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Design exploration and performance assessment of advanced recuperated hybrid-electric UAM rotorcraft

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ABSTRACT

The design of efficient, environmentally friendly and quiet powerplant for rotorcraft architectures constitutes a key enabler for Urban Air Mobility (UAM) application. This work focuses on the development and application of a generic methodology for the design, performance and environmental impact assessment of a parallel hybrid-electric propulsion system, utilizing simple and advanced recuperated engine cycles. A simulation framework for rotorcraft analysis comprising models for rotor aerodynamics, flight dynamics and hybrid-electric powerplant performance is deployed for the design exploration and optimization of a hybrid-electric rotorcraft, modelled after the NASA XV-15, adapted for civil applications. Optimally designed powerplants for payload-range capacity, energy efficiency and environmental impact have been obtained. A comparative evaluation has been performed for the optimum designs. The respective trade-offs between engine, heat exchanger weight, thermal efficiency, as well as mission fuel burn and environmental impact have been quantified. It has been demonstrated that a recuperated gas turbine based hybrid-electric architecture may provide improvements of up to 6% in mission range capability without sacrificing useful load. At the same time, analyses performed for a representative 100 km mission suggest reductions in fuel burn and NO_x emissions of up to 12.9% and 5.2% respectively. Analyses are carried at aircraft and mission level using realistic UAM mission scenarios.

Keywords: Urban Air Mobility (UAM), tilt-rotor, Hybrid-Electric Propulsion System (HEPS), recuperated cycles, Design Space Exploration (DSE), environmental impact, preliminary design.

NOMENCLATURE

Acronyms

AUM	All-Up-Mass
BEMT	Blade Element Momentum Theory
CO ₂	Carbon dioxide
DP	Design Point
DOH	Degree-of-Hybridization
DSE	Design Space Exploration
EW	Empty Weight
HE	Hybrid Electric
HX	Heat Exchanger
HEPS	Hybrid Electric Propulsion System
IRP	Intermediate Rating Power
MCR	Maximum Continuous Rating
MTOW	Maximum Take-Off Weight
OEW	Operating Empty Weight
RMS	Root-Mean-Square
SFC	Specific Fuel Consumption
SOC	State-of-charge
TET	Turbine Entry Temperature
UAM	Urban Air Mobility
VTOL	Vertical Take-Off and Landing

Symbols

H _E	Degree-of-Hybridization of energy	%
ε _{Bat}	Battery specific energy	Wh/kg

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ϵ_{HX}	Heat exchanger effectiveness	%
w	Component weight	kg
$E_{total, mission}$	Total mission electric energy demand	kWh
E_{Bat}	Battery installed energy	kWh
PAX	Number of passengers carried	-
$\eta_{ElecSys}$	Total efficiency of the electric system (from motors to the batteries)	%
Δw_{fuel}	Fuel burn delta, $100 \cdot (w_{fuel_{HE}} - w_{fuel_{GT}})/w_{fuel_{GT}}$	%
η_{ov}	Overall system efficiency	%
i_N	Nacelle angle	deg
δ_F	Flap setting angle	deg
Subscripts		
$()_{GT/Bat/HX}$	Referring to the gas turbine, battery or heat exchanger, respectively	
$()_{ElecSys}$	Referring to the electric system (battery, motor, controllers)	
$()_{HE/conv}$	Referring to the hybrid-electric tilt-rotor or conventional tilt-rotor, respectively	

1. INTRODUCTION

1.1 Background

Current trends in aviation dictate increasing demands for rotorcraft operations for passenger transport/air-taxi. At the same time, the environmental goals set by the aviation industry [1,2] has spurred the exploration of alternative configurations and propulsion systems targeting sustainable solutions. Urban Air Mobility (UAM) is a new market within the aviation industry expected to boom in the near future with a forecasted market worth of \$500 billion by 2030 [3].

This new application targets to ease congestion in urban areas, increase mobility reach and reduce the environmental impact stemming from urban transportation. It is envisioned to make use of up to 15-passenger hybrid or all-electric Vertical Take-Off and Landing (VTOL) configurations operating in an intra-urban environment for short and frequent flights of 50 nautical miles or less [4].

The UAM vision is predicated on the development of new technologies to address these goals. Large research and development activities are currently undertaken on novel rotorcraft and propulsion architectures. Improving thermal efficiency using conventional technologies and without major changes in engine design has become increasingly difficult. For this reason, the investigation of enabling technologies is essential to attain the future environmental targets.

1.2 Hybrid-electric propulsion

The ‘more-electric’ rotorcraft has been recognized as a milestone towards the adoption of sustainable solutions for UAM. Hybrid Electric Propulsion Systems (HEPSs) offer improved flexibility and redundancy in case of engine failure, lower maintenance costs and capability to reduce the need for engine oversizing [5].

