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MULTI-OBJECTIVE OPTIMIZATION OF A REGENERATIVE ROTORCRAFT POWERPLANT: QUANTIFICATION OF OVERALL ENGINE WEIGHT AND FUEL ECONOMY

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ABSTRACT

A computationally efficient and cost effective simulation framework has been implemented to perform design space exploration and multi-objective optimization for an advanced regenerative rotorcraft powerplant configuration at mission level. The proposed framework is developed by coupling a comprehensive rotorcraft mission analysis code with a design space exploration and optimization package. The overall approach is deployed to design and optimize the powerplant of a reference twin-engine light rotorcraft, modelled after the Bo105 helicopter, manufactured by Airbus Helicopters. Firstly, a sensitivity analysis of the regenerative engine is carried out to quantify the interrelationship between the engine thermodynamic cycle design parameters, engine weight, and overall mission fuel economy. Secondly, through the execution of a multi-objective optimization strategy, a Pareto front surface is constructed, quantifying the optimum trade-off between the fuel economy offered by a regenerative engine and the associated weight penalty. The optimum sets of cycle design parameters obtained from the structured Pareto front suggest that the employed heat exchanger effectiveness is the key design parameter affecting the engine weight and fuel efficiency. Furthermore, through quantification of the benefits suggested by the acquired Pareto front, it is shown that, the fuel economy offered by the simple cycle rotorcraft engine can be substantially improved with the implementation of regeneration technology, without degrading the payload-range and airworthiness (One-Engine-Inoperative) requirements of the rotorcraft.

NOTATION

Roman symbols

CO_2	Carbon dioxide
MF_{mean}	Mean mission mean fuel flow, kg/sec
NO_x	Nitrogen oxides emissions
P_{DP}	Engine design point shaft power, W
SFC_{DP}	Specific fuel consumption at design point, μg/J
TET_{DP}	Turbine entry temperature at design point, K
$\dot{W}$	Mass flow at engine design point, kg/sec

Greek Symbols

$\Delta AUM_i^{\%}$	Percentage difference initial all-up-mass
$\Delta CO_2^{\%}$	Percentage difference carbon dioxide
$\Delta EW^{\%}$	Percentage difference engine weight
$\Delta MFB^{\%}$	Percentage difference mission fuel burn
$\Delta NO_x^{\%}$	Percentage difference nitrogen oxides
$\Delta SAR^{\%}$	Percentage difference specific air range

Acronyms

ACARE	Advisory Council for Aeronautics Research in Europe
DOE	Design Of Experiment
DP	Design Point
EW	Engine Weight, kg
HEE	Heat Exchanger Effectiveness, %
HECTOR	HeliCopTer Omni-disciplinary Research-platform
HPC	High Pressure Compressor
LHS	Latin Hypercube Sampling
LPC	Low Pressure Compressor
MFB	Mission Fuel Burn, kg
mPSO	Multi-objective Particle Swarm Optimizer
OPR	Overall Pressure Ratio
PATM	Passenger Air Taxi Mission
PR	Pressure Ratio
PSO	Particle Swarm Optimizer
RSM	Response Surface Model
SFC	Specific Fuel Consumption, μg/J
SAR	Specific Air Range, km/kg of fuel
sPSO	Single-Objective Particle Swarm Optimizer
TET	Turbine Entry Temperature, K
TEL	Twin Engine Light

INTRODUCTION

Background: A rotorcraft is a highly complex integrated system, to such extent that, almost every design decision is embraced with compromise. As elaborated by Prouty (Ref. 1) "*In no other vehicle will the relationship between the*

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empty weight (EW) and payload be so uncompromisingly one-to-one. The rotorcraft designer cannot be said to be seeking the optimum design, but the least worse compromise". The development activity of any new rotorcraft design is driven by the quest to accomplish a set of predefined aircraft-level mission requirements. Often, these requirements are fulfilled by modifying an existing rotorcraft design (Ref. 1) or alternatively, a progressive design philosophy is employed to fulfill the desired design requirements. The modern-day design requirements are essentially dependent on intended mission and the environment within the rotorcraft is destined to serve throughout its projected lifecycle. Among others the most fundamental performance requirements are the payload, range, endurance, and speed. While the effectiveness of the integrated rotorcraft as a system is an underpinning prerequisite to proficiently fulfill these requirements. The integration of a robust and efficient powerplant system at aircraft level plays a key role in meeting the required performance parameters.

In terms of powerplant integration, among others the most important performance requirements in the selection process are i) high power-to-weight ratio, ii) good fuel efficiency (specific fuel consumption, SFC) at both design and part power operation. The former parameter is important to minimize rotorcraft empty weight, hence to maximize useful payload capability, and the latter parameter contributes towards the overall performance of the rotorcraft in terms of its payload-range and endurance capability. However, from the prospective of engine design the development of a powerplant to efficiently satisfy both aforementioned parameters concurrently is an enormous design challenge. This is predominantly due to the conflicting design requirements associated with the engine design philosophies directed towards achieving simultaneous improvement in engine weight and fuel efficiency for a given power output and technology level (Ref. 2 – 4). The aforementioned design complexity becomes even more formidable when alternative engine design technologies are conceived that may require introduction of additional components to enable a step change in engine technology; one such example is regeneration technology that has been recognized as one of the most promising concept towards enabling drastic reduction in fuel consumption (Ref. 4 -11).

Furthermore, the aviation industry of the 21st century has set new standards that must be met by the aero-engines of next generation, in order to satisfy their marketability and compliance with the associated legislation. Among other important imperatives of future commercial aviation, the most politically and publically intensified imperative is associated with their contribution towards the environmental degradation (Ref. 12). The helicopter operations resulting from civil and military operations, although comprising a significantly smaller portion of the aircraft market in comparison with the fixed-wing aircraft, are experiencing the same concerns with respect to the amount of gaseous emissions produced. The rotorcraft plays a specific and inimitable role in air transportation and it is often used for purposes where the environmental concerns are secondary, (e.g. Medical Rescue operations, Law Enforcement, Search And Rescue, Fire Suppression, Surveillance, Military Combat and Transport purposes). However, the rotorcraft traffic related to passenger transport/air taxi requirements that up to now has been marginal, is expected to grow rapidly in the near future. This is mainly driven by the exponential growth in passenger air travel demand that is foreseen for the 2015 – 2020 period (2 to 3 fold increase) (Ref. 13). The Advisory Council for Aeronautics Research in Europe (ACARE), in an attempt to manage the environmental impact of civil aviation, has set a number of goals to be achieved by the year 2020 (Ref. 12). These goals include, among others, reduction of produced carbon dioxide (CO_2) and nitrogen oxides (NO_x) emissions by the order of 50% and 80%, respectively.

The aforementioned challenges associated with revolutionizing the rotorcraft powerplant to achieve better fuel efficiency and power-to-weight ratio in conjunction with mitigating their growing impact towards environmental degradation has exposed the rotorcraft engine design activity to increased complexity and conflicting design requirements. The increased use of multidisciplinary high-fidelity computational tools within the engine conceptual/preliminary design stage has been identified as prerequisite for overcoming the significant challenges of designing sustainable future engine designs (Ref. 2, 3, 14-17).

