Multi-Objective Optimization of a Conventional and Regenerated UHB Turbofan

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The evolution of aircraft gas turbine engines from turbojets to the first generation of turbofans with low bypass ratio resulted in the goal of improving the engine efficiency. Today high bypass ratio turbofans are the most globalized type of engine in commercial aviation. Following many years of technological developments and improvements, this type of engine has proved to be the most reliable facing the commercial aviation requirements. In search of more efficiency, the engine manufacturers tend to increase the bypass ratio leading to an ultra-high bypass ratio (UHB) engines. Increased bypass ratio has clear benefits in terms of propulsion system like reducing the specific fuel consumption. This study applies a multi-objective optimization to and ultra-bypass ratio engine, with the objectives of reducing the specific fuel consumption (TSFC) and maximizing the specific thrust. Also it is considered an alternative engine cycle (regeneration) where it is evaluated the possibility of introduction of this cycle in this new range of bypass ratios.

Nomenclature

BPR = bypass ratio
C_p = specific heat
C_{pc} = specifc heat of the cold air
C_{pg} = specifc heat of the hot gases
CROR = counter rotating open rotor
ft. = flight altitude
GA = genetic algorithms
GTF = geared turbofan
HPC = high pressure compressuror
IR = intercooler and regenerator
K = temperature
LPT = low pressure turbine
MO = multi optimization
m/s = velocity
N = force
N_{ox} = nitrogen oxides
OPR = overall pressure ratio
Pa = pressure
Q_{net} = average calorific power of the fuel
R = specifc gas constant
rpc = compressor ratio
rpfan = fan pressure ratio
SFC = specifc fuel consumption
ST = specifc thrust
TET = turbine entry temperature
TSFC = traction specifc fuel consumption
UHB = ultra-high bypass ratio
γ = adiabatic index

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γ_c = adiabatic index before combustion
γ_g = adiabatic index after combustion

I. Introduction

The increasingly manifestations of the planet's environment, are leading to a society that more than ever, needs to pay attention to all the issues that dictate the future years of environmental stability. The environment should not represent the final barrier in any industrial/technological areas, avoiding them to develop, but it has to be taken as the main path to bring them to the next level. For now and for the future, they must give more environmental benefits and performances than their predecessors. . The propulsion area must be one of the leading areas to give the example and show proofed results of this shifting. Since the appearance of the first aircrafts that the Aeronautical World has its footprint in the planet's environment and being one area where propulsion is more advanced, it is imperative that changes take the first steps there. The aircrafts are major fuel consumers and for that, a contribution in global warming is due to their activity. Designing new engines where the consumption is reduced significantly and the values of its performance are not compromised, are the plans of engine manufacturers in the present and future. It is necessary to study future possibilities that put the bets even higher, always with the intention of contributing for a more eco-friendly and powerful engines that will take the planet in consideration.

Many works have been developed in the last 30 years related to the possible ways to improve the performance of the Turbofan engines. Intentions of optimization of these kinds of engines have always been present after they proved in early years of service, their fantastic capabilities in commercial aviation. The goals of reducing fuel consumption and recently cutting pollutant emissions turned the attentions once more to a successfully applied concept in ground systems for many years: regeneration. With the recent UHB Turbofan engines for single aisle aircraft announced to be introduced in the market alongside with new the airframes in the near future, it is important to review the past and recent work investigations related with this type of engine. Different approaches of Turbofan optimization as well as the tools and technologies developed, are summarized in this section to help understand the path taken until the present days. In the first place, we analise a report[1], that translates the trend of aero engines market in the year of 2012 and predicts the behaviour of the market for the next years. This study shows that the delivered powerplants to the majority of the airliners are from the CFM International and Pratt & Whitney. It is up to these manufacturers to supply the next generation of narrowbodies in order to enable a step-change in operating economics. With the new A320neo and 737 Max arrivals in a few months choosing the right engine never have been more important or harder. "The choice between the CFM Leap-1A and P&W PurePower1100G is no longer a soft bet on a secondary supplier to an already chosen airframe." With a more attention to the Airbus 320neo, the airframe has some minor changes except the engine that will power it. The commitment and strategies of the engine makers to achieve the 15% rise in fuel efficiency imposed by Airbus, translates this is not a simple race to see who provides the engine but can be the choosing side from the airliners for the technology that dictates the future of gas turbine technologies. From one side, the debate of the reliance on new and exotic materials by the Leap-1A and on the other side the introduction of a reduction gear inside the PW1100G. In the near future, CFM will equip the 737Max with the Leap engine, although it can be an option for the A320neo. However the second option for the new A320 is the Pratt & Whitney PW1000G geared turbofan.