Rotorcraft operate at part load and hence, increased Specific Fuel Consumption (SFC) for the majority of the flight (80-90% of the total flight time) [6]. Introducing a hybrid-electric system may allow for reduced engine size and operation at conditions that are more favourable by moving the ‘average’ operating point towards higher relative power and hence, lower SFC [5]. These benefits come at a cost of increased Empty Weight (EW) and complexity of the propulsion system [5, 7]. Current state-of-the-art batteries are limited in terms of energy density and hence, the performance improvement comes at a cost of reduced payload capability [42]. As discussed by Roumeliotis [5], a battery-boosted parallel architecture for a twin-engine medium helicopter can improve overall mission SFC relative to the conventional aircraft, especially at part load operations.

Danis et al. [7] presented a conceptual design methodology for hybrid-electric rotorcraft. In this study, various hybrid tilt-rotor variants were investigated, by re-configuring the NASA XV-15 with a HEPS. It was demonstrated that the hybrid configuration provides improved overall performance due to the battery-boosting capability. This resulted in a maximum reduction of 10% in cruise fuel with a weight penalty of 25% increase in EW relative to the conventional configuration.

1.3 Advanced recuperated cycles

The concept of advanced recuperated cycles can improve SFC especially during part-load operation of rotorcraft. Thus, targeting higher efficiency, the deployment of recuperation in helicopters is an attractive technology to enhance performance and operational capabilities. Regenerative technology for helicopters has been investigated since the 1960s [8] with early recuperated rotorcraft resulting in improved fuel efficiency. These configurations, however, were impractical due to the significant increase in engine weight, volume and maintenance complexity [9].

It is generally accepted that the simple cycle configuration has approached its performance limits and any significant improvement in thermal efficiency cannot be achieved without the consideration of innovative and novel designs [10] or a step-change improvement in material capabilities. Specifically, improvements up to 10% on SFC are predicted for advanced simple cycle turboshafts [14]. At the same time, advanced recuperated cycles may offer up to a 30% reduction of SFC [14]. Recuperated cycles have been previously considered for rotorcraft configurations in various studies in the literature [10-12]. Fahkre et al. [11] concluded that the recuperated helicopter can lead to significant improvement in fuel economy and enhanced payload-range capability with a penalty of increased weight and NOx emissions.

The main disadvantage of the recuperated cycle is the increased weight and volume of the heat exchanger as well as the additional pressure losses for both exhaust gas and compressed air [14]. The added pressure losses result in lower specific power, making the recuperated engine inappropriate to retrofit existing helicopters that require maintaining constant power ratings [5]. In addition, the recuperator usually presents a large thermal inertia effect resulting in longer engine reaction times [13].

1.4 Scope of present work

The disadvantages of the two technologies considered; electric propulsion and recuperated cycles, are associated with low energy densities for electric propulsion leading to impractical payload and reduced range capability [42] and increased pressure losses, weight and volume of the heat exchanger leading to reduced specific power and engine lag for the recuperated cycle. Roumeliotis et al. [5] have shown that a hybrid-electric system coupled with a recuperated gas turbine can alleviate the above-mentioned disadvantages. Specifically, the advanced recuperated cycle may offer significant improvements in thermal efficiency, while the electric powertrain may act as a key enabler by providing the additional power boost required by the system due to the introduction of additional pressure losses inherent in the heat exchanger. Additionally, the electric system may potentially be used to negate the transient disadvantages of the recuperated gas turbine cycle [5].

Although recuperation has been identified as a promising cycle for hybridization [5], its full potential has not been assessed in the literature. A comprehensive design space exploration and trade-off study in terms of payload-range capacity and fuel economy of advanced recuperated thermo-electric powerplants has not been addressed in a multidisciplinary environment. Additionally, the environmental impact stemming from the utilization of hybrid-electric recuperated gas turbine based architectures has not been examined in the literature. For this reason, a multidisciplinary optimization framework considering gas turbine and electric powertrain design, including weight estimation is coupled with a suitable rotorcraft performance model to enable coupled rotorcraft – HEPs assessment. Models for rotor aerodynamics, flight dynamics, weight estimation, mission analysis are developed and validated for each respective discipline [42] and coupled with software for gas turbine performance [15] and emissions prediction [16]. The developed simulation framework is used to explore the design space of a recuperated gas turbine based hybrid-electric tilt-rotor using a full factorial sampling approach.

The aforementioned framework is deployed for the design space exploration and trade-off study in terms of payload-range capacity, fuel economy, and environmental impact for a civil tilt-rotor with the implicit considerations of the design complexity of HEPs. The methodology proposed within this paper offers an integrated approach in addressing the trade-offs associated with the development of future rotorcraft powerplant that are based on heat exchanged engines, or semi-closed cycle engine architectures.

