The objective of the study is to compare the performance of distributed propulsion systems featuring BLI engines to that of a conventional propulsion system applied to a BWB aircraft. Both an 8- and 12-engine distributed propulsion system with BLI are evaluated and compared to a 3-engine classic strut-mounted propulsion system. Furthermore, a 3-, and 4-engine BLI propulsion system are also evaluated to obtain more insight in the separate effects of distributed propulsion and boundary layer ingestion.

The fuel mass flow W_{fuel} at start-of-cruise is taken as figure of merit. It is evaluated for two values of combined inlet- and S-duct[§] pressure recovery, π_{1-2}. The following values for π_{1-2} are considered: a reasonable value $\pi_{1-2} = 0.97$ which takes into account the in literature suggested additional 2% pressure loss resulting from the S-duct[8] and a pessimistic value $\pi_{1-2} = 0.95$ that could reflect increased pressure losses due to flattening of the intake[**,5].

Optimal engine-aircraft combinations for both BLI and non-BLI propulsion systems are obtained by numerical optimization of mission fuel weight for a 12500 km cruise mission. Therefore an optimizer environment is developed which couples a genetic algorithm optimizer with a gas turbine performance tool, a gas turbine weight prediction tool and a mission performance tool.

To simplify the design process it is decided to optimize the aircraft-engine combinations for cruise only which was found to give a reasonable estimate of the static sea-level thrust requirement.

The propulsion systems are designed for equal technology level by selecting an appropriate maximum allowable turbine temperature which applies to all propulsion systems.

Limitations of physics and technology are kept apart from the difference in current application and from the differences in previous availability of development resources. This is necessary since engines of different size are considered for the same application and since currently large engines are further developed than small engines due to larger development budgets in the past. This means that current limitations for small engines may stretch out beyond today's limits when full development resources are allocated to the development of small engines. An example is the high pressure compressor last stage minimal blade height constraint which is set lower than the current limit of today's production techniques.

A limitation of physics associated with the use of small engines are the increased viscous losses due to a lower Reynolds number, also known as scale effects[5] or P1 effects[9]. These are considered secondary (weak) effects, but when comparing engines of different size its influence on compressor and turbine efficiencies cannot be neglected.

Various engine configurations can be considered an option for both propulsion systems, but this study is limited to unmixed three-spool engines. Similar results are expected for two-spool and/or mixed engine configurations. A proper embedding of BLI engines probably requires mixed engine configurations, but to keep some transparency in the results and simplicity in the design, unmixed configurations are used.

III. Modeling

A. Boundary Layer Ingestion Modeling

With embedded engines it is not quite straightforward anymore to distinguish airframe drag from the aerodynamic forces acting on the propulsion system and the propulsive force. New definitions of thrust and efficiency are therefore derived that allow the independent evaluation of aircraft and propulsion system for embedded engines. These new definitions are based on an equivalent intake velocity V_i in the manner of Lundbladh

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[§] An S-duct is necessary to offset the flow vertically to preserve a smooth outer airframe shape.

[**] Flattening of the intake is another means of increasing the amount of ingested drag.

and Grönstedt[5] based on Smith[10]. Here, V_i is the velocity immediately upstream of the intake and it should be taken as the velocity which at the freestream static pressure gives the same total pressure as that at the engine intake.

The ingested drag Ding, as defined by Lundbladh and Grondstedt[5], is the momentum deficit in the air ingested by the propulsion system corresponding to part of the viscous drag of the aircraft.

From a simple momentum balance on a control volume starting from free stream up to the embedded engine intake (Fig. 2) it follows that:
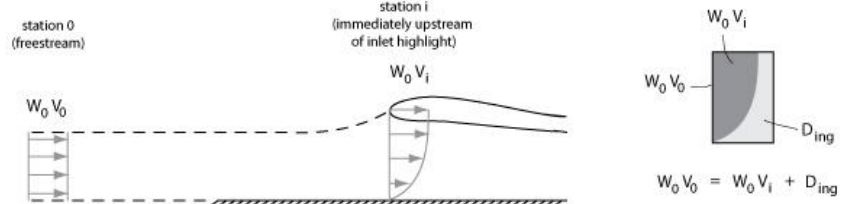