Integrated Rotorcraft Design and Optimization Framework

In light of the aforementioned background related to the design of conceptual rotorcraft powerplants, a comprehensive and simultaneously cost-effective methodology targeting the comprehensive assessment and optimization of combined rotorcraft–powerplant systems, has been developed at Cranfield University. This framework has been named "HECTOR" (HEliCopTer Omni-disciplinary Research). The modelling fidelity incorporated within HECTOR belongs to the Padfield's level 3 simulation hierarchy (Ref. 18-20), and is therefore well suited for the design assessment and optimization of integrated rotorcraft systems at conceptual and preliminary design level. An advanced level of simulation fidelity is therefore incorporated in order to capture the associated performance trade-offs between rotorcraft system designs optimized in a multidisciplinary manner. As a result, the focus of the design process can be placed on the overall performance within designated types of operations, rather than on pre-defined sets of flight conditions, thus the associated design trade-offs can be quantified at aircraft operational level.

The execution of such an approach represents a major step forward in rotorcraft engine conceptual/preliminary design process as it builds the foundations for accounting for synergies between the multiple disciplines at rotorcraft operational level. The effective implementation of such exercise comes with a considerable increase in computational cost. Since the usual practice of trial-and-error applied within such multidisciplinary problems is deemed as prohibiting as it is carried out in a multi-variable and multi-output context and it is considerably challenging to make decisions on the grounds of multiple competing outputs without the use of a robust optimization strategy. In order to tackle the aforementioned complexities a consistent multi-objective optimization strategy is required. Taking into account the computational expenses that might be incurred by running high-fidelity HECTOR simulations numerous times as well as realizing the highly non-linear relations between the multitude of inputs and outputs.

The theoretical and computational development of HECTOR has been extensively documented in (Ref. 2, 3, 19-25). An extensive literature related to the conceptual rotorcraft powerplant development and the application of HETOR for various rotorcraft flight dynamic, engine performance , mission analysis and multidisciplinary optimization studies is separately reported by the authors in (Ref. 2, 3, 24-25).

The work presented in this paper serves as a continuation of the research work reported by the authors in (Ref. 2, 3). The research addressed within this paper aims towards closing the gap in the literature in terms of multidisciplinary design and optimization of conceptual regenerative rotorcraft powerplants by implementing a robust and computationally efficient multi-objective optimization strategy developed by the authors in (Ref. 3), to quantify the interrelationship between the regenerative engine weight and SFC_{DP} corresponding to a Twin Engine Light rotorcraft (TEL) configuration.

Review of previous research done

The study carried out by the authors in (Ref. 2) was based on the deployment of a single-objective optimization package within the HECTOR, with an effort to acquire an optimum regenerative powerplant configuration corresponding to improved rotorcraft operational and environmental performance. Although the aim of the paper was accompanied sufficiently, the most promising configuration acquired through the single-objective optimization strategy offered 36.02% increase in mission range through the reduction of Mission Fuel Burn (MFB), while it increased the mission NO_x inventory by 11% compared to the sub-optimal simple cycle engine, imposing a trade-off between the fuel economy and environmental performance of the rotorcraft.

Following the successful implementation of single-objective optimization analyses, in reference (Ref. 3) authors have further expanded the design effort and implemented a multi-objective optimization strategy within HECTOR to quantify the aforementioned trade-off between engine fuel efficiency and environmental impact in terms of MFB and NO_x inventory. The most promising configuration acquired through the multi-objective optimization offered 36.02% increase in rotorcraft range capability (at mission cruise conditions), 7.3% reduction in mission NO_x inventory, while it increased the initial all-up-mass (AUM_i) of the rotorcraft by $\approx$1.7% compared to the sub-optimum baseline engine (Ref. 3).

It was therefore concluded to further expand the design activity with respect to regenerative rotorcraft application in the quest to achieve following three objectives: i) to quantify the interrelationship between the engine fuel efficiency (SFC) and engine weight, ii) to acquire an optimum conceptual regenerative engine design corresponding to minimum compromise (trade-off) between the engine weight and SFC_{DP}, and iii) to quantify the benefits arising from the acquired optimum configurations at rotorcraft operational level. The particular study was encouraged primarily to explore the employment of regenerative powerplants for rotorcraft applications where the associated environmental impact are considered secondary (e.g. Medical Rescue operations, Law Enforcement, Search And Rescue, Fire Suppression, Surveillance, Military Combat and Transport purposes), therefore the primary engine design objective functions being the maximization of engine fuel efficiency (to maximize rotorcraft range capability) and minimization of engine weight (to maximize rotorcraft payload capability). The execution of this study therefore serves as a continuation of work and is solely devoted towards the quantification of the aforementioned engine design parameters in terms of rotorcraft operational performance; however the inclusion of environmental impact has also been catered for completeness.

Scope of the present work

In light of the literature currently available on regeneration technology with regards to its application to rotorcraft reveals a gap in knowledge (Ref. 2, 3, 7, 10, 26). The research gap remains with the systematic quantification of interrelationship between the engine weight and fuel efficiency as well as its corresponding implications on the engine cycle design parameters i.e. Overall Pressure Ratio, Turbine Entry Temperature, Mass Flow (OPR, TET, $\dot{W}$) and rotorcraft operational level parameters in terms of MFB, Initial-All-Up-Mass and Specific Air Range (e.g. AUM_i, SAR). Furthermore, the interdependency between the regenerative engine weight and fuel efficiency remains to be one of the “development dilemma" for the engine designers, primarily due to their concerns associated with the weight penalty arising from the incorporation of the heat exchanger(s) (Ref. 5-7). Therefore, in order to systematically quantify the interrelationship and the corresponding trade-off between the both objective functions, the deployment of a robust and computationally efficient multi-objective optimization approach is necessary to enable the designer to reach a balanced compromise between both competing design objectives.

In this work the design space exploration approach and the optimization strategy developed by the authors in reference (Ref. 3) corresponding to Bo105 TEL helicopter configuration has been further implemented to perform a multi-objective optimization study at mission level. The aim of the study is to acquire Pareto front surface corresponding to minimum engine weight and minimum engine SFC_{DP} at constant technology level, while maintaining the respective rotorcraft airworthiness requirements i.e. One Engine Inoperative (OEI).

The developed design space based on one-hundred-twenty HECTOR non-linear design of experiments and the corresponding response surface models established by the authors in reference (Ref. 3) and those developed for the purpose of this study have been utilized to construct Pareto front surface, quantifying the interrelationship and the corresponding trade-off between the regenerative engine delta weight ($\Delta EW = Baseline\ EW - conceptual\ EW$) and engine SFC$_{DP}$. The formation process of the acquired Pareto front surface dictates simultaneous minimization of engine SFC$_{DP}$ with minimization of ΔEW. The engine cycle design parameters corresponding to the span of the Pareto front surface suggest that the heat exchanger design effectiveness is the key factor affecting the ΔEW and SFC$_{DP}$. Furthermore, through the quantification of the acquired optimum Pareto front surface, it has been established that, the fuel economy of the conventional technology rotorcraft engine can be substantially improved with the incorporation of the regeneration technology, while maintaining the corresponding AUM$_i$ and airworthiness requirements (i.e. OEI) of the respective helicopter. Finally it has been demonstrated that, with respect to the application of the regeneration technology in order to reach a balanced compromise between the engine weight and fuel efficiency as well as to conceive a systematic and well-informed engine development decision, both demand the successful deployment of a systematic aircraft-level powerplant design optimization approach.