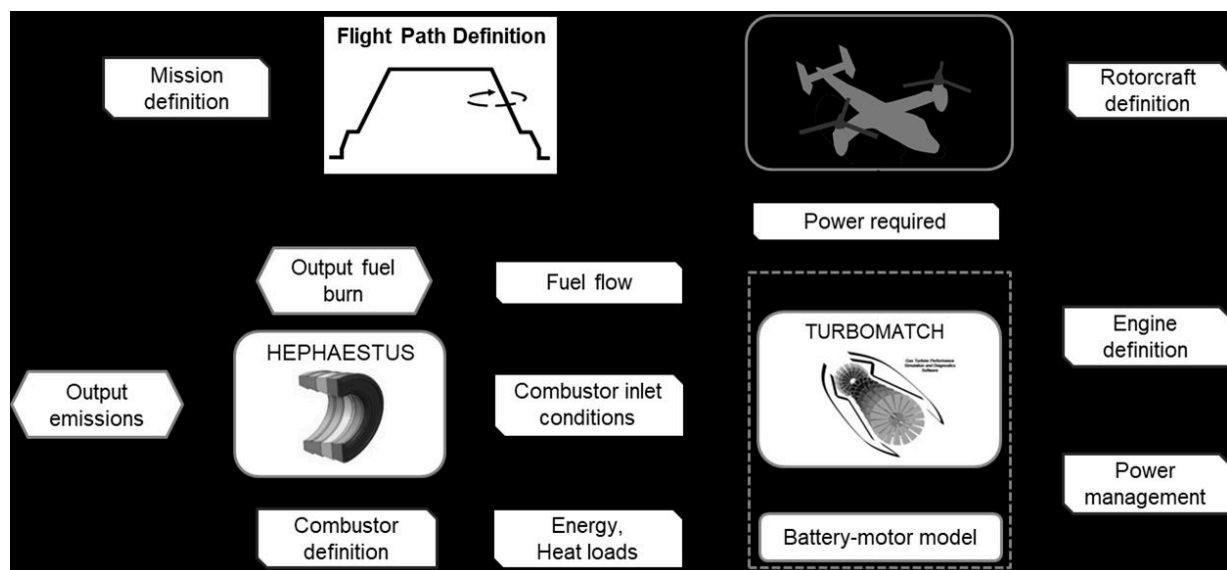


Figure 1 Multidisciplinary hybrid-electric rotorcraft framework

2. SIMULATION METHODOLOGY

The modelling approach comprises a set of comprehensive modules, each applicable to the different aspects of rotorcraft and powerplant performance. Models for rotorcraft performance were developed, validated and coupled with software for engine performance analysis [15] and gaseous emissions estimation [16] as presented in [42]. The engine performance software is coupled with a battery-motor simulation module [17] and a weight estimation module is also incorporated within the framework. The different simulation models are integrated within a mission analysis module enabling performance analysis at aircraft and mission level as illustrated in Figure 1. A brief description of the individual modules is provided below.

2.1 Tilt-rotor performance

The integrated modelling approach intends to incorporate the features of the 1st level of Padfield's hierarchical paradigm, appropriate for performance studies [18]. The rotorcraft performance model comprises a set of aerodynamic models for the different aircraft components; rotor, fuselage, empennage and wings as well as a nonlinear trim model.

The rotor model utilizes steady-state non-linear blade element theory coupled with different inflow models for axial propeller flight and flight with an edgewise flow component. The blades are assumed to be rigid bodies, with no flap deflection [19].

In hovering or high-speed cruise flight, the rotor aerodynamics model is coupled with Bhagwat's induced inflow model [20]. In conversion mode, the rotor aerodynamics model is coupled with the Mangler and Squire [22,23] inflow model with the definition of the inflow described by Bramwell [21]. Look-up tables describing the steady-state aerodynamic characteristics for the two-dimensional airfoil sections are deployed.

The tilt-rotor is a laterally symmetric vehicle which allows to de-couple the roll-yaw degrees-of-freedom [24]. Experimental look-up tables expressed as functions of incidence and side-slip angles are utilized for the prediction of fuselage and wing-pylon forces and moments [28]. The aerodynamic data of the aforementioned components are extracted for the XV-15 tilt-rotor from Refs. [25-26].

The wing is modelled considering the portion of it in the freestream and slipstream separately as presented in [28]. A Newton-Raphson approach is applied to obtain the control and fuselage attitude angles required to achieve an equilibrium trim state for a specified operating condition. The process converges to a set of control inputs to reach equilibrium.

2.2 HEPS performance

A steady-state performance model of the engine in TURBOMATCH [15,29,30] was coupled with a battery simulation model for Lithium-Ion type (Li-Ion) batteries developed based on [17]. Fixed efficiency models are assumed for the rest of the electrical components. A flexible energy management module is also incorporated to allow the control of the power distribution between the two energy sources.

The battery weight is estimated based on the maximum energy and power requirements. The motors and generators are sized based on the method reported in [31]. An additional mass factor of 10% is added to account for the weight of cables, mounting and cooling system as proposed in [5].

2.3 Gaseous emissions estimation

HEPHAESTUS is a generic software for gaseous emissions estimation developed at Cranfield University [16]. The software is based on the stirred reactor concept and is combined with simplified chemical reaction equations. It has been originally developed for civil-aero engines and was later extended for turboshaft engines [16]. Extensive validation for turboshaft applications has been presented in the literature [16,30]. Detailed numerical formulation and validation against closed-form approximations and experimental measurements are presented in [16].

2.4 Integrated mission analysis

The mission analysis methodology originally reported by Goulos et al. [32] has been adapted for dual-energy rotorcraft [42]. The rotorcraft and hybrid-powerplant are assumed to operate at steady-state trim conditions and steady-state off-design conditions for the whole mission, respectively.