Fig. 2 Control volume from free stream up to the embedded engine intake

$$W_0 V_0 - D_{ing} = W_0 V_i \tag{1}$$

Where, W_0 represents the free stream mass flow through one engine and V_0 the free stream velocity of this mass flow. Using V_i instead of V_0 in the common expressions for net thrust, propulsive- and thermal efficiency gives:

$$F_{NBLI} = W_0 (V_j - V_i) \tag{2}$$

$$\eta_{pBLI} = \frac{V_0 T_0}{\dfrac{W_j V_j^2}{2} - \dfrac{W_0 V_i^2}{2}} = \frac{V_0 T_0}{P_j - P_i} \tag{3}$$

$$\eta_{thBLI} = \frac{\dfrac{W_j V_j^2}{2} - \dfrac{W_0 V_i^2}{2}}{W_{fuel} FHV} = \frac{P_j - P_i}{W_{fuel} FHV} \tag{4}$$

Using these definitions, the engine thrust and efficiency do not depend on the airframe drag upstream of the engine. In fact, they purely depend on the process from the engine intake to the exhaust[5]. Note that the definitions reduce to their non-BLI counterparts when the corresponding intake velocity is used, i.e. when V_0 is used instead of V_i. Hence, the introduction of V_i allows us to treat BLI propulsion systems in the same way as strut-mounted systems.

The definitions of thrust and efficiency are expressed in terms of V_i, where V_i is evaluated from the total pressure at the intake. Hence, this approach still requires some means of obtaining the total pressure at the engine intake. High-fidelity computations on total pressure losses due to viscosity require Navier-Stokes analysis. However, CFD calculations are being avoided in this study since these require too much computational effort in the conceptual design stage.

A useful concept to estimate V_i without using detailed CFD analysis is the concept of D_{ing}/T proposed by Smith[10]. Here, D_{ing}/T is a fixed parameter which is a measure of the amount of ingested drag as fraction of the net-propulsive force, or when considering steady flight as fraction of airframe drag since $T_N = D_A$ in steady flight. Applying the concept to Eq. (1) results in:

$$V_0 - V_i = \left(\frac{D_{ing}}{T} \right) \frac{T_N}{W_0} \tag{5}$$

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Where T_N should be taken as the net propulsive force provided by one engine and W_0 as the mass flow through one engine. The attainable D_{ing}/T depends on the ability of the propulsion system to pick up enough boundary layer air and is dependent on engine size, engine location and airframe drag composition.

The fidelity of the results obtained with this method relies heavily on the accuracy of the estimation of D_{ing}/T. Therefore, future work on this subject should include CFD calculations to verify the assumptions made in this research study.

For the BLI propulsion systems, the propulsion related drag is reduced to 30% of the strut-mounted value due to elimination of the pylon and lower friction drag due to lower wetted area. Nacelle weight is reduced with 50% since the wing surface replaces part of the nacelle outer fairing. The remaining 50% weight represents the weight of a sealed bay to confine the engine and S-duct. Aircraft drag for the BLI case is assumed to be equal to that of the classic propulsion case.

For a more detailed understanding of modeling BLI the reader is encouraged to read Ref. 11 where also the equivalent velocity approach is checked for consistency with the original expressions derived by Smith[10].

B. Gas Turbine Performance Modeling
The general procedure for engine cycle evaluation is as follows:

1. Estimate the attainable D_{ing}/T
2. Calculate the corresponding equivalent intake velocity V_i
3. Calculate from V_i the corresponding free stream total pressure loss, π_{0-1}
4. Evaluate the engine cycle with the obtained V_i and π_{0-1}

A new design point gas turbine performance tool is developed in the Matlab environment to evaluate the engine cycle of a three-spool high bypass turbofan engine. The performance tool is a 0D model since the averaged fluid characteristics are computed at discrete positions inside the engine, that is, at the inlet and the outlet of each component. An off-design performance tool is also developed although it is not used in this study since only design point performance is used to evaluate the cruise mission. Both performance tools are structured such that their components can be replaced with higher fidelity ones.

The application of the design performance tool is not restricted to the current optimizer environment since it can be used in a generic sense, possibly even in a MDO framework. It can also be used for different aircraft configurations like for example the Prandtl-plane or it can be updated to model a different engine configuration.