Focusing our attention to the engine parameters, we can find several studies where the objective is directed to study the thermodynamic cycles of the engines in an attempt to lower pollutant emissions to the environment. According to the authors[2], pollutant emissions in commercial aviation, have been a concern since the 1960s. In the authors' vision, operational changes in the airline flight profiles would benefit the reduction of NO_x but would involve a major economic penalty. It is reminded that the total exhaust emissions are a result of the overall efficiency of the aircraft. This includes the thermodynamic cycle of the engine as well the aerodynamic drag of the airframe. Due to the high emission of gases in the atmosphere in modern aviation, alternative cycles applied to the direct drive turbofan could be the answer to ensure more efficient and environmental friendly engines. The need of reducing fuel consumption is not only related to the rising costs of fuel, but also the idea of increasing the maximum payload. This is achieved by improving the global efficiency of the engine which is dependent of the propulsive and thermal propulsive efficiency. The authors[3] advance that the trend in actual propulsion systems is to use very high values for cycle maximum temperature, with an increasing discharge temperature due to operative modalities of the discharge nozzle, often working in off design conditions. This makes the heat discharged a strong influence in the system performance and heat recovery appears to be a way that needs further improvements and investigations. However there are limitations to implement this concept like the engine configuration and limitations, as weight, overall dimensions and reliability. According to the authors[3] the concept of regeneration in a turbofan is particularly interesting at high by-pass ratio. Results show that the recovery not only influences the process positively but also amplifies the influence of other operative parameters, being the conventional heat transfer method the one that revealed minimum level of fuel consumption compared to the others. However, the thermal efficiency is always better when the heat transfer is processed during the expansion. As conclusions, based on results, the authors enhance the regeneration as the possibility of improving the engine characteristics. Another study[4], following alternative thermodynamic cycles applied to high bypass ratio turbofans was performed. The results with regeneration, show a higher thermal efficiency, than the conventional case. However, these results are valid for low pressure ratios. The propulsion efficiency is also superior than the conventional situation but once more at lower pressure ratios, due to the reduced gas kinetic energy in the exhaust, since the heat extracted has been subtracted in the heat exchanger. To finish their study, the authors, enhance the problems of size, weight and integration with the engine and the aircraft in both concepts (regeneration and intercooling). Another way to manufacture better environmental engines is the introduction of heat exchangers on engines with two spools[5]. The conclusions of this work revealed that the engine only with intercooler has the worst SFC results and lower thermal efficiency. The engine with intercooler and regenerator has better SFC and thermal efficiency compared to the conventional engine used in this study, “But it is not the one with better values of specific fuel consumption and thermal efficiency. The engine with only regeneration has the lowest values of specific fuel consumption and the highest for thermal efficiency.” The IR also has lower values of performance compared to the engine with only regenerator. “With this behaviour can be deduced that the influence of the regenerator is larger than the intercooler for the range of parameters considered.” The engine with regenerator is pointed to be the best in SFC and thermal efficiency. Regarding the thermal efficiency, it is suggested[6] that increasing the overall pressure ratio (OPR) and the turbine entry temperature (TET) is necessary to achieve the desired goals. The geared turbofan concept is the answer suggested by the author for aiming those kinds of bypass ratios and OPRs. Later, an analysis of the concept and the development status of the geared turbofan is made[7]. This concept represents the next step in performance, emissions (due to low fuel burn), noise and does not impose unreasonable risk to the customer, as a more revolutionary step like the counter-rotating turbo machinery concept. However the open rotor concepts can provide higher TSFC and fuel burn benefits, they are struggling with achieving noise requirements and the technology improvement is still one decade away. There is a need of dramatic changes of engine/airframe integration. An optimization study of the GTF engine is performed, where the authors[8] concluded that all characteristics combined with other structural innovations can potentially deliver fuel benefits for GTF engine. The weight reduction and the lower stage loading with higher component efficiencies prove to be the next step of the turbofan market. The two future engine concepts (Geared Turbofan and Open Rotor) are often compared in similar conditions. While the first is the next step in ducted turbofans, the other brings a more revolutionary arquitecture design. Benefits and drawbacks meet these two kinds of engine and are exposed in a recent study[9]. As conclusions from this work, the authors state that despite the weight penalty of 28% of the CROR compared to the GTF, its propulsive efficiency outweighed the issue with a 12-13% fuel burn cut over the GTF. However engine installation effects of the study need to be more developed to assure the described benefits, which sustains[7] conclusion of this topic. Nevertheless, the authors point the open rotor as the next answer over the near term new engines (PW1000G and LEAP-X) with the potential to offer even more benefits for the 2025 engine generation. Another similar study[10], in which a geared open rotor and an ultra-high bypass ratio geared turbofan engine are compared and assessed. Results show that the open rotor concept provides substantial fuel saving potential compared to the ducted fans, it gives 14% lower SFC than the GTF. Although heavier in weight, the reduced SFC and nacelle drag can compensate the drawbacks. The variation of the open rotor bypass is bigger than the GTF in different operating points.

The new GTF engine will be the next turbofan step in commercial aircraft for the next years. This technological step will represent the best answer in current technology to cut down pollutant emissions; however, the application of alternative cycles creates the question if the goals can be pushed further. These cycles were previously studied in the direct drive turbofans and now are starting to be explored in this next engine generation.

Finding the best combination of parameters to achieve an engine that combines the maximum SFC with the lowest TSFC, is where the multi optimization through genetic algorithms appears ti be a very useful tool for this purpose. The purpose of the work[11] is to give a general formulation of MO optimization, Pareto optimality concepts and solution approaches. The investigation performed enhance that “Optimization is an essential process in many business, management, and engineering applications. In these fields, multiple and often conflicting objectives need to be satisfied.”. A former study[12], consisted in a multi-objective optimization performed in a turbofan, which the objectives were to minimize the specific fuel consumption at cruise conditions, as well as to maximize the specific thrust during the take-off phase. As conclusions the authors highlight the contributions of the GAs providing the best solutions to this particular problem and suggest that additional effects such as noise, or pollutant emissions should be introduced in the model to define new variables to be evaluated. For a more realistic optimization, aerodynamic, mechanic and thermal simulations on engine components are needed in future studies.