The flight dynamics code is used to trim the rotorcraft in each segment to calculate the power requirement. The power management module is used to distribute the power on the two sources based on specified power-split schedules. The engine fuel flow and SOC of the battery are calculated subsequently and the weight of the rotorcraft is updated based on the fuel burned at each segment [42]. A fixed-point iteration scheme is employed to solve for mission fuel burn, as per Goulos et al. [32].

3. REFERENCE VTOL – POWERPLANT DEFINITION

3.1 Test case: hybrid-electric tilt-rotor

The aircraft configuration selected for this study is a civil rotorcraft, modelled after the NASA XV-15 tilt-rotor [27]. The XV-15 is equipped with two nacelle-mounted turboshaft engines [33] and has been extensively documented in Refs. [34-36]. An engine based on General Electric T700-GE-700 suitable for this application is used as the baseline. The corresponding engine has been modelled and validated in TURBOMATCH by Ortiz-Carretero et al. [30]. The maximum power setting is set as the Design Point (DP). Table 1 presents the rotorcraft main design parameters.

Table 1 Tilt-rotor main design parameters [25,26].

Design parameter	Value	Unit
Empty Weight	4116	kg
MTOW	6803	kg
Number of blades	3	-
Blade radius	3.81	m
Root cut-out	0.0875	%
Blade chord	0.3557	m
Blade twist	41	deg
Rotor solidity	0.089	-
Nominal rotor speed	61.7	rad/s
Turboshaft engine	T700-GE-700	-
Number of engines	2	-

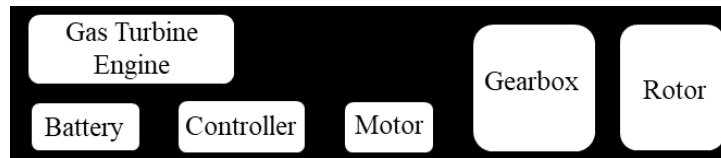


Figure 2 Conceptual hybrid-electric powerplant

The conventional tilt-rotor is designed to carry 9 passengers for eight sequential UAM short flights of 90 km. A parallel hybrid propulsion system is selected for the hybrid tilt-rotor, as illustrated in Figure 2. The present powerplant comprises two energy sources; fossil fuel and battery, providing energy to the gas turbine and motor respectively. The gas turbine and battery-motor system are connected with a gearbox that acts as a power splitter. The installed specific energy and specific power of the battery are assumed to be 250 Wh/kg and 900 W/kg as presented in Table 2, respectively.

Table 2 Propulsion component technology level assumptions.

Design parameter	Value	Unit
Battery specific energy	250	Wh/kg
Battery specific power	900	W/kg
SOC _{min}	15	%
Motor specific power	8	kW/kg
Motor efficiency	97	%

3.2 Comparison with experimental and flight test data

The integrated simulation framework is based on a multidisciplinary approach comprising models for the different aspects of rotorcraft and hybrid-electric powerplant performance. To gain confidence in the developed framework for the configuration of interest, the tilt-rotor and gas turbine models have been validated using experimental and flight test data.

Predictions for the fuselage pitch angle and rotor power requirement for the XV-15 tilt-rotor operating in straight and level flight are dissipated in Figure 3. The results are presented as functions of nacelle angle (i_N) and flap setting (δ_F). Comparisons with flight test data reported in [38] are included for validation purposes.

Overall a very good agreement between simulation and flight test data is shown for the prop-rotors at near-vertical orientation (90/40) as well as near-horizontal orientation (0/20, 0/0), with a 5.1% and 3.8% Root-Mean-

Square (RMS) error relative to the flight test data respectively. The larger discrepancies observed are attributed to component interactions which are significant for intermediate nacelle angles (30 and 60°). The employed method uses a simplified interaction approach that may not be able to capture the magnitude of these effects.

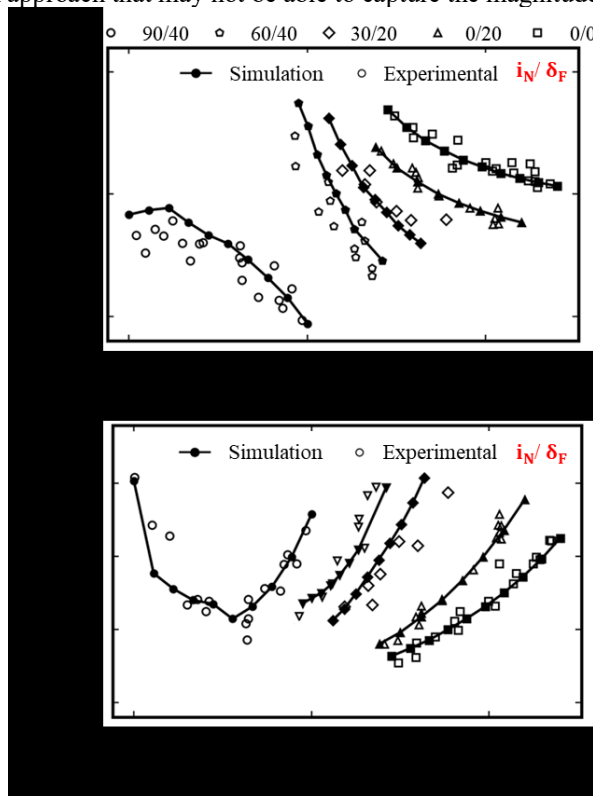


Figure 3 Flight dynamics trim results for the XV-15 tilt-rotor – comparison with flight test data extracted from [26, 38] (a) Fuselage pitch angle, (b) Single rotor power required at different nacelle angles/flap angles at SLS conditions