The International Standard Atmosphere is used as atmosphere definition. The used thermo-chemical gas model is a variable specific heat (VSH) gas model in which the variation of specific heat at constant pressure (c_p) varies with temperature and chemical gas composition. This model is based on correlations and coefficients proposed by Walsh and Fletcher[9]. Both models, i.e. the atmosphere and thermo-chemical gas model, can be replaced by higher fidelity ones.

The developed gas turbine performance tool includes reductions in polytropic efficiency of rotating components which represent additional internal losses for small engines due to low Reynolds number and higher leakages. These higher losses are called scale effects and their modeling is discussed below.

In order to obtain a level of confidence regarding the modeling error which originates from the use of a lower fidelity thermo-chemical gas model, data obtained with the performance tool is compared with data from the commercial codes GasTurb and GSP. It is shown in table 1 and in more detail in Ref. 11 that the overall performance parameters are all within a 1% error with respect to values obtained with the commercial codes.

Table 1. Modeling error with respect to commercial codes GasTurb and GSP at cruise flight conditions

	Fuel consumption	Propulsive efficiency	Net-installed thrust
GasTurb	0.76%	0.19%	0.76%
GSP	0.86%	0.23%	0.93%

C. Gas Turbine Weight Prediction
The gas turbine weight is predicted by a semi-empirical method proposed by Gerend[12]. This method is based on statistical correlations derived from a broad engine database. The gas turbine weight is proportional to the engine mass flow and is corrected with a number of correction factors which take into account the effect of bypass ratio,

combustor outlet temperature, overall pressure ratio, air mass flow and technology level. Although, the model dates back to 1970, moderate projections to future configurations have been found to give reasonable results. The shift of the reference engine from a 1962 turbojet to a 1985 turbofan (Trent 772) reduces the extrapolation cumulative prediction error. Nacelle weight is correlated to standard day corrected mass flow. According to Lundbladh and Grönstedt[5] a linear extrapolation gives reasonable results. Due to limited data on nacelle weights, it was difficult to find an appropriate coefficient for the linear extrapolation. Since for the Trent-series nacelle weight makes up about 22% of the total propulsion package (see Bradley[13]) it was decided to use a linear coefficient of 1.45. The weight module was validated by predicting the weight of 15 modern gas turbine engines all within 20% accuracy.

D. Turbofan Scale Effects Modeling

Turbofan scale effects are modeled by variations in compressor- and turbine efficiency with size. Polytropic compressor efficiencies are correlated to a Reynolds number of the high pressure compressor exit. Often the efficiency is related to turbulent skin friction losses (a function of $Re^{-0.2}$) only, which would neglect the advancements in secondary flow reduction of newer designs. Lundbladh and Grönstedt[5] deduced a power law, Eq. (6) that provided a good fit for state of the art compressor and turbine data. Since this fit is based on statistical data, the reduced secondary flows of the newer designs are taken into account at least approximately. For compressors Lundbladh and Grönstedt use:

$$\eta_c = 1 - C_c\, Re_{c,out}^{-0.4} \tag{6}$$

$$Re_{c,out} = \frac{\sqrt{W_{c,out}^*}\, P_{c,out}}{T_{c,out}^{1.7}} \tag{7}$$

where W^*_c, out is the normalized mass flow and C_c is a constant. The idea behind the correlation is that the normalized mass flow is related to the physical size of the HPC outlet, which in turn is related to flow losses because of tip clearance, viscous effects, geometry deviations and surface irregularities.

Note that the relation in Eq. (7) is a stronger relationship than the $Re^{-0.2}$ expected from turbulent skin friction only. The Reynolds number definition is consistent with a blade velocity independent of compressor size and that the hub-tip ratio and blade aspect ratio does not have a significant trend with size. Turbine polytropic efficiencies are related to a Reynolds number based on the HPT inlet:

$$\eta_t = 1 - C_t\, Re_{t,in}^{-0.2} \tag{8}$$

$$Re_{t,in} = \frac{\sqrt{W_t^*}\, P_{t,in}}{T_{t,in}^{1.7}} \tag{9}$$

The constants C_c and C_t are set in such a way that the correlations are calibrated to the efficiencies used in the classic propulsion system.