So, this paper is focused on verification if the brand new type of engine could deliver even less fuel consumption from what is announced without compromising their performance, providing a set of viable and optimized options of configuration.

I. Study Objectives and Approach

The objectives of this study are to perform a multi-objective optimization on a UHB turbofan where a conventional and a regenerated configuration are evaluated. The reference engine will be a two spool turbofan in cruise conditions. Independent engine parameters were considered (*rpc*, *rpfan*, *BPR* and *TET*) and are optimized by a genetic algorithm. With this optimization it is intended to minimize the TSFC and maximize the ST. This optimization also explores a regenerative cycle for the same engine and flight conditions. The regenerator is installed at the exit of the LPT and connects to the exit of the HPC. In the end, both optimized cycles are compared and conclusions are made.

II. Engine Parameters

Being based on the new trends of the aircraft and engine market for the next coming years, the new airframes from Airbus and Boeing (the A320neo and the Boeing 737Max), will be equipped with a new generation of engines that will have a BPR superior to its predecessors. Although these aircraft manufacturers bring new airframes to the market, the propulsion requirements of theses airframes are similar to the old ones.

For the purpose of this study, some engine characteristics will be imposed based in the propulsion requirements of the old airframes and engines. However, at the same time, it will be changed and explored the already known characteristics from the engines makers (Pratt & Whitney and CFM), like a higher BPR, higher TET, new fan and compressor ratios and an increase in efficiency of the components.

Therefore the engine in study will be based on a two shaft engine with a high bypass ratio destined to power the new narrowbodies from Airbus and Boeing (A320neo and 737Max respectively). The new engines will have BPRs superior or equal to 10.

This project creates several setups of engines by taking into account some specific imposed requirements which will be tried to match each analysis. The flight point in study will be the cruise phase. The following Table 1 shows the fixed characteristics of the engine as well as the flight phase.

Table 1. Fixed Engine and Flight Characteristics[13–15]

Cruise Altitude: 36 000 [ft.]

Cruise Temperature: 216.8 [K]

Cruise Pressure: 22 700 [Pa]

Cruise Speed: 230 [m/s]

Cruise Thrust: 32 785.839 [N]

A. Assumptions

To perform the calculations[16] to obtain the engine values, it is necessary to define some conditions and assumptions that will influence the calculation process. Therefore the assumptions are:

1) One dimensional flow;
2) Steady flow;
3) The fluid detains a perfect gas behaviour at a constant molecular weight;
4) Bleed air is not considered;
5) The compression and expansion processes are polytropic;
6) Before the combustion phase, the values of C_p and Υ for the air are: $C_{pc} = 1005\frac{J}{Kg}.K$ and $\gamma_c = 1.4$;
7) After the combustion phase, the values of C_p and Υ for the air are: $C_{pg} = 1148\frac{J}{Kg}.K$ and $\gamma_g = 1.333$;

8) The specific gas constant is $R = 287 \frac{J}{Kg} K$;
9) The temperature at the exit of the LPT must always be superior than at the exit of the HPC in order to assure the integrity of the cycle;
10) The average calorific power of the fuel is $Q_{net} = 43.1\ MJ/Kg$;

B. Component Efficiencies

The next Table 2 will present the component efficiencies that were assumed and kept constant during all the calculation process:

Table 2. Assumed Component Efficiencies[17]

Component	Symbol	Value
Admission Efficiency	η_i	0.98
Fan Efficiency	η_{fan}	0.90
LPC Polytropic Efficiency	η_{LPC}	0.90
HPC Polytropic Efficiency	η_{LPC}	0.90
Burner Efficiency	η_b	0.995
Burner Pressure Ratio	Π_b	0.96
LPT Polytropic Efficiency	η_{LPT}	0.89
HPT Polytropic Efficiency	η_{HPT}	0.91
Regenerator Efficiency	η_{reg}	0.80
Regenerator Pressure Ratio	Π_{reg}	0.95
Nozzle Efficiency	η_n	0.90
Mechanical Efficiency	η_m	0.995

II. Multi-Objective Optimization

To perform the MOO problem it is necessary to expose some concepts before procedding to its execution. Since this optimization is performed by a genetic algorithm a brief description about its methodology is presented. Later the MOO problem is mathematicaly exposed, as well as the chosen setup for this optimization.

A. Genetic Algorithm

When a Genetic Algorithm is applied, all the concepts of the Evolutionary Computation[18] are to be taken in account, since the genetic algorithm is one of the evolutionary computation paradigms.

It is used to solve constrained and unconstrained optimization problems that are based on natural selection. The genetic algorithm repeatedly modifies a population of individual solutions. At each step, the genetic algorithm selects individuals at random from the current population to be parents and uses them to produce the children for the next generation. Over successive generations, the population reaches an optimal solution. It uses three main types of rules to create the next generation from the current population:

1) Selection rules;
2) Crossover rules;
3) Mutation rules;

The advantages of the genetic algorithms against the classical algorithms for this type of optimization are mentioned by [11].