Figure 4 presents the engine performance validation based on simulations performed using the TURBOMATCH T700-GE-700 model as developed in [30]. It is observed that the TURBOMATCH model matches very well with the experimental data [41] for the whole operating envelope.

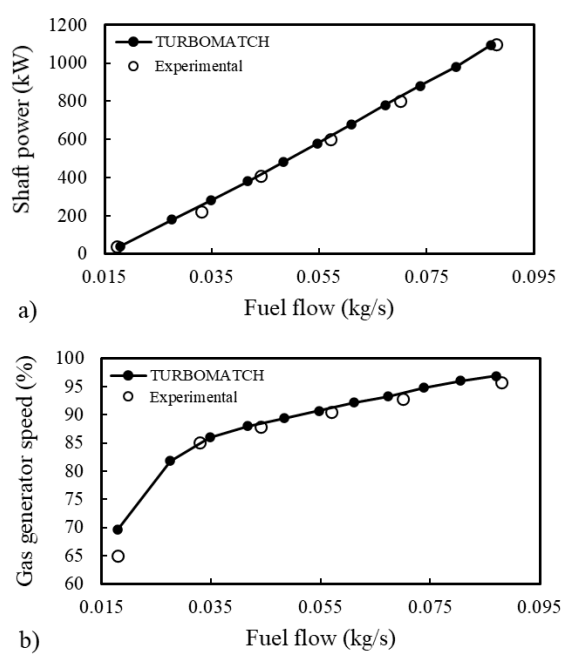


Figure 4 TURBOMATCH engine model comparison with measured data extracted from [41] for steady-state operation (a) shaft power, (b) gas generator speed versus fuel flow

4 DESIGN SPACE EXPLORATION FRAMEWORK

In this work, the integrated framework is extended for the exploration of the design space of a retrofitted civil rotorcraft utilizing simple and advanced cycles. The design and sizing approach is illustrated in Figure 5. To retrofit any rotorcraft model with a hybrid powerplant, several design and performance requirements must be fulfilled. The certification and safety constraints considered are:

- One Engine Inoperative (OEI) capability
- Fixed payload-range capacity
- Constant engine power ratings
- Constant Maximum Take-Off Weight (MTOW)

The Design Space Exploration (DSE) makes use of two design variables; the Degree-of-Hybridization (DoH) of energy (H_E) [37] and the effectiveness of the heat exchanger (ϵ_{HX}) [40], annotated in red (Fig. 5). H_E is expressed as a ratio of battery installed energy (E_{Bat}) to the total required energy (Eq. 1) during the sizing payload-range mission ($E_{total,mission} = \frac{\text{Propulsive Energy}}{\eta_{ElecSys}}$). The propulsive energy is an integral calculated numerically based on the mission analysis and a constant efficiency of $\eta_{ElecSys} = 90\%$. This is a simplified assumption essential for this calculation, as the battery efficiency varies throughout the mission based on its discharge characteristics. The battery weight is calculated based on H_E and the battery pack architecture is evaluated [17] based on the technology assumptions regarding battery specific power and energy presented in Table 2.

$$H_E = \frac{E_{Bat} \text{ [kWh]}}{E_{total,mission} \text{ [kWh]}} \quad (1)$$

The second design variable is the heat exchanger effectiveness (ϵ_{HX}). The introduced heat exchanger assumes a design point pressure drop of 4% for the cold and 5% for the hot side including duct losses with the values suggested by [40]. According to previous studies by McDonald et al. [10], the ϵ_{HX} is expected to be in the range of 40-74%. However, in the present work, the design point ϵ_{HX} is selected to vary in the range of 20-80% to explore the full design space.