SIMULATION METHODOLOGY

HECTOR – Integrated multidisciplinary Design and Optimization Framework

The successful execution of this study requires the integrated modelling of various rotorcraft sub-systems (e.g. main rotor, airframe, tail rotor, powerplant, combustion chamber etc.) to represent a system level modelling fidelity simulated at mission level. In addition, in order to enable efficient exploration of the design space and identification of optimum solutions, a computationally efficient and robust design space exploration and optimization package becomes an underpinning prerequisite; to work conjunction with the aforementioned comprehensive rotorcraft simulation tool. To satisfy this requirement, for the purpose of this study the Cranfield University in-house Integrated Rotorcraft Design and Optimization Framework – HECTOR has been deployed, allowing for efficient design space exploration and optimization of conceptual rotorcraft powerplant configurations in a multi-objective manner. The deployed framework is presented in Fig. 1 and all its corresponding models in terms of flight path model, unsteady aeroelastic rotor model, nonlinear trim model, engine performance and weight estimation model, emission model and the employed design space exploration and optimization package have been separately reported by the authors in reference (Ref. 2, 3, 19-25), therefore further elaboration shall be omitted. As elaborated earlier, the scope of this study is to further implement the methodology reported by the authors in (Ref. 2, 3) with the execution of a multi-objective optimization study devoted towards the quantification of interrelationship between the engine weight and SFC$_{DP}$. All the relevant details relating to the baseline rotorcraft and its corresponding design space as well as the specifics related to the devised optimization strategy employed herein have been separately reported by the authors in reference (Ref. 3) which the interested readers can cite to for further information, herein the focus will only be devoted towards the results and discussions arising from the investigation addressed under the scope of this work.

RESULTS AND DISCUSSION

Overview

In reference (Ref. 3) authors have successfully established the design space corresponding to the conceptual regenerative Bo105 configuration. The entire system response in terms of system linear correlation coefficients corresponding to the conceptual engine inputs/outputs OPR, TET, $\dot{W}$, HEE, SFC$_{DP}$, P$_{DP}$, EW as well as mission outputs, MFB, CO$_2$ and NO$_x$ emissions inventory have been thoroughly reported by the authors in reference (Ref. 3). Herein, firstly, through the execution of a comprehensive engine design sensitivity analyses based on the readily available system linear correlation (Ref. 3), the interdependencies between the engine design inputs (e.g. OPR, TET, $\dot{W}$, HEE) and outputs (e.g. engine dry weight, SFC$_{DP}$) as well as mission output parameter in terms of MFB have been quantified. Secondly, a multi-objective optimization analyses have been carried out to acquire Pareto front surface corresponding to minimum ΔEW and minimum engine SFC$_{DP}$. The benefits arising from the acquired Pareto surface are subsequently quantified at rotorcraft operational level, targeting improvements in the overall payload-range capability of the respective rotorcraft. Both aforementioned design activity tasks are elaborated in the following sections.

Engine design sensitivity analysis

Figure 2 presents the engine design sensitivity analysis conducted based on the linear correlation coefficients corresponding to the conceptual regenerated helicopter design space presented in Table 1. It can be established from Fig. 2(a) that all the corresponding engine design parameters (e.g. OPR, TET, $\dot{W}$, HEE) exhibit a positive correlation towards the engine weight. Amongst all the engine design parameters, the engine turbine entry temperature exhibits the lowest influence, whereas and the design point mass flow is found to have the highest influence on engine weight. The advancement in the former parameter is predominantly achieved through employment of technologies (e.g. advanced super alloys, thermal barrier coatings etc.) that enable expansion in the metallurgical boundaries of the components comprised within the hot side of the gas turbine i.e. combustor chamber and turbine etc. (Ref. 27) and their integration is generally realised without incurring significant impact on the overall size and weight of the engine (Ref. 27). Therefore, embarking minimum influence on engine weight. Whereas, the advancement in the latter parameter, requires significant changes in the overall physical size of the engine as well as the turbomachinery components, and specifically the on-board heat exchanger(s) (Ref. 11, 28). Hence, imposes the greatest impact on engine weight compared to all other engine design parameters.

Furthermore, it can be established from Fig. 2 (a) that the advancement in engine OPR has a relatively greater influence on the engine weight compare to TET, which is attributed to the fact that the advancement in the engine OPR imposes some physical alterations in the overall size and length of the engine i.e. additional compressor stage(s), larger centrifugal compressor (or both simultaneously), and under some cases additional turbine stage(s). Whereas in case of the advancement in TET, such design alterations are generally unforeseen, apart from some common changes in the turbine stage(s). With regards to the heat exchanger design effectiveness, it is apparent from the Fig. 2(a) that it exhibits a major influence on engine weight, this is predominantly attributed due to the gross weight added by the on-board heat exchanger(s), and since the weight of the heat exchanger is a function of the engine design point mass flow (Ref. 4-6) (as shown in Fig. 9), it follows almost identical trend and order of magnitude towards engine weight as one exhibited by $\dot{W}$.

In Fig. 2(b) similar engine design sensitivities are presented with respect to engine SFC_{DP}, and as expected all engine design point cycle parameters exhibit inverse relation towards the engine SFC_{DP} compare to their trends depicted in Fig. 3 against the engine weight, except for the $\dot{W}$, which is found to have a no influence on the engine SFC_{DP} within the respective design space bound of 1 – 2 kg/sec. The specific inverse interdependencies of engine design point parameters towards weight and SFC_{DP} substantiates the engine design trade-off between the both aforementioned engine design outputs. As it can be established from Figs. 2 - 6 that, increase in engine OPR, HEE and TET, results in improved engine SFC_{DP} and therefore the MFB, however, the improvement in MFB through reduction in engine SFC_{DP} is attained with a penalty in engine weight.

An interesting observation to note here is that, although the $\dot{W}$ has no influence on engine SFC_{DP}, it exhibits a significant impact on mission fuel burn. This is encouraged due to the fact that, the engine mass flow has a significant impact on the overall engine weight, thus, on the rotorcraft Initial All-Up-Mass (AUM_i), the required power, fuel flow, and therefore on overall mission fuel burn (Ref. 10, 20, 24).

Multi-objective optimization of SFC_{DP} and EW

The optimum regenerative configurations acquired by the authors in (Ref. 3) through the application of a multi-objective Particle Swarm Optimizer (mPSO), corresponds to the solutions that are optimized for MFB and NO_x emissions inventory, quantifying the trade-off between the engine fuel efficiency and the environmental impact. In order to effectively implement the additional design criterion related to engine fuel efficiency and engine weight as highlighted in the preceding section; the associated trade-off between engine SFC_{DP} and engine weight needs to be thoroughly addressed and quantified.

Before proceeding with the quantification of the engine SFC_{DP} and engine weight, it is to be noted that, since the SFC_{DP} is an engine level parameter. Therefore, in order to correlate the engine fuel efficiency with mission fuel economy (fuel burn). The associated interrelationship between the engine SFC_{DP} and mission fuel burn needs to be systematically quantified. Figure 7 shows the Mission Fuel burn and engine SFC_{DP} scatter for all the design of experiments corresponding to the design space bounds defined in Table 2 for the conceptual regenerative helicopter. It is evident that the both outputs are strongly correlated and have a strong linear dependency, with a linear correlation coefficient of 0.88.