The following steps summarize how the genetic algorithm works [19]:

1) The algorithm begins by creating a random initial population;
2) The algorithm then creates a sequence of new populations. At each step, it uses the individuals in the current generation to create the next population. In order to create the new population, the algorithm performs the following steps:
    a. Scores each member of the current population by computing its fitness value.
    b. Scales the raw fitness scores to convert them into a more usable range of values.
    c. Selects members, called parents, based on their fitness.

    d. Some of the individuals in the current population that have lower fitness are chosen as elite. These elite individuals are passed to the next population.
    e. Produces children from the parents. Children are produced either by making random changes to a single parent by mutation or by combining the vector entries of a pair of parents using crossover.
    f. Finally the current population is replaced with the children to form the next generation.
3) The algorithm stops when the stopping criterion is met.

B. Multi-Optimization Problem

The purpose of this method is to explore all the possible values and combinations of the engine components in order to obtain several optimized engine setups.

Several real-world problems need simultaneous optimization of a number of objective functions. However, some of the objectives may be in conflict with one another. For example, finding optimal routes in data communications networks, where the objective is to minimize congestion, and to maximize utilization of physical infrastructure. It is considered that an important trade-off between these two objectives exists. Minimization of congestion is achieved by reducing the utilization of links. A reduction in utilization, on the other hand, means that infrastructure, for which high installation and maintenance costs are incurred, is under-utilized.

Following, is a brief description of the Multi-objective concepts applied in the MOO problem of this study using a genetic algorithm. The concepts are found in [18,19].

Let $\mathcal{S} \subseteq \mathbb{R}^{n_x}$, where n_x is the dimensional search and decision space, and $\mathcal{F} \subseteq \mathcal{S}$ is the feasible space. Note that with no constrains, the feasible space is the same as the search space. Let $x = (x_1, x_2, \dots, x_{n_x}) \in \mathcal{S}$, referred to as a decision vector. A single objective function, $f_k(x)$, is defined as $f_k : \mathbb{R}^{n_x} \rightarrow \mathbb{R}$. Let $f(x) = \left(f_1(x),\ f_2(x), \dots, f_{n_k}(x)\right) \in \mathcal{O} \subseteq \mathbb{R}^{n_k}$ be an objective vector containing n_k objective function evaluations; $\mathcal{O}$ is assumed as the objective space. Therefore the multi-objective problem is defined as:

$$\begin{gathered}\text{Minimize } f(x)\\ \text{Subject to } g_m(x) \leq 0,\ m = 1, \dots, n_g\\ h_m(x) = 0, \qquad m = n_g + 1, \dots, n_g + n_h\\ \text{Where } x \in [x_{min}, x_{max}]^{n_x}\end{gathered} \tag{1}$$

g_m and h_m are respectively the inequality and equality constraints while $\in [x_{min}, x_{max}]$ represents the boundary constraints.

Finding an optimum solution in a MOO does not represent the same as finding an optimum solution in a SO, where only one objective is optimized, a local optimum and global optimum is calculated. The main problem is the presence of conflicting objectives, where improvement in one objective may cause deterioration in another objective. As an example, the maximization of the structural stability of a mechanical structure may cause an increase in costs, working against the additional objective to minimize costs. The procedure is to find solutions that balance trade-offs between objectives. Such a balance is achieved when a solution cannot improve any objective without degrading one or more of the other objectives. These solutions are referred to as non-dominated solutions.

Therefore, the objective when solving a MOP is to create a set of good compromises, instead of a single solution. This set of solutions is referred to as the non-dominated set, or the Pareto-optimal set. Genetic Algorithm approaches for solving MOPs can be grouped into three main categories:

1) Weighted aggregation approaches where the objective is defined as a weighted sum of sub-objectives;
2) Population-based non-Pareto approaches, which do not make use of the dominance relation;
3) Pareto-based approaches, which apply the dominance relation to find and approximation of the Pareto front;

Following it will be resumed several definitions that are crucial to interpret a MOO. These definitions assume minimization.

C. Dominance Definition

A decision vector, $x_1$dominates a decision vector, x_2, if and only if:

- x_1 is not worse than x_2 in all objectives, i.e. $f_k(x_1) \leq f_k(x_2), \forall k = 1, \dots, n_k$, and x_1 is strictly better than x_2 in at least one objective, i.e. $\exists k = 1, \dots, n_k\colon f_k(x_1) < f_k(x_2)$.

An objective vector, f_1, dominates another objective vector, f_2, if f_1 is not worse than f_2 in all objective values, and f_1 is better than f_2 in at least one of the objective values.

This concept is exhibited in the Figure 1, for a two-objective function. $f(x) = \left(f_1(x), f_2(x)\right)$. The striped area marks the objective vectors dominated by f.

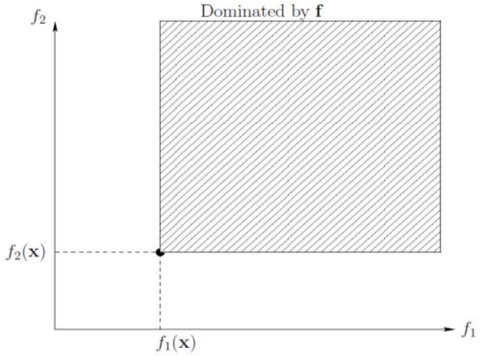

Figure 1. Dominance Example[18]

D. Pareto Optimal Definition

A decision vector, $x^* \in \mathcal{F}$ is Pareto-optimal if there does not exist a decision vector, $x \neq x^* \in \mathcal{F}$ that dominates it. This is, $\nexists k$: $f_k(x) < f_k(x^*)$. An objective vector, $f^*(x)$, is Pareto-optimal if x is Pareto-optimal.