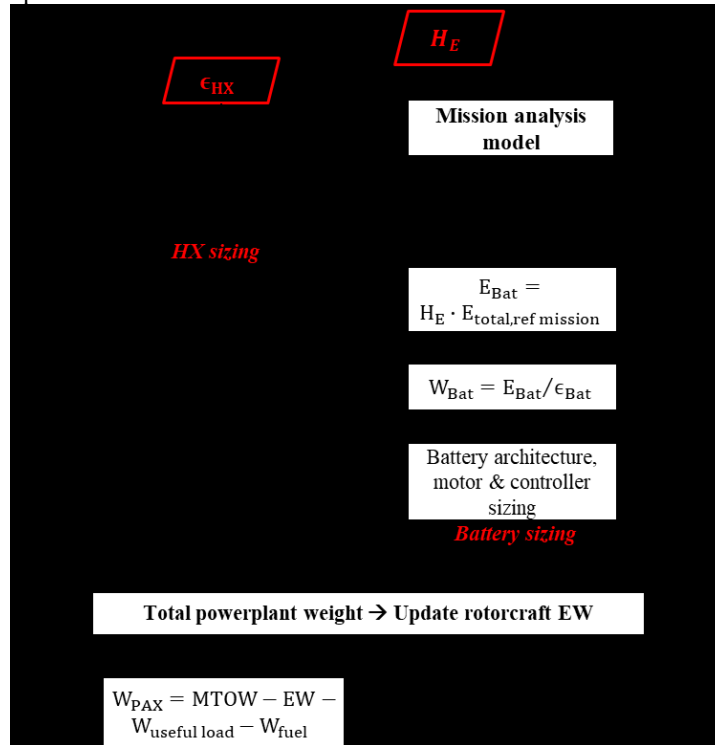


Figure 5 Hybrid-electric recuperated propulsion system design exploration

The maximum continuous rating (MCR) and maximum Intermediate Rated Power (IRP) of the recuperated engine are defined to match the Turbine Entry Temperature (TET) values of the simple cycle engine. Thus, the simple cycle MCR and IRP as reported in [39] are used to calculate the TET at each power rating. Figure 6

illustrates the SFC as a function of power for the turboshaft engine with varying degrees of Heat Exchanger (HX) effectiveness.

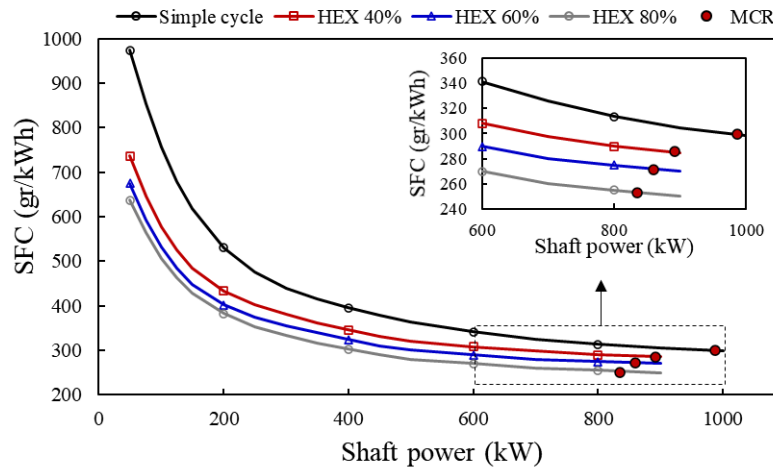


Figure 6 Specific fuel consumption versus power for a reference turboshaft engine – Comparison of simple cycle with recuperated cycle at 40%, 60% and 80% effectiveness

The recuperated cycle turboshaft is associated with significant improvement in SFC, which is more pronounced at part power with benefits becoming greater for higher heat exchanger effectiveness. However, the introduction of a recuperator is associated with additional pressure losses leading to reduced engine power ratings. From Figure 6, it is observed that the MCR of the recuperated cycle reduces for increased ϵ_{HX} compared to the simple cycle. Specifically, the MCR is reduced by a maximum value of 150 kW for a heat exchanger with $\epsilon_{HX}=80\%$. To recover baseline power ratings, a hybrid-electric propulsion system may be introduced with the battery supplying the remaining power required.

As presented in Figure 5, the heat exchanger and battery are sized based on the effectiveness and hybridization degree, respectively. The heat exchanger weight depends on the effectiveness and engine inlet mass flow and is calculated based on the weight correlation presented in Figure 7, adopted from [6]. The correlation in Figure 5 refers to the heat exchanger weight per engine. In this work, the heat exchanger lower limit was selected for the calculation of the heat exchanger weight. For effectiveness below 40%, the weight of the heat exchanger was assumed to remain constant to the value at 40%. Next, the MCR limit is evaluated based on the ϵ_{HX} and TET of the simple cycle. Given the weight of the heat-exchanger and battery-system architecture, the new powerplant is designed and its weight is used to update the rotorcraft EW accordingly.

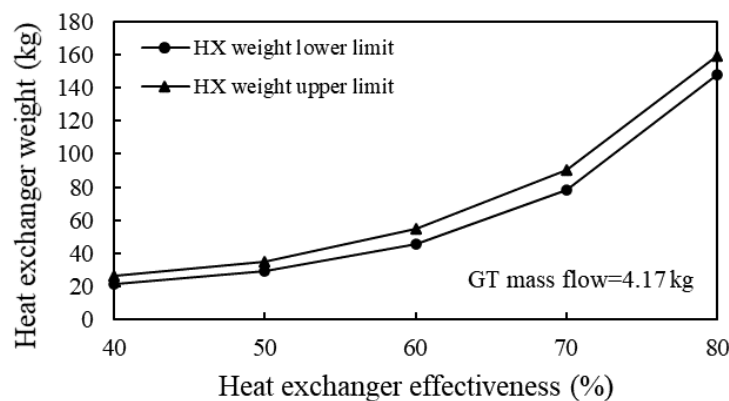


Figure 7 Recuperated T700-GE-700 turboshaft – heat exchanger weight correlation

5 RESULTS & DISCUSSION

Having developed and validated a simulation model for the design and performance assessment of HE tilt-rotor aircraft, the design space of the tilt-rotor utilizing simple and recuperated engines is investigated. The powerplant is sized based on the heat exchanger effectiveness (ϵ_{HX}) and hybridization of energy (H_E) (Fig. 5). The recuperated hybrid-electric powerplants are first evaluated at payload-range capacity level. For this reason, a sizing mission based on the payload-range diagram of the baseline rotorcraft is selected and shown in Figure 8.