To further quantify the interdependency between the engine SFC_{DP} and the mission fuel burn. A Pareto front surface was constructed corresponding to the design space bounds and constraints presented in Table 1. The objective functions of the Pareto front formation process dictate simultaneous minimization of engine SFC_{DP} with minimization of mission fuel burn. The acquired Pareto front surface is shown in Fig. 8. It is evident that the span of the acquired Pareto front surface is insignificant. The obtained variation in the both objective functions falls within a value of 1.5%. This small variation in both outputs can be primarily attributed to the overall error associated with the developed RSMs, which is found to be of the order of 1.2% as presented in Table 2. Therefore, based on the acquired Pareto it can be concluded that engine SFC_{DP} (fuel efficiency) can be used to quantify mission fuel burn (fuel economy).

It has been therefore been demonstrated that the for the established design space the engine SFC_{DP} can be used as an output parameter to quantify mission level output e.g. fuel burn.

A Pareto front surface has been structured for minimum SFC_{DP} and minimum ΔEW based on the design of experiments (DOE) results acquired through the LHS approach, and the acquired RSMs presented in the preceding section. The Pareto front surface acquired for the conceptual regenerative Bo105 helicopter corresponds to the design space and constraints presented in Table 1.

The acquired Pareto front surface is presented in Fig. 9, the objective functions of the Pareto front surface formation process dictate simultaneous minimization of SFC_{DP} with minimization of ΔEW. It is apparent from the acquired Pareto front surface that the ΔEW increases almost linearly with minimization of SFC_{DP}. The part of the Pareto front surface that corresponds to minimum engine SFC_{DP} employs heat exchangers effectiveness that corresponds to the upper limit of the defined design space (e.g. 80%) reaching the maximum possible limit. On the other hand the part of the Pareto front surface that corresponds to minimum engine minimum ΔEW incorporate minimum attainable heat exchanger and design point mass flow values, under the defined design space and constraints.

Considering the acquired Pareto front surface, three configurations are of prime importance, as highlighted in Figure 9. Insights into the aforementioned configurations engine cycle design point parameters will help to established in-depth understanding of the associated trade-offs and interrelationship between the SFC_{DP} and ΔEW as well as their influence on the respective engine cycle design parameters.

It is to be noted that, the employed RSMs have been structured using the DOE results acquired from the execution of non-linear HECTOR simulations. Thus, the overall error associated with the developed RSMs is primarily attributed to the interpolation method deployed for the numerical formulation of the respective RSMs. It was expected that the RSM error would propagate to the acquired Pareto front surface. Therefore before proceeding with further analysis it was imperative to validate the quality of the Pareto models acquired. For that purpose the aforementioned three representative points were selected, highlighted in Fig. 9. Separate HECTOR simulations were performed for all three optimum configurations of choice. An average Pareto model relative error obtained was up to -1.20%, presented in Table 2, corresponding to all three selected configurations.

Table 3 presents the Pareto optimum engine design parameters acquired for all three selected configurations against the baseline. The acquired optimum configuration corresponding to minimum SFC_{DP} has 28.06% higher engine OPR, 20.51% lower $\dot{\text{W}}$ and 67.78% higher EW, with the potential to reduce the MFB by approximately 52.38%, compared to the baseline engine.

The Pareto optimum engine design parameters acquired for minimum ΔEW configuration has 27.78% higher engine OPR, 23.71% lower $\dot{\text{W}}$, no weight penalty, and has the potential to reduce the MFB by approximately 42.24%, compared to the baseline engine.

Finally, the Pareto optimum engine design parameters are acquired for the optimum engine configuration that represents the minimum trade-off between engine SFC_{DP} and ΔEW. The particular configuration has 28.06% higher engine OPR, 21.79% lower $\dot{\text{W}}$ and 26.45% higher EW, with the potential to reduce the MFB by approximately 46.64%, compared to the baseline engine.

An important observation to highlight here is that, due to the imposed objective functions; minimization of SFC and minimization of ΔEW. The engine OPR corresponding to all acquired Pareto models is noticeably higher than the baseline engine and maintains almost a constant value throughout the entire span of the Pareto front, as depicted in Fig. 8. This is predominantly attributed to the fact that, the engine OPR has a strong influence on minimizing the engine SFC_{DP} (e.g. thermal efficiency) whereas when considering the defined bounds of the design space, the influence of engine OPR on engine weight is insignificant, compared to other engine design variables (e.g. $\dot{\text{W}}$ and HEE), as shown in Fig. 2(a). Furthermore, the relative difference between all acquired Pareto models and baseline OPR is $\approx 23\%$, and therefore imposes to only small amount of change in engine weight, almost negligible. Therefore, it can be said that the acquired Pareto surface belongs to those feasible regions within the design space where engine OPR is maximized, whilst other engine design parameters (e.g. $\dot{\text{W}}$, HEE) that exhibit stronger influence on engine weight are minimized correspondingly, under the imposed design constraint(s).

Furthermore, the fact that the value of engine mass flow varies within a very narrow bound (practically almost constant) throughout the span of the Pareto front, as depicted in Fig. 10, this is predominantly encouraged due to two reasons i) as elaborated earlier, increasing or decreasing the engine design point mass flow has a major influence on the physical size of the overall engine and therefore its weight, ii) the gross weight of the heat exchanger is a function of engine design mass flow, thus, in order to maintain the overall engine weight within minimized limits along with a simultaneous increase in engine SFC_{DP}, the engine design point mass flow must be minimized to the lowest attainable value under the imposed constraint(s).

Another interesting observation that is of worth mentioning here is that, the heat exchanger effectiveness value corresponding to the minimum ΔEW configuration (56%) does not corresponds to the lower bound of the defined design space e.g. 40%, presented in Table 1. However, one should expect a simultaneous minimization of the heat exchanger effectiveness across the span of the acquired Pareto front surface and capture the complete design space (e.g. 40% to 80%). The fact that the acquired Pareto minimum ΔEW configuration has not been further minimized to reach the minimum design space bound of 40% is encouraged due to two reasons, i) the objective function corresponding to the minimization of engine SFC_{DP} dictates maximization of heat exchanger effectiveness and OPR, ii) the variation in heat exchanger gross weight when advancing from 40% to 55% does not significantly vary (e.g. $\approx 3\ to\ 4\ kg/[kg\ of\ \dot{\text{W}}]$, as shown in Fig. 11. Since the OPR is maximized and is kept constant throughout the span of the Pareto front, therefore, the point at which the SFC_{DP} is said to be fully minimized while simultaneously maintaining minimum ΔEW must occurs at the point of break-even; the point where the added weight of the heat exchanger is fully compensated by the amount of weight savings arising from the reduction in engine weight of the optimized engine. For the problem at hand, the acquired minimum ΔEW configuration corresponds to the heat exchanger effectiveness value of 56%, which represents heat exchanger gross weight of $\approx 11kg$ using the correlation presented in Fig. 9 (implemented in HECTOR to account for onboard heat exchanger weight). However, the significantly lower weight penalty of $\approx 11kg$ associated with the on-board heat exchanger has been offset by the reduction in overall engine dry weight of the optimized engine. This is predominantly due to the weight savings arising from the reduction of 23.71% in the mass flow of the optimized engine with respect to the baseline, leading to equal engine weight despite the addition of a heat exchanger with 56% of design effectiveness. Any further increase in the heat exchanger effectiveness beyond the break-even point will incur engine weight penalty and therefore will not comply with the imposed objective functions dictated by the formation process of the Pareto front, under the imposed constraints.