E. Pareto Optimal Set

The set of all Pareto-optimal decision vectors form the Pareto-optimal set, $\mathcal{P}^*$. Which is:

$$\mathcal{P}^* = \{x^* \in \mathcal{F} | \nexists x \in \mathcal{F}: x \prec x^*\} \tag{2}$$

It contains the set of solutions, or balanced trade-offs, for the MOP. The corresponding objective vectors are referred to as the Pareto-optimal front.

F. Pareto Optimal Front

Created by the objective vector, $f(x)$, and the Pareto-optimal solution set, $\mathcal{P}^*$, then the Pareto-optimal front, $\mathcal{P}^*\mathcal{F} \subseteq \mathcal{O}$, is defined as

$$\mathcal{P}^*\mathcal{F} = \left\{f = \left(f_1(x^*), f_2(x^*), \dots, f_k(x^*)\right) | x^* \in \mathcal{P}\right\} \tag{3}$$

Therefore, it contains all the objective vectors corresponding to decision vectors that are not dominated by any other decision vector. Following in Figure 2 is an example of Pareto Front.

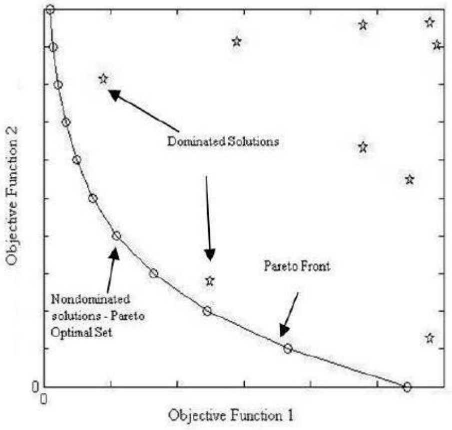

Figure 2. Pareto Front Example[21]

G. Multi Objective Optimization Setup

The multi-objective GA function applied, uses a controlled elitist genetic algorithm (a variant of NSGA-II). An elitist GA always favours individuals with better fitness value (rank) while a controlled elitist GA also favours individuals that can help to increase the diversity of the population even if they have a lower fitness value. One of the crucial points to assure convergence to an optimal Pareto front is to maintain the diversity. This multi-objective optimization was developed in a Matlab code, using and editing several built-in functions to assess the intended objectives.

This multi-optimization is applied with the intention of refining the parameterization results and to apply the optimization objectives to all possible engine setups. By not considering fixed values for each independent variable and perform an optimization of each one in a continuous range, it is possible to create several engine setups according to the optimization setups. It will be defined for this optimization, that a maximization of the specific thrust is one objective while the minimization of the TSFC is also important.

The optimization objectives are in the context of the requirements for the new generation of turbofan engines that will power the next airframes generations. Reducing pollutants (noise and consumption) saving the performance of the engines/aircraft are the two main drivers of engine and airframe manufacturers. Also, airlines and international community embrace this new objectives that force technology to react effectively. The new A320neo and the Boeing 737 Max will have power units that are the main drivers of this concept.

Therefore, the independent variables are the same used in the parameterization study but with an increase on the range values. This will provide to the GA a wider search space to apply the fitness function. The fitness function is composed by the engine cycle equations and the two objectives: minimize the TSFC and maximize the Fs.

The range of the independent variables is:

- BPR: from 10 to 20;
- The Fan Pressure Ratio (*rpfan*): from 1.1 to 2;
- The Compressor Pressure Ratio (*rpc*): from 3.8 to 20;
- The Turbine Entry Temperature (TET): 1500K to 2200K;

Following is the Table 3 of the Multi-Optimization Setup configurations:

Table 3. Multi-Optimization Setup for Conventional and Regenerated Cycles.

Parameter	Configuration/Value
Population Initial Range	[1.1 10 1500 3.8] to [2 20 2200 20]
Population Size	200
Crossover Fraction	0.6
Pareto Fraction	0.4
Stall Generations Limit	10
Function Tolerance	$1e10^{-5}$
Generations	1000
Creation Function	Linear Feasible
Selection Function	Tournament
Crossover Function	Heuristic: 0.6
Mutation Function	Adaptive Feasible

- Crossover Fraction: is the percentage of individuals present in each population that are generated by the Crossover function;
- Distance Measure Function: helps to maintain the diversity on a Pareto front by favouring individuals that are relatively fay away on the front. The crowding distance measure function takes an optional argument to calculate distance either in function space (phenotype) or design space (genotype);
- Pareto Fraction: represents the percentage of individuals from the population that are present in the Pareto front.
- Stall Generations Limit: if the weighted average change in the fitness function value of a defined number of generations is less than the Function Tolerance, the algorithm stops.
- Function Tolerance: if the weighted average change in the fitness function value of a defined number of generations is less than the Function Tolerance, the algorithm stops.
- Generations: is the maximum number of iterations that the GA performs;
- Creation Function: creates a random initial population the bounds and linear constraints;