Next, the optimum designs sized based on this mission are evaluated and compared. Finally, the optimum recuperated designs are assessed within a holistic analysis environment for missions of various ranges. For the aforementioned analyses, a fixed number of 9 passengers (9 PAX) is assumed.

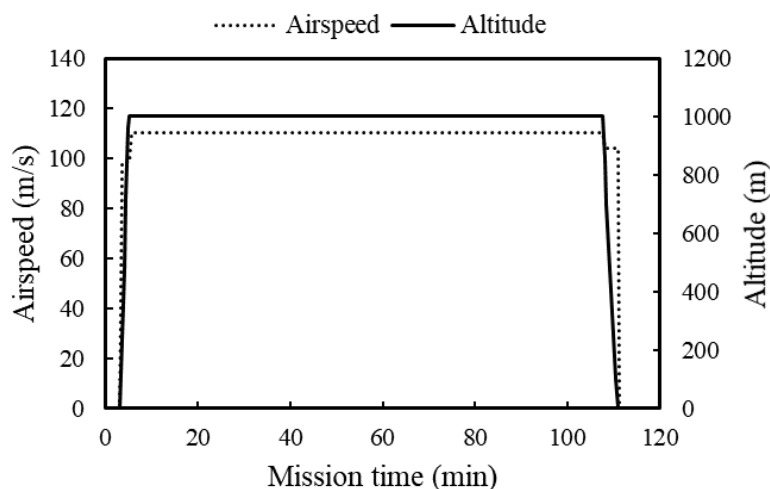


Figure 8 Mission altitude and flight speed profile for the sizing mission

5.1 HE recuperated powerplant design – Impact on payload

The impact of H_E and ϵ_{HX} on rotorcraft Operating Empty Weight (OEW), expressed as the summation of EW and fixed useful load, is presented in Figure 9. Each of the presented contour plots comprises approximately 300 simulation points. Each point on the contour plots represents a unique powerplant sized based on the methodology presented. The hashed regions indicate designs for which the rotorcraft OEW exceeds the MTOW. It is highlighted that the highly constrained design space is an outcome of technology limitations associated primarily with battery energy density (250 Wh/kg). With current state-of-the-art batteries, the DoH cannot exceed 15%, even with 5 passengers (450 kg payload).

The design space is also constrained with a red line (MCR limit) associated with the reduction of power ratings imposed by the pressure losses inherit in the heat exchanger (Fig. 6). Thus, this line represents the essential hybridization to be installed to maintain the power ratings of the baseline aircraft. With an increasing number of passengers, the feasibility region progressively shrinks to approximately 9% DoH for a payload of 9 passengers.

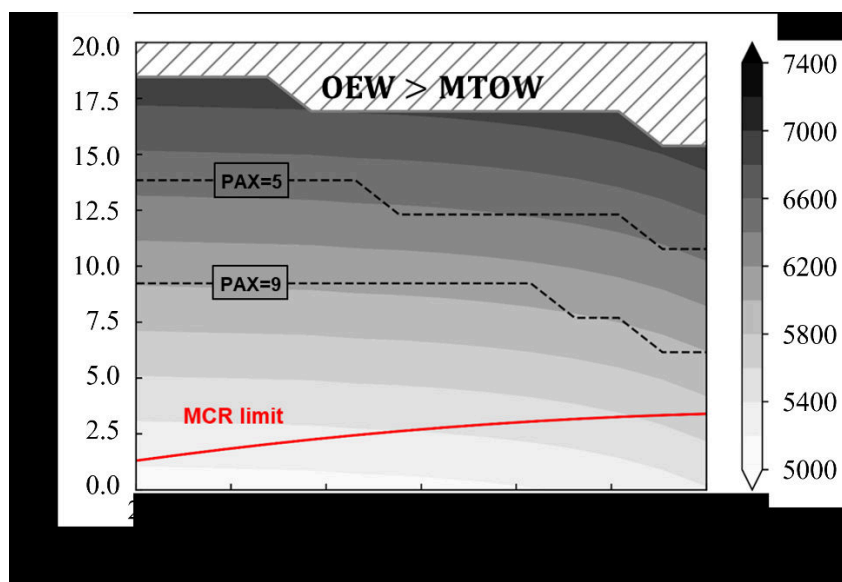


Figure 9 Effect of DoH and heat exchanger effectiveness on rotorcraft OEW

From Figure 9, for fixed hybridization, the OEW increases significantly for $\epsilon_{HX} > 60\%$. This is explained by the fact that the heat exchanger weight increases sharply for $\epsilon_{HX} > 60\%$. This is also illustrated in Figure 10, where the heat exchanger weight is nearly constant for $\epsilon_{HX} < 50\%$ and increases sharply for higher effectiveness. For the T700-GE-700 baseline turboshaft, the heat exchanger weight can rise to 149 kg for $\epsilon_{HX} = 80\%$.