It can therefore be said that, in terms of the regeneration technology, i) the design effectiveness of the on-board heat exchanger is a key factor affecting the ΔEW and SFC$_{DP}$, ii) the results acquired so far suggest that the regeneration technology has the potential to substantially improve the fuel efficiency of a conventional technology rotorcraft engine without incurring any penalty in the engine weight, if a systematic powerplant optimization approach is conceived.

The acquired Pareto front surface can therefore be regarded as preliminary guide with respect to the engine design process. The span of the front allows for engine sizing as well as for selection of thermodynamic cycle parameters in an optimum manner, using a single design criterion; the associated trade-off between mission fuel economy and the payload–range capability are the compromises that the designer has to accept.

Quantified benefits of optimized solutions at operational level

As elaborated under section 1.2, the primary focus of the implemented optimization study is devoted towards those rotorcraft applications (e.g. Medical Rescue operations, Law Enforcement, Search And Rescue, Fire Suppression, Surveillance, Military Combat and Transport purposes) where the primary engine design goals are to maximize rotorcraft operational performance in terms of its range and payload capability, and the environmental performance is regarded as a secondary engine design goal, and is therefore under the scope and demonstration purpose of this study is considered as exemptible.

Considering the aforementioned design goals, the most promising configuration is therefore considered as the one that offers maximum fuel savings, while simultaneously resulting in minimum ΔEW. Fuel savings can only be utilized either as an increase in payload capacity of the rotorcraft and/or towards increasing the range capability of the rotorcraft. In order to establish a consistent comparison between the acquired optimum configurations, it is assumed that the acquired fuel savings are used towards increasing the overall range capability of the rotorcraft.

Table 4 presents the key operational level parameters derived from the benefits realized from the aforementioned acquired optimum configurations. SAR, AUM$_i$ and the NO$_x$ inventory deltas are established for all three acquired optimized configurations, with respect to the baseline configuration. It is evident from Fig. 12, that the operational benefits offered by the configuration corresponding to minimum ΔEW can be placed close to the imposed design criterion. The particular configuration offers an increase in rotorcraft range capability by 72.77% (at mission cruise conditions), without incurring any penalty in the AUM$_i$ of the rotorcraft.

It has therefore been demonstrated that the deployed methodology can be applied to identify advanced regenerative optimum design specifications for rotorcraft in terms of sizing and thermodynamic cycle parameters, using a single design criterion; the respective trade-off that the designer is willing to accept between the payload–range capability of the rotorcraft.

CONCLUSIONS

A computationally efficient and cost effective simulation framework has been deployed to perform a multidisciplinary design and optimization of a conceptual regenerative rotorcraft powerplant configuration at mission level. The proposed simulation framework is capable of computing the flight dynamics, engine performance, engine weight, and gaseous emissions for any defined helicopter–engine within any designated rotorcraft operation. The aforementioned framework is coupled with a robust and efficient optimization package, utilizing multi-objective particle-swarm optimizer. The overall methodology has been applied to conduct a multidisciplinary design and optimization of a reference twin-engine light rotorcraft modelled after the Airbus Helicopters Bo105 configuration, operated on a representative mission scenario.

Through the execution of a multi-objective optimization strategy a Pareto front surface has been established for conceptual regenerative engine quantifying the interrelationship and the corresponding trade-off between the engine fuel efficiency and engine weight. The formation process of the acquired Pareto front surface suggests that engine weight increases linearly with minimization of engine fuel efficiency.

The acquired engine cycle design parameters corresponding to the span of the Pareto front suggest that the heat exchanger design effectiveness is the key factor affecting the engine weight and fuel efficiency. Furthermore, through the quantification of the benefits realized from the acquired Pareto front surface, it has been demonstrated that, the fuel economy of the conventional technology rotorcraft engine can be substantially improved with the incorporation of the regeneration technology, while maintaining the corresponding initial-all-up-mass and airworthiness requirements (One-Engine-Inoperative) of the respective helicopter.

Finally it has been emphasized that, with respect to the application of the regeneration technology in order to reach a balanced compromise between the engine weight and fuel efficiency as well as to conceive a systematic and well-informed engine development decision, both demand the successful deployment of a systematic aircraft-level powerplant design optimization approach.

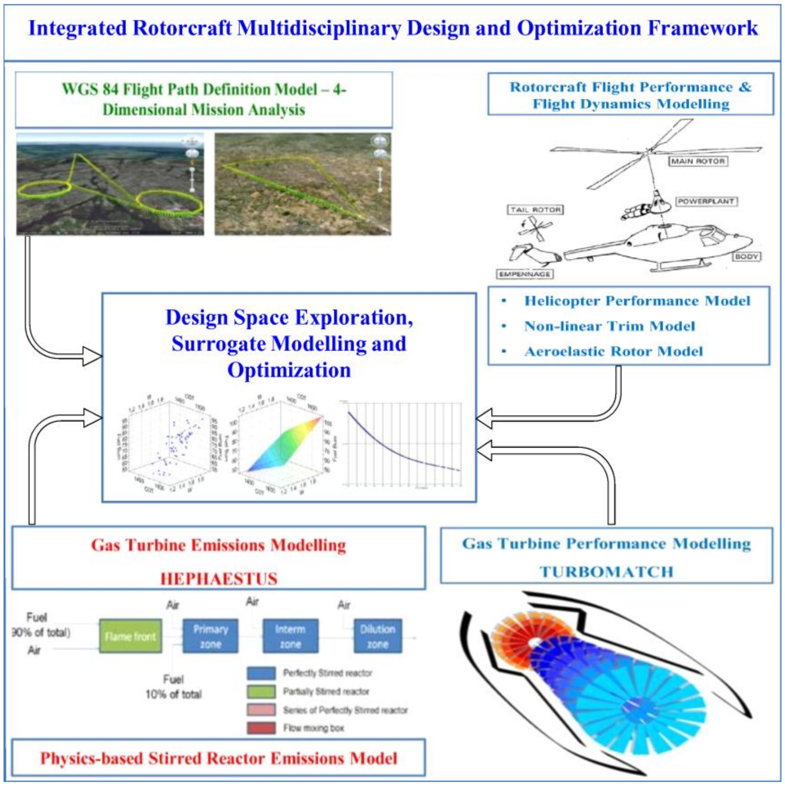

Fig. 1: HECTOR; Architecture of integrated rotorcraft design and optimization framework, deployed for the design analysis and optimization of conceptual rotorcraft powerplant configurations.

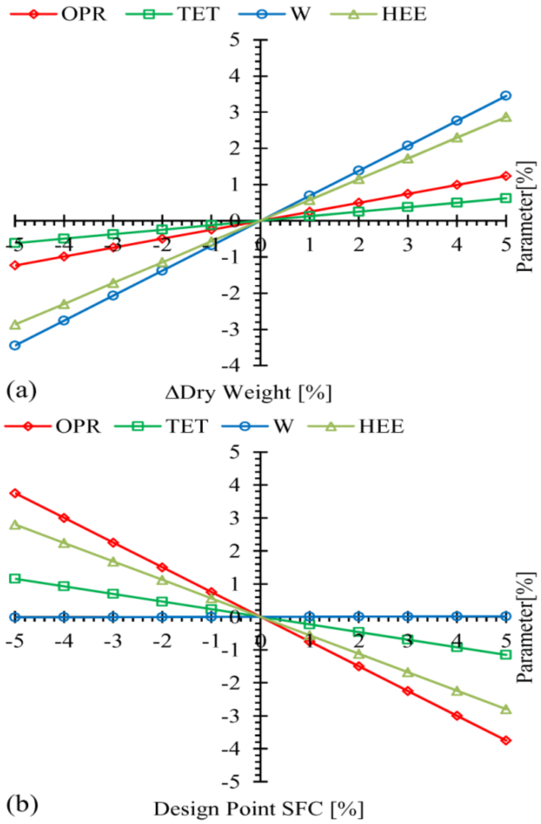

Fig. 2: a) Sensitivity analysis of regenerated engine design parameters against engine weight, b) Sensitivity analysis of regenerated engine design parameters against engine SFC$_{Dp}$.