- Selection Function: chooses parents for the next generation based on their scaled values from the fitness function. The Tournament type selects each parent by choosing two individuals randomly, and then choosing the best individual of that set to be a parent;
- Crossover Function: combines two individuals, or parents, to form a new individual, or child, for the next generation. The Heuristic type creates children that randomly lie on the line containing the two parents, a small distance away from the parent with the better fitness value, in the direction away from the parent with the worse fitness value;
- Mutation Function: the mutation function make small random changes in the individuals of each population, which provide genetic diversity and enable the GA ro search a broader space. Choosing the Adaptive Feasible mode, it randomly generates directions that are adaptive with respect to the last successful or unsuccessful generation. A step length is chosen along with each direction so that linear constraint and bounds can be satisfied;

III. Results

In this section are presented the optimization results for the conventional cycle and with the addition of regeneration.

The following tables and graphics will show Pareto front solutions. Secondly it will be extracted from that results a zone, where it couples median trade-offs regarding the TSFC and Fs.

H. Conventional Cycle

The respective results are plotted in the Pareto front (Figure 3); a tendency curve is added to the results.

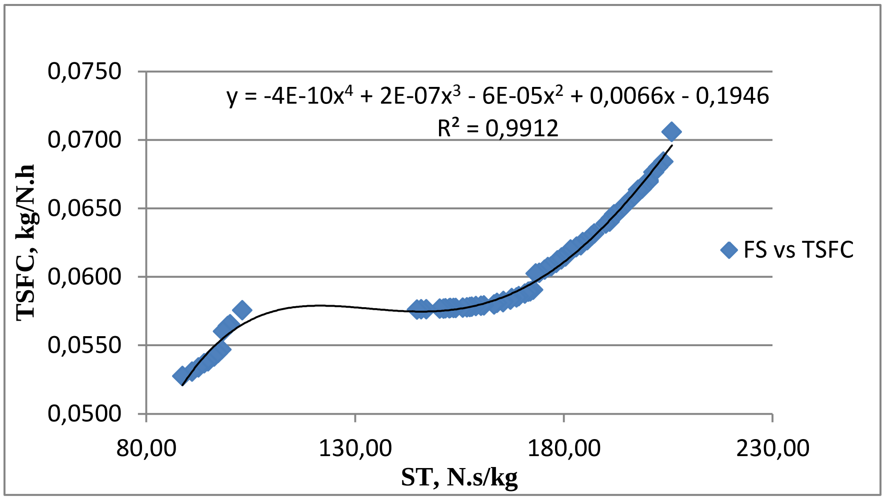

Figure 3. ST vs TSFC Pareto front results.

Following, in Table 4, are the median trade-off results, where the ST and the TSFC are plotted with similar decision weights in Pareto front.

Table 4. Median trade-off results of the Pareto front for the conventional cycle.

rpfan	BPR	TET, K	*rpc*	ST, N.s/kg	TSFC, kg/N.h
1,99	14	2176	19,94	172,66	0,0590
1,99	14	2177	19,98	172,02	0,0589
1,99	14	2175	19,89	171,52	0,0589
1,99	14	2175	19,98	170,69	0,0588
1,99	14	2175	19,95	169,21	0,0586
1,99	14	2175	19,98	168,71	0,0585

1,99	15	2174	19,95	167,53	0,0584
1,99	15	2175	19,95	167,21	0,0583
1,99	15	2173	19,85	165,54	0,0582
1,99	15	2175	19,97	165,48	0,0581
1,98	15	2172	19,98	164,00	0,0581
1,99	15	2175	19,97	163,36	0,0580
1,97	15	2170	19,97	160,90	0,0579
1,99	15	2173	19,85	160,21	0,0579
1,96	16	2168	19,98	159,00	0,0578
1,99	16	2171	19,98	158,01	0,0578
1,96	16	2167	19,98	157,49	0,0578
1,96	16	2167	19,98	156,83	0,0578
1,95	16	2166	19,98	155,82	0,0577
1,94	16	2163	19,98	154,18	0,0577
1,93	16	2161	19,98	153,63	0,0577
1,93	16	2159	19,99	152,82	0,0577
1,93	16	2160	19,99	152,58	0,0577
1,92	16	2159	19,99	151,71	0,0577
1,92	16	2158	19,99	151,21	0,0577
1,91	16	2156	19,99	150,34	0,0577
1,89	17	2150	19,99	147,08	0,0576
1,88	17	2149	20,00	145,85	0,0576
1,87	17	2147	20,00	144,88	0,0576

The respective median trade-off results are plotted in Figure 4; a tendency curve is added to the results.