Fan flow is dominated by transonic and shock losses and Lundbladh and Grönstedt[5] did not detect a strong correlation with size. Combustor flow losses are designed for combustion stability and do not vary with engine size. Other flow losses are small and their dependence on size can be neglected.

E. Mission performance

The mission performance assessment evaluates the cruise drag and covered range for a certain mass flow and fuel weight respectively. Both parameters, mass flow and fuel weight, are iterated in the optimization as explained in section IV. Cruise drag is obtained from a simple lift-drag polar based on aerodynamic data of the MOB aircraft and covered range is calculated via the Brequet range equation.

IV.   Numerical Optimization

A. Optimizer environment

The general method used for the optimization is that of Whellens[16]. Whellens successfully applied a genetic algorithm to optimize the intercooled recuperative turbofan engine for various engine – aircraft combinations. The optimizer environment in the current study consists of several Matlab routines, Two main sets of routines can be identified; (1) the genetic algorithm and (2) the gas turbine and mission performance routines. In short, the gas turbine performance model is capable of predicting the performance of a given propulsion system in a given flight condition. This routine is combined with a weight prediction tool and a mission performance tool such that the overall mission performance of the aircraft engine combination can be analyzed in terms of fuel consumption. The genetic algorithm is then used to optimize the complete system, i.e. to find the engine specifications that result in minimal fuel consumption for a given configuration (e.g. 12 embedded engines). The overall structure of this system, which is similar to that of Whellens[16], is presented in Fig. 3. The main data flows within the optimizer are shown schematically in Fig. 1. The main boxes in the analysis are; the gas turbine performance module, the gas turbine weight prediction module and the mission performance module.
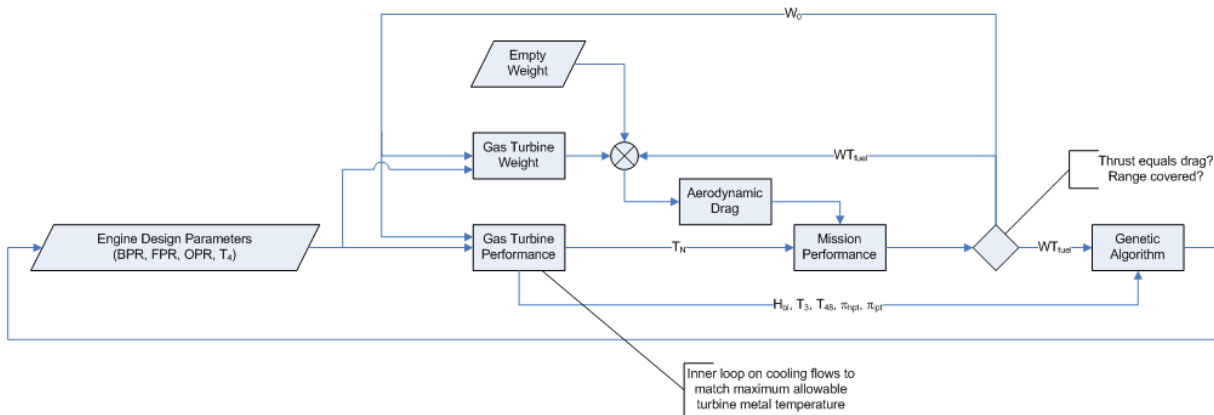

Figure 3. General layout of optimizer environment

Each aircraft-engine combination analyzed by the GA is described by a vector of four design parameters: bypass ratio (BPR), fan pressure ratio (FPR), overall pressure ratio (OPR) and turbine entry temperature (T_4). Each individual is analyzed by the genetic algorithm and a fitness value is assigned to it. The overall objective is to minimize the mission fuel weight. The fitness value depends on the value of the objective function. If constraints are violated, then penalties are introduced in the fitness value. The constraints imposed in the optimization routine are the following:

- Minimum blade height of the last HPC stage (h_{bl}). This constraint reflects the difficulty with manufacturing small compressor blades and the high aerodynamic losses associated to small compressor blades.
- HPC outlet temperature (T_3). This constraint translates the material capability of the last compressor stages which is one of the limiting factors to OPR that can be achieved.
- LPT inlet temperature (T_{48}). This constraint reflects the material capability of the low pressure turbine since this one is uncooled.
- HPT and IPT pressure ratios (π_{HPT} en π_{IPT}). These constraints are imposed to limit the turbines to single stage turbines from a weight point-of-view.