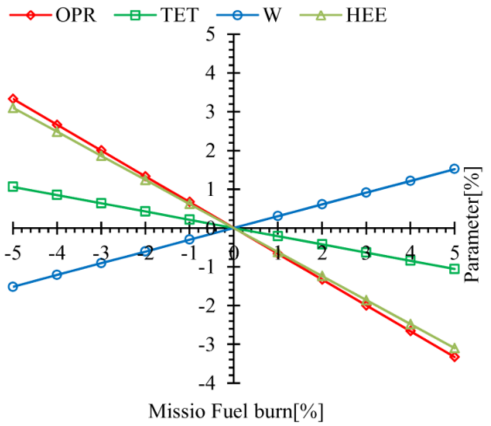

Fig. 3: Sensitivity analysis of regenerated engine design parameters against mission fuel burn.

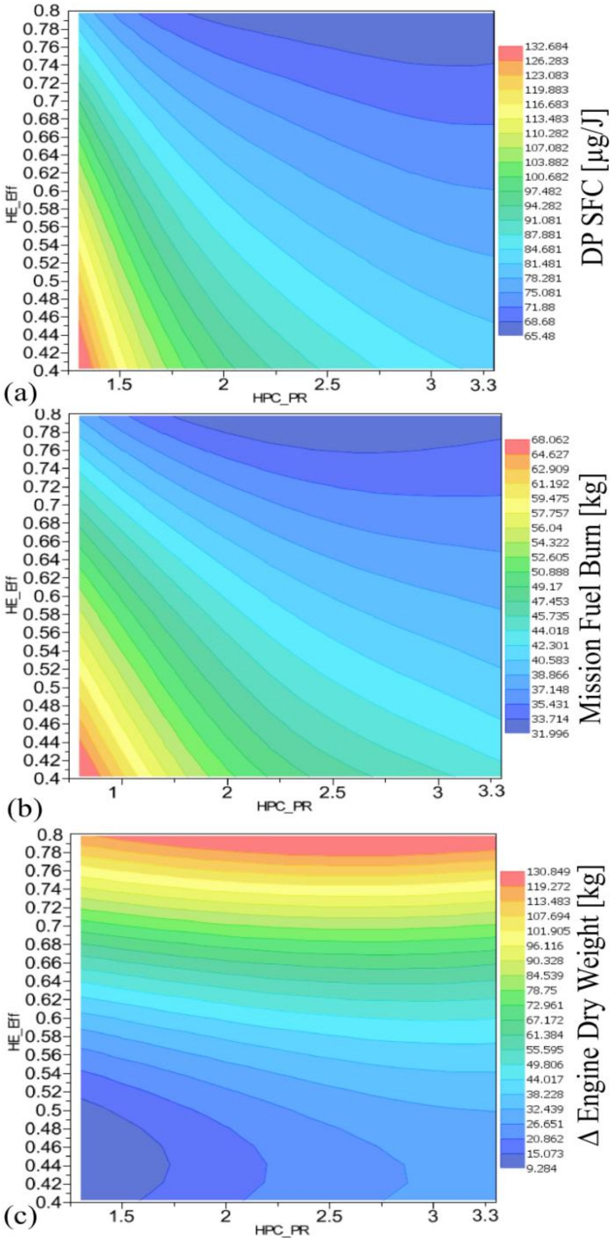

Fig. 4: a) RSM for engine SFC$_{DP}$ versus engine HPC PR and HEE, b) RSM for mission fuel burn versus engine HPC PR and HEE, b) RSM for engine weight versus engine HPC PR and HEE; conceptual regenerated Bo105 helicopter, PATM.

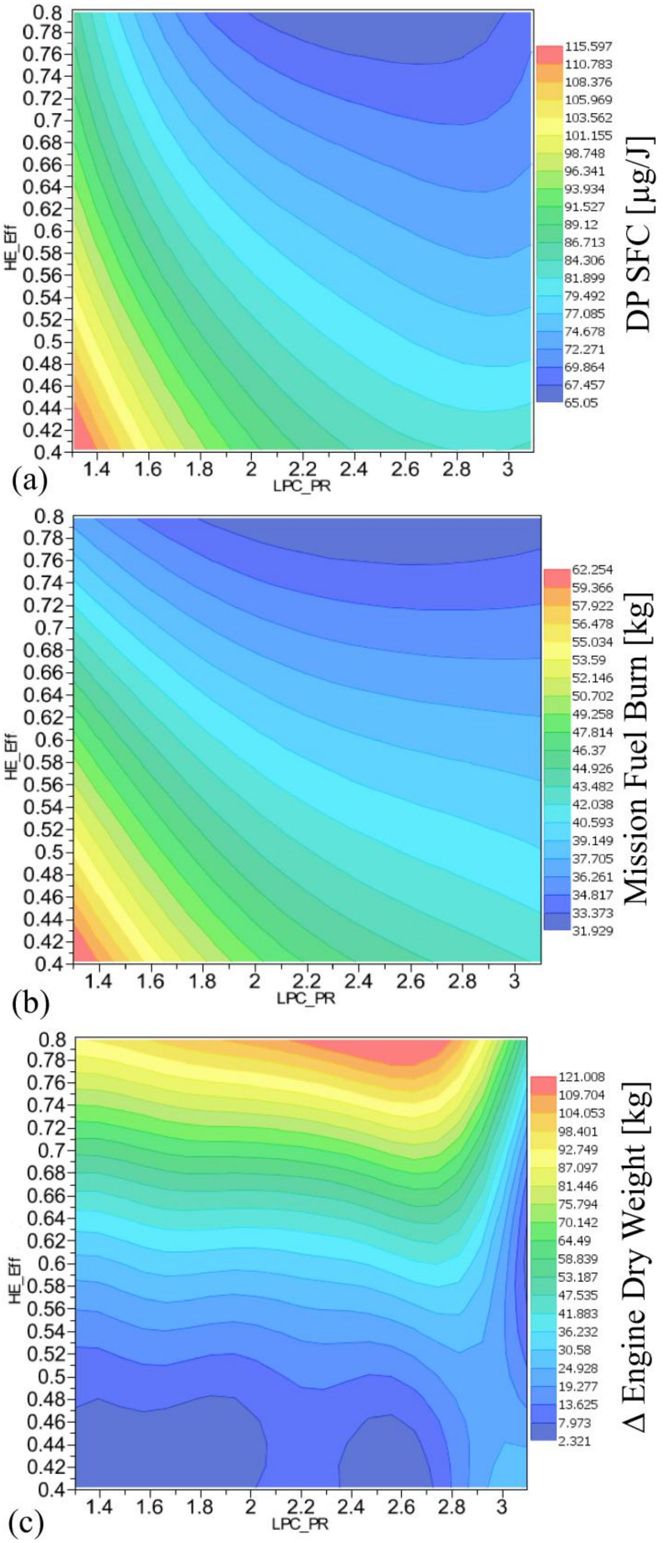

Fig. 5: a) RSM for mission fuel burn versus engine LPC PR and HEE, b) RSM for mission fuel burn versus engine LPC PR and HEE, c) RSM for engine weight versus engine LPC PR and HEE; conceptual regenerated Bo105 helicopter, PATM.