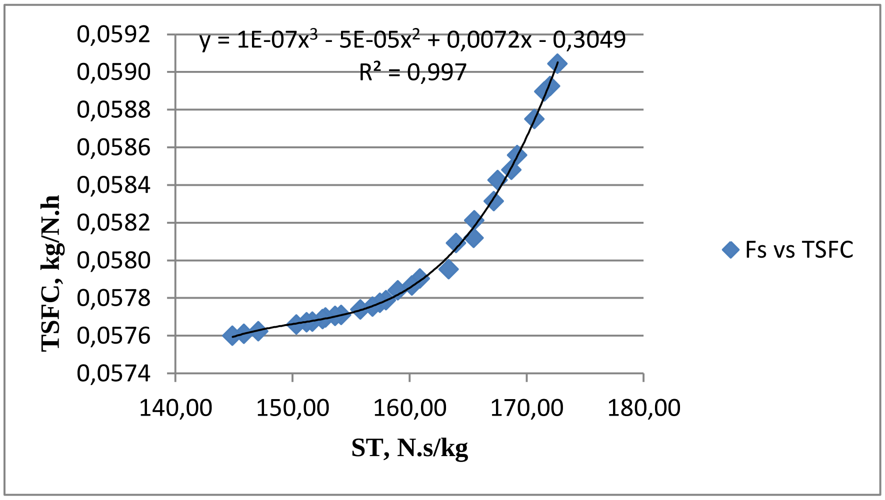

Figure 4. Median Trade-off results of the Pareto front for the conventional cycle.

I. Regenerated Cycle

The respective results are plotted in the Pareto front (Figure 5); a tendency curve is added to the results.

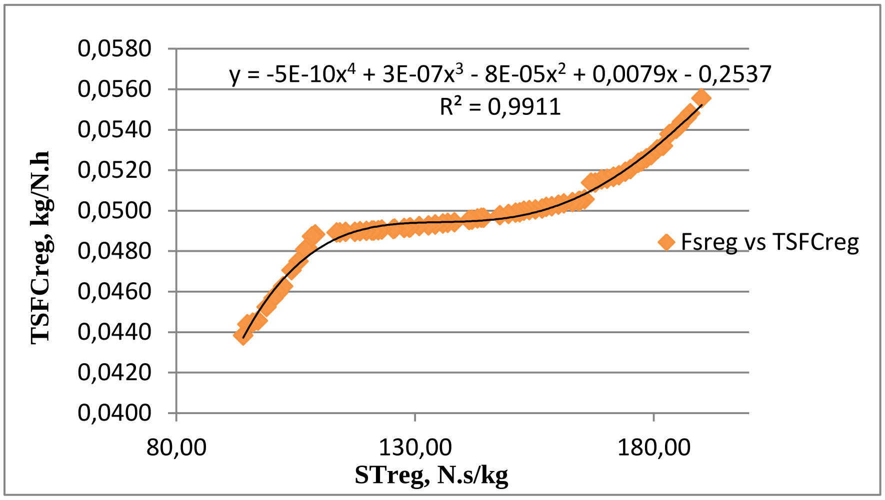

Figure 5. STreg vs TSFCreg Pareto front results.

Following, in the Table 5, are the median trade-off results, where the Fsreg and the TSFCreg are plotted with similar decision weights in Pareto front.

Table 5: Median trade-off results of the Pareto front for the regenerated cycle.

rpfan	**BPR**	**TET, K**	***rpc***	**STreg, N.s/kg**	**TSFCreg, kg/N.h**
1,99	12	2188	7,88	165,55	0,0506
1,97	12	2189	7,67	164,59	0,0505
1,97	12	2189	7,67	164,28	0,0505
1,96	12	2189	7,84	163,00	0,0504
1,95	13	2189	7,87	161,20	0,0503
1,93	13	2189	7,84	160,09	0,0503
1,95	13	2190	7,33	158,66	0,0502
1,91	13	2189	7,89	157,52	0,0502
1,92	13	2190	7,31	156,69	0,0501
1,90	13	2189	7,66	155,26	0,0501
1,89	13	2189	7,79	153,98	0,0500
1,88	13	2190	8,22	152,86	0,0500
1,89	13	2190	7,37	151,99	0,0499
1,87	14	2189	7,74	151,11	0,0499
1,87	14	2190	7,51	149,65	0,0498
1,86	14	2190	7,68	147,81	0,0498
1,83	14	2190	7,66	144,37	0,0496
1,83	15	2190	7,73	143,93	0,0496
1,82	15	2190	7,68	143,10	0,0496
1,80	15	2190	7,53	141,99	0,0495
1,81	15	2190	7,67	141,35	0,0495
1,78	15	2190	7,64	138,31	0,0494

1,78	15	2191	7,67	136,87	0,0494
1,77	16	2190	7,86	135,85	0,0494
1,76	16	2191	7,51	134,30	0,0493
1,76	16	2191	7,51	134,30	0,0493
1,74	16	2190	7,83	132,89	0,0493
1,74	16	2190	7,68	130,94	0,0492
1,71	16	2191	7,63	129,06	0,0492
1,71	16	2191	7,63	128,85	0,0492
1,71	17	2191	7,62	127,75	0,0491
1,70	17	2191	7,73	125,77	0,0491
1,70	17	2192	7,79	125,51	0,0491
1,69	17	2192	7,71	123,04	0,0491
1,68	17	2191	7,71	122,32	0,0490
1,67	18	2192	7,71	121,40	0,0490
1,67	18	2192	7,73	120,97	0,0490
1,66	18	2191	7,70	119,86	0,0490
1,65	18	2192	7,73	118,52	0,0490
1,64	18	2192	7,70	117,44	0,0489
1,63	19	2192	7,62	115,48	0,0489
1,62	19	2191	7,60	114,29	0,0489
1,62	19	2191	7,59	113,61	0,0489

The respective median trade-off results are plotted in Figure 6; a tendency curve is added to the results.