Table 2 lists the numerical values of these constraints used in the optimization studies.

Table 2. Applied constraints and their numerical value

h_{BL}	>	11 mm
T_3	<	850 K
T_{48}	<	1100 K
π_{HPT}	>	0.25
π_{IPT}	>	0.25

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An internal loop within the analysis tool ensures that the inlet mass flow at cruise is sufficient to ensure equilibrium at the cruise condition, that is: the gas turbine is capable of delivering the required net propulsive force. The fuel weight is also iterated in the loop to ensure the right amount of fuel is brought along. Another loop inside the gas turbine performance tool ensures proper cooling flows are assigned to match the maximum allowable metal temperature in the HPT and IPT. This maximum allowable metal temperature represents the technology level of the engine and is equal for both BLI and non-BLI propulsion systems.

B. Genetic Algorithm based Optimizer

Genetic algorithms (GA) are an example of a non-gradient based optimization method and are often used in optimization problems for engineering applications. They are based on the underlying genetic process in biological organisms and on the natural evolution principles of populations. Some examples of GAs utilized in the gas turbine design process can be found in Refs. 14-18. Especially Whellens[16] proved to be very useful in developing the GA for the optimization process in this study. The same approach is followed with some adjustments to the internal looping system and to the GA's operators.

The overall process of the GA is presented in Fig. 4. The basic idea is to maintain a population of chromosomes, which represents search space solutions to the minimization problem that evolve over time through a process of competition and controlled variation.
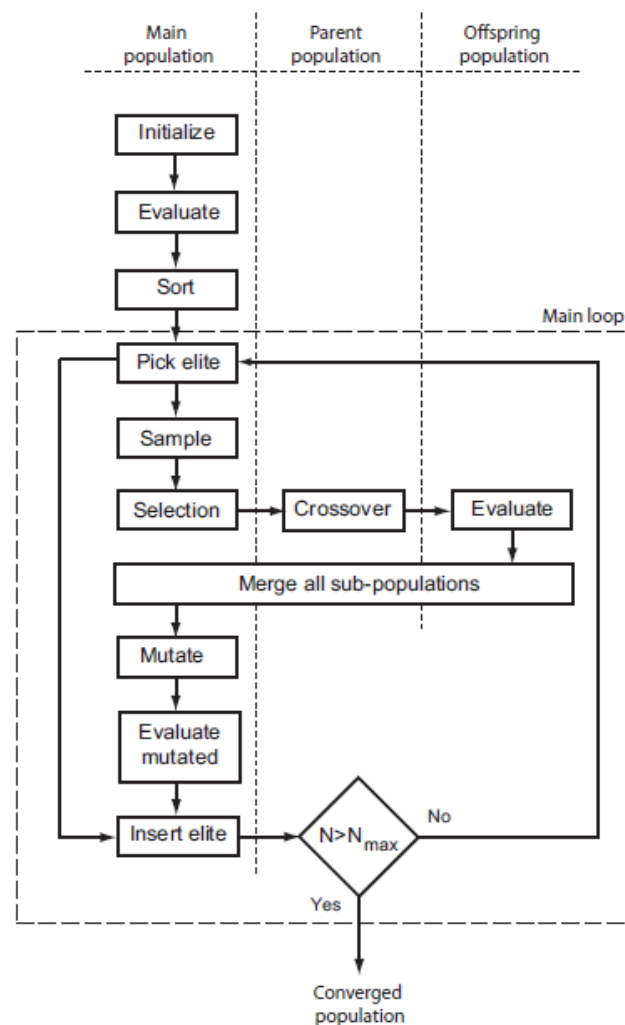

Figure 4. Overall structure of Genetic Algorithm optimizer

The optimization starts by initializing a random population. The fitness of the population (total fuel weight needed and penalties for violated constraints) is then evaluated and the population is sorted accordingly. Elitism is