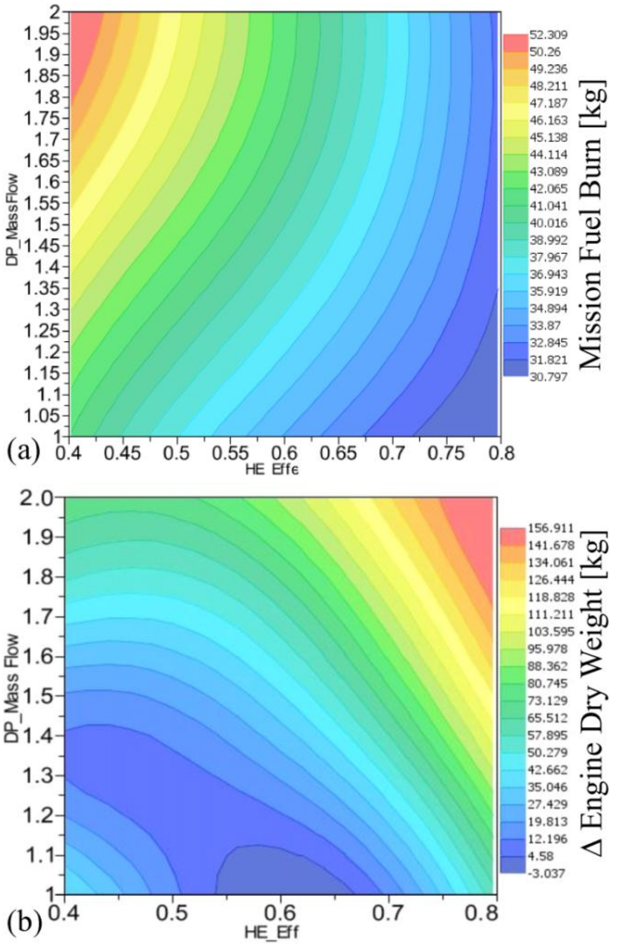

Fig. 6: a) RSM for mission fuel burn versus engine $\dot{W}$ and HEE, b) RSM for engine weight versus engine $\dot{W}$ and HEE; conceptual regenerated Bo105 helicopter, PATM.

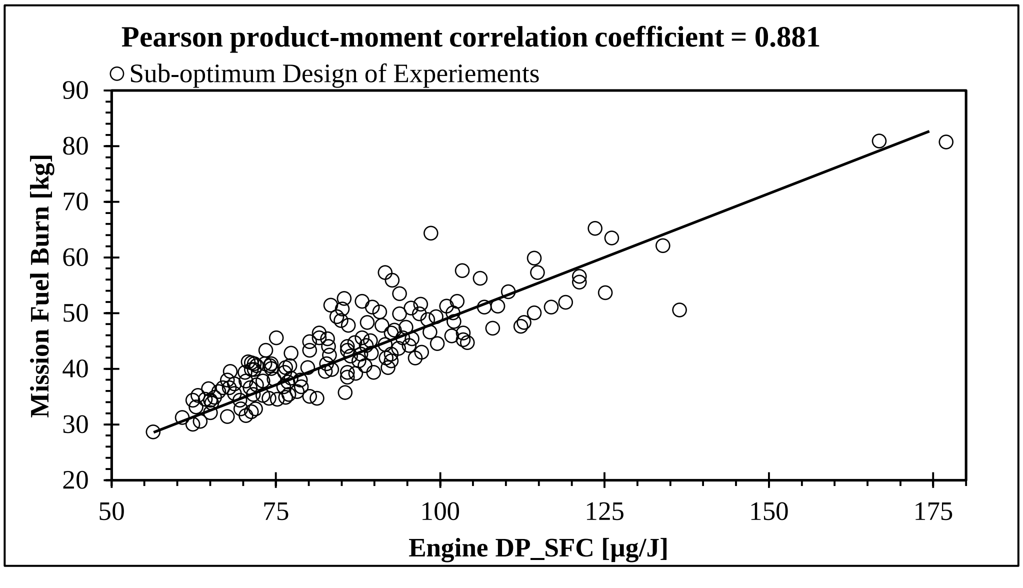

Fig. 7: Mission Fuel burn and engine design point specific fuel consumption scatter of design of experiments; conceptual regenerative Bo105 helicopter, passenger mission.

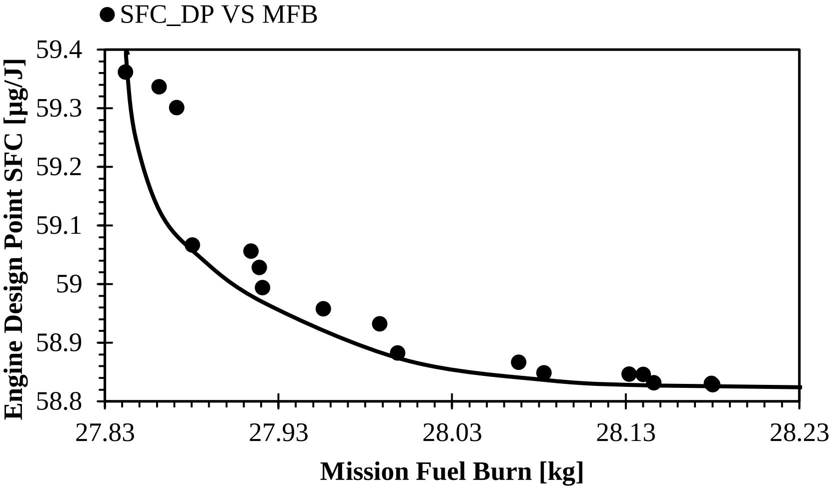

Fig. 8: Multi-objective results, Pareto front surface for minimum design point SFC and minimum mission fuel burn; conceptual regenerated Bo105 helicopter, PATM.