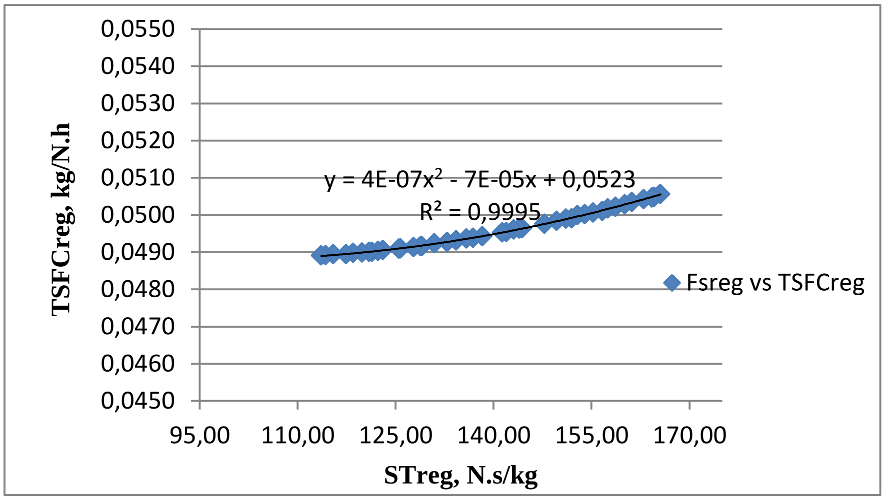

Figure 6. Median Trade-off results of the Pareto front for the regenerated cycle.

III. Conclusions

In this work a performance and an optimization study of a two spool turbofan engine in UHB conditions was performed. Accordingly to the trend of higher bypass ratio in the incoming engines for the Airbus A320neo and the Boeing 737Max, this study tries to envision some characteristics and behaviours of the new turbofan engines. For flight conditions, the cruise point was chosen where all the atmospheric and engine known/predicted conditions were taken in consideration. To evaluate these characteristics it was selected a group of independent variables: the

BPR, the TET, fan pressure ratio (*rpfan*) and compressor pressure ratio (*rpc*). The results were translated in several performance readings of the engine, where the TSFC and the ST were main references. It is good to notice that the study applies equations where several parameters are considered constant, therefore the results may not translate into real values but are still able to provide some viable conclusions. For more accurate results, the continuation of this study should be developed, where the addition of more variable parameters will be required.

Being this study a MOO problem a genetic algorithm was successfully applied. The intention was to meet two objectives of actual interest of the airliners: reduce the TSFC while maximizing the specific thrust available. Therefore, each independent variable was optimized, generating a Pareto front. This provided not a unique set of optimized values, but instead several optimized sets were calculated with different weights regarding both objectives. This situation provides the decision maker the possibility of choosing a set of variables privileging one of the objectives or both. The Pareto fronts generated are well distributed, indicating a good diversity of results within the ranges considered. The disparities on each Pareto front are due to the changes of the BPR, which will influence the status of both cold and hot nozzle.

In the median trade-off zones, on both cases, the changing of the TSFC with the Fs values is less than in other explored zones (especially in the regenerated case). This allows the engine to work satisfactorily in a larger range of ST without greater change in the TSFC. The optimal working point depends on the flight conditions or mission.

So a compromise of tradeoffs is necessary to choose a set of values to the independent variables, taking into account the proposed objectives in the optimization process. An example is suggested by [8] concerning the increasing of the BPR, where the addition of stages on the LPT is necessary as the BPR increases. Another consequence to consider is a wider fan. Both issues will add weight to the overall engine.

Accordingly to the performed study, there are positive indications for regenerated cycle on the new UHB turbofans, despite the use of the current equations where the specific heat and bleeds were considered constant. However, for a precise evaluation, further studies must be performed considering other aspects such as aerodynamic issues, weight, structural, mechanical and security points. With the current progress of technology, the use of a regenerated cycle may be closer than in the previous years due to the introduction of new materials, design concepts and engine modules that will provide the space and weight saving for the introduction of a regenerating system.

In the median trade-off zone in the regeneration case can be observed that the TSFC do not change significantly. Therefore, it can be concluded that there are several combinations of the independent variables (*rpfan*, *rpc*, BPR and TET) which use can increase the specific thrust without changing significantly the fuel consumption. In a cruise scenario, where atmospheric conditions change continuously, applying regeneration, high fuel saving might be achieved with small changes of the independent parameters.

The trend of increasing the bypass ratio is certainly one of the chosen paths of engine manufacturers to reduce the TSFC. However, the components of the engine must keep up to meet the imposed objectives. One of the examples is the trend of using higher TET that is provided by more resistant materials. Values for other components are suggested in this study.

The introduction of a gearbox, gives the possibility for the low pressure spool to run at optimum velocities and also reducing the turbine stages. This concept is not new, however only now it was brought to a commercial level due to all the technology development that permitted to add an extra system to the engine, keeping or even increasing the performance compared to the DDTF. But, it is also important to notice that in some situations a geared configuration may not result in an increase of performance. Thus, it is necessary to evaluate the mission objective of the engine, in order to decide the best engine parameter values which can dictate whether to use a geared or a conventional configuration setup, as indicated by [20].

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