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an option in the process that can be selected by the user. When selected, the best individual of a population is determined and placed in the next generation. This option reduces the required number of iterations. Now the population is sampled by a 'stochastic universal sampling' method. After sampling, the selected chromosomes are then mated through a one-point BLX-α crossover operator which includes an exploration factor. A tournament selection technique is used to combine the new offspring with the main population. In order to keep diversity levels high, the population is subsequently mutated by a dynamic mutation algorithm. Dynamic mutation applies several mutation operators simultaneously and adjusts the probability of each operator according to its progress towards the minimum. Here, random mutation and non-uniform mutation are used. This iterative process is repeated until the maximum number of generations is reached or when the change in the average fitness value becomes lower than a user-defined value. Before applying the algorithm to the engineering problem in this paper, it was tested on several relatively simple test functions provided by Herrera[19] and Michlewicz[20]. For these test functions, which included constrained and un-constrained functions, the minimum or maximum were found after a couple of thousand generations.

V. Results

The evaluated propulsion systems are summarized in table 3. The 3-engine non-BLI propulsion system ($D_{ing}/T = 0$) is used as reference for the other propulsion systems.

Table 3. Evaluated Propulsion Systems

Engines	3	3	4	4	8	8	12	12
D_{ing} / T	-	0.03	0.05	0.05	0.15	0.15	0.20	0.20
π_{1-2}	0.99	0.97	0.95	0.97	0.95	0.97	0.95	0.97

The optimization results are displayed in Fig. 5 as function of the number of engines for the two values of combined inlet and S-duct pressure recovery. The solid line represents the optimistic intake pressure loss and the dashed line the pessimistic loss. The results in Fig. 5 are plotted as fraction of the non-BLI configuration value. More detailed data on the propulsion systems is presented in the appendix.

From the numerical results on cruise fuel consumption it can be concluded that the potential of distributed propulsion systems relies heavily on a weak dominance of beneficial effects over negative effects of similar magnitude. High efficiency cycles are required to obtain beneficial effects. Decreased component efficiencies (increased losses) due to scale effects and intake pressure recovery form a solid bottleneck in achieving this high efficiency cycle. The 8-engine propulsion system shows a 2% fuel consumption benefit over the classic propulsion system. But this benefit is cancelled by a not unrealistic 2% increase in pressure loss. The 12-engine propulsion system does not show a fuel consumption benefit at all.

It gives reason from a performance point of view to abandon the distributed propulsion concept and to focus on larger engines instead since they do not suffer high internal losses. As an illustration of this, a 4-engine configuration has been evaluated which showed a 3% reduction in fuel consumption for a 2% increase in pressure loss. The 3-engine configuration shows a 5% reduction in fuel consumption for the optimistic intake pressure loss.

From Fig. 5 it can be concluded that in terms of minimal fuel consumption the 3-engine BLI propulsion system is the most promising concept of all investigated concepts. Subsequently, a sensitivity analysis is conducted to show the influence of the parameter D_{ing}/T on the designs.