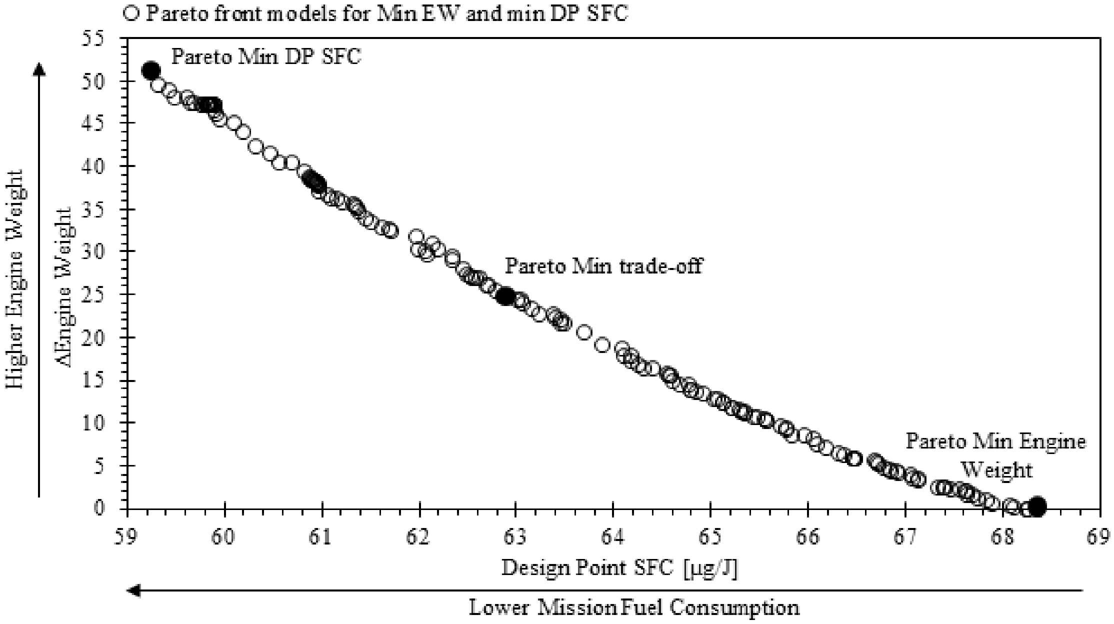

Fig. 9: Multi-objective results, (a) Pareto front surface for minimum design point SFC and minimum delta engine weight; conceptual regenerated Bo105 helicopter, PATM.

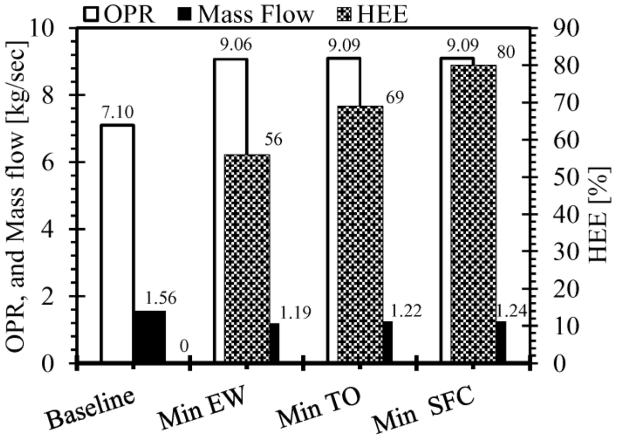

Fig. 10: Comparison between the optimized engine design cycle parameters; conceptual regenerated TEL Bo105 helicopter, conceptual regenerated Bo105 helicopter, PATM.

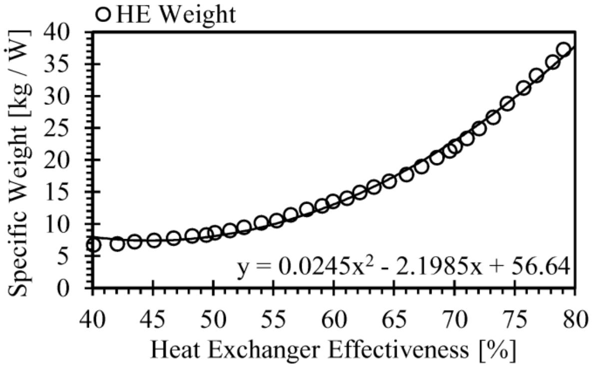

Fig. 11. Regenerated turboshaft configuration, fixed geometry tubular type heat exchanger specific weight correlation adopted from (Ref. 9) integrated in HECTOR.

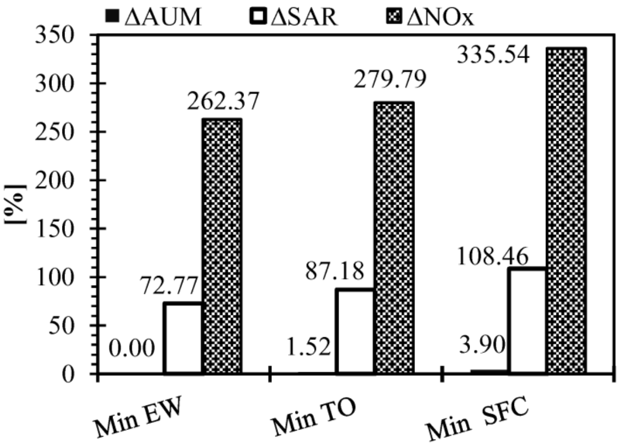

Fig. 12: a) Comparison between baseline and three selected Pareto front surface; mission level parameters and deltas; Bo105 helicopter

Table 1: Design space bounds and constraints for engine size and thermodynamic cycle parameters; imposed for multi-objective optimizations.

Design Parameter	Lower Bound	Higher Bound	Units
LPC PR	1.3	3.1	-
HPC PR	1.3	3.3	-
$\dot{W}$	1.0	2.0	kg/sec
TET$_{DP}$	1300.0	1600.0	K
HEE	40.0	80.0	%
Constraints for implemented multi-objective optimization			
TET$_{DP}$	1470.0		K
P$_{DP}$	313000.0		W

Table 2. Multi-objective results, response surface model relative error for all three selected Pareto optimum models.

Configuration	RSM	HECTOR	Units	RSM rel.error %
RSM relative error for minimum SFC$_{DP}$				
Baseline	58.80	59.99	kg	-1.98
Optimized	28.57	28.69	kg	-0.42
Reduction	-51.41	-52.18	%	Avg rel. error -1.20
RSM relative error for minimum ΔEW				
Baseline	58.80	59.99	kg	-1.98
Optimized	34.65	34.73	kg	-0.23
Reduction	-41.07	-42.11	%	Avg rel. error -1.10
RSM relative error for minimum trade-off between SFC$_{DP}$ and ΔEW				
Baseline	58.80	59.99	kg	-1.98
Optimized	32.01	32.05	kg	-0.12
Reduction	-45.56	-46.57	%	Avg rel. error1.05

Table 3. Multi-objective results, comparison between baseline and all three selected Pareto models; Bo105 helicopter passenger air taxi mission.

Design parameter	Baseline	Min SFC_{DP}	Min EW	Min Trade-off	Units	Min SFC_{DP} Rel. %	Min EW Rel. %	Min trade-off Rel. %
LPC PR	2.73	3.04	3.02	3.04	-	11.36	10.62	11.36
HPC PR	2.60	2.99	3.10	2.99	-	15.00	19.23	15.00
OPR	7.09	9.09	9.36	9.09	-	28.06	31.90	28.06
TET_{DP}	1470.00	1470.00	1470.00	1470.00	K	0.00	0.00	0.00
$\dot{W}$	1.56	1.24	1.19	1.22	kg/sec	-20.51	-23.71	-21.79
HEE	0.00	80.00	56.00	69.00	%	80.00	57.00	56.00
Engine and mission output parameters								
EW	144.00	241.60	144.00	182.09	kg	67.78	0.00	26.45
MFB	59.99	28.57	34.65	32.01	kg	-52.38	-42.24	-46.64
NO_x	0.287	1.250	1.110	1.093	kg	335.54	286.76	279.79

Table 4. Multi-objective results, comparison between baseline and all three selected Pareto models; mission level parameters and deltas.

Parameter	Baseline	Min SFC	Min EW	Min trade-off	Units
SAR	2.29	4.79	3.97	4.30	km/kg of fuel
Fuel $flow_{mean}$	0.018	0.010	0.009	0.008	kg/sec
ΔFuel burn	-	-52.38	-42.24	-46.64	%
ΔSAR	-	108.46	72.77	87.46	%
ΔNO_x	-	335.54	286.76	279.79	%
ΔAUM_i	-	3.90	0.00	1.52	%

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