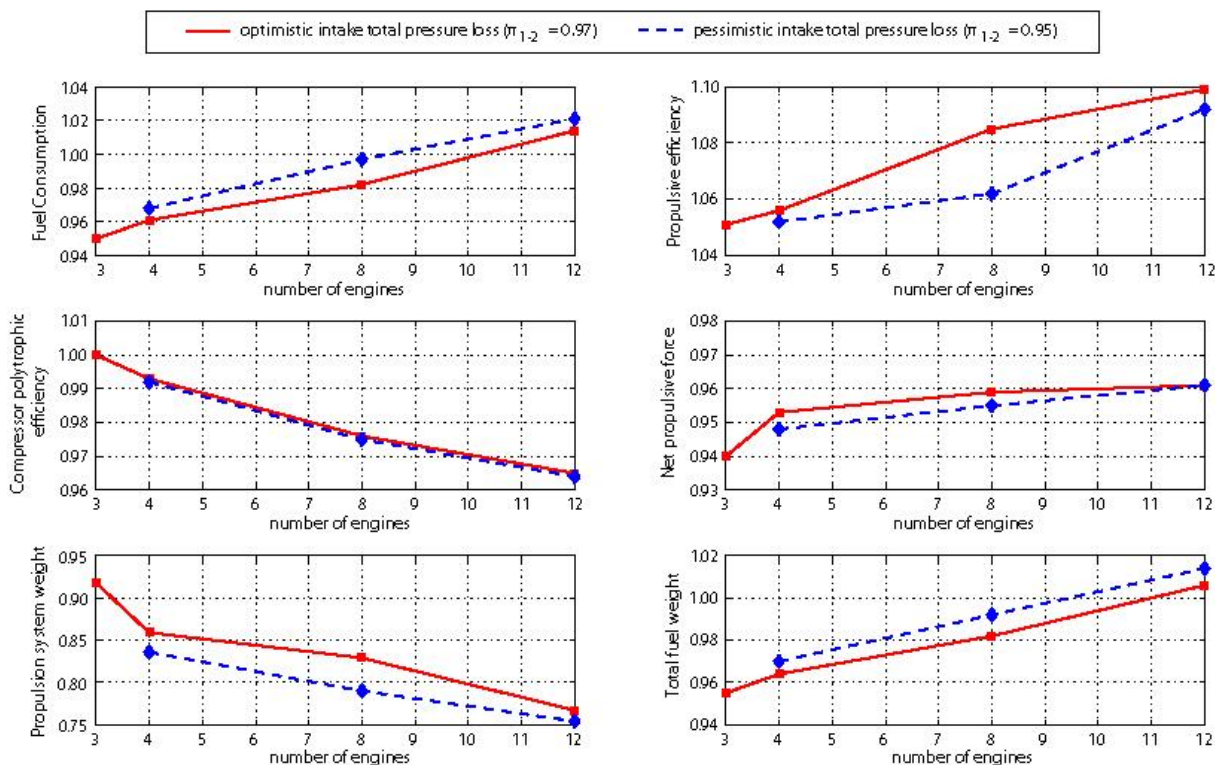American Institute of Aeronautics and Astronautics

Figure 5. Optimization results displayed as fraction of non-BLI configuration.

The sensitivity analysis (Fig. 6) shows that a larger amount of ingested drag results in a slightly lower fuel consumption and a slightly larger propulsive efficiency. The engine design parameters change accordingly. That is, the overall pressure ratio increases, fan pressure ratio increases and the bypass ratio decreases with larger amounts of ingested drag. Based on this sensitivity analysis, it is deemed that the overall conclusions, as presented before, still hold.

When safety is associated with the required rudder deflection to trim the aircraft with the critical engine inoperative it can be concluded that from a safety point of view, the distributed propulsion systems outclass the classic system. Since the generated asymmetric thrust moment becomes smaller with increasing the number of engines. This can be valuable since BWB aircraft have small directional control power even when all engines are operative
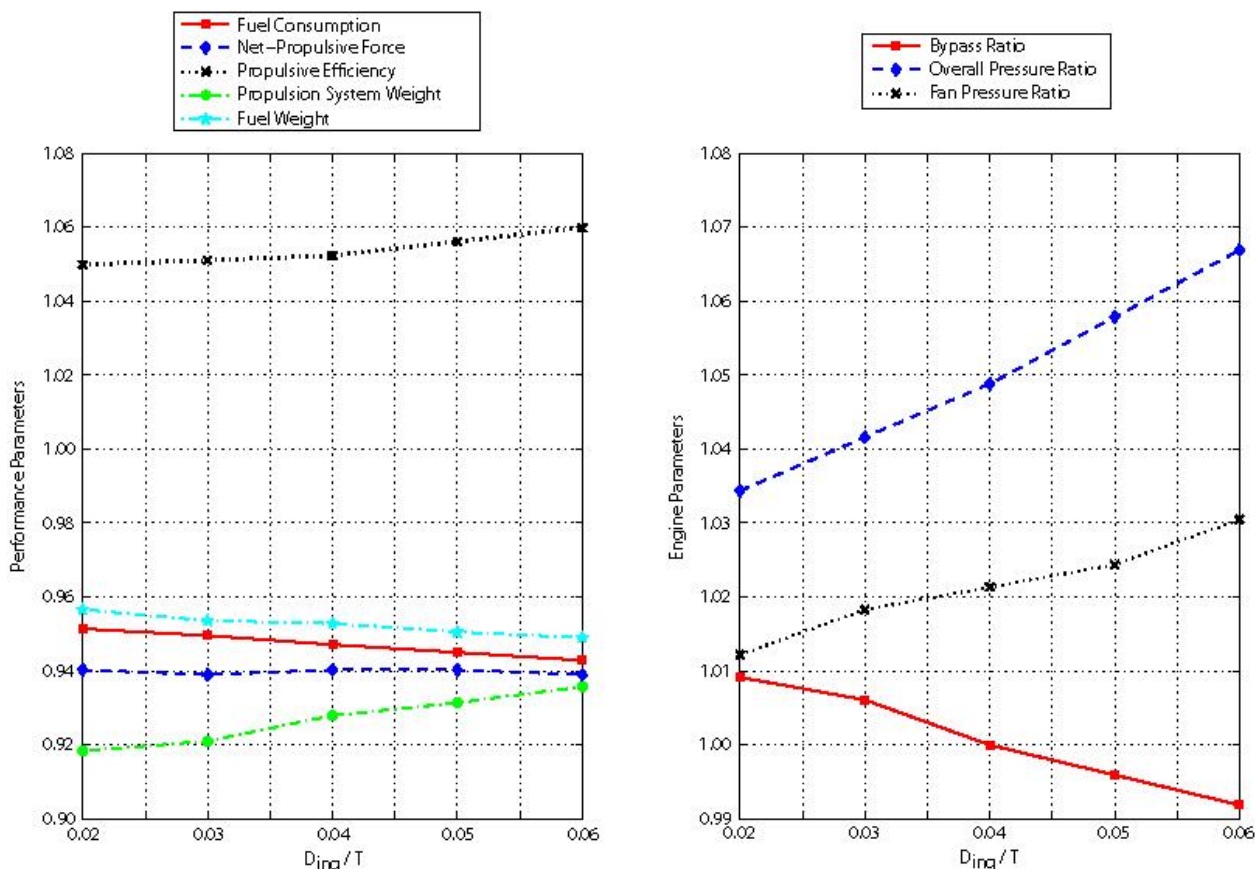
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Figure 6. Sensitivity analysis on D_{ing} / T for the 3-engine configuration

VI Conclusions

Overall it can be concluded that BLI shows better potential when applied to large engines since small engines feature high efficiency losses due to scale effects which realistically cannot be overcome by the beneficial effects of embedding the engines and ingesting part of the aircraft boundary layer. Also the increased number of accessory systems, like for example additional fuel system components will increase maintenance work and most likely also maintenance cost.

Therefore distributed propulsion must be avoided, although it decreases the directional control power requirement in critical engine out conditions since the generated asymmetric thrust moment will be smaller. This is valuable for BWB aircraft since they have small directional control power even when all engines are operative.

The most promising configuration is the 3- engine configuration with BLI engines. This configuration shows an improvement of approximately 5 percent in terms of fuel consumption for a given mission. The results clearly depend on the assumed amount of ingested drag as a fraction of thrust and also on the assumed pressure recovery of the combined inlet/S-duct. A sensitivity analysis of the assumed amount of ingested drag as fraction of thrust on the overall performance shows that for the most promising 3-engine BLI configuration, fuel consumption and decreases slightly and propulsive efficiency increases slightly with increased amounts of ingested drag.

It is a recommendation for further work to commence a detailed design study into the most promising configurations (3- and 4- BLI engines). It would be very useful to determine the actual amount of ingested drag and the pressure losses in the S-duct with CFD calculations.

Appendix

Table 5 contains detailed data on the classic and 3-engine BLI ($D_{ing/T} = 0.03$) propulsion system.

Table 5. Detailed propulsion system data

Parameter	Unit	Classic	BLI
Number of engines	[-]	3	3
π_{1-2}	[-]	0.99	0.97
D_{ing}/T	[-]	0	0.03
BPR	[-]	9.84	9.90
T_4	[K]	1656	1627
FPR	[-]	1.64	1.67
OPR	[-]	55.3	57.6
W_0	[kg/s]	603	597
$\eta_{c,hpc}$	[-]	0.910	0.909
$\eta_{c,ipc}$	[-]	0.910	0.909

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