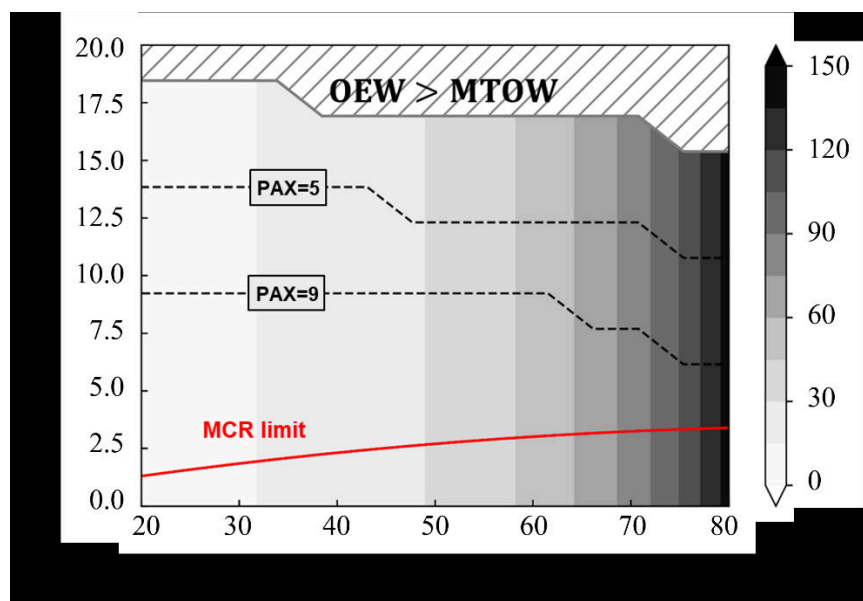


Figure 10 Effect of DoH and heat exchanger effectiveness on heat exchanger weight

5.2 HE recuperated powerplant design – Impact on range

Figures 11-12 illustrate the impact of the design variables on mission range relative to the baseline aircraft (ΔRange) and energy efficiency (η_{ov}) for the payload-range sizing mission. A reference sizing mission is selected to construct the payload-range diagram for the conventional rotorcraft, which is used as a baseline model as seen in Figure 8. This mission consists of a 5-min idle period where all the power is produced by the gas turbine, a take-off and climb segment up to 1000 m and a subsequent descent and land segment. The fuel tanks are assumed to be filled at the maximum capacity, hence the fuel capacity (w_{Fuel}) is set to 675 kg.

For each point in the contour plot, the non-linear mission analysis framework is deployed to size the powerplant and a payload-range mission is carried out, assuming a fixed w_{Fuel} to obtain the maximum range. The batteries are assumed to be charged only when the aircraft is getting refuelled. The red line (MCR limit) represents the essential hybridization degree to comply with the power ratings of the baseline aircraft for each ϵ_{HX} . A line of optimum energy efficiency is annotating the figures, which indicates that there is optimum hybridization for each value of ϵ_{HX} .

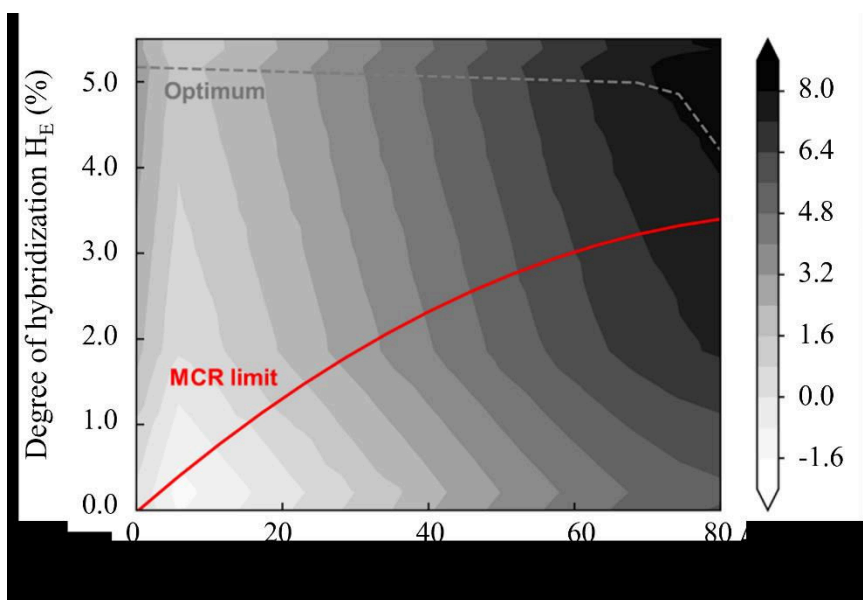


Figure 11 Effect of DoH and heat exchanger effectiveness on maximum range for the payload-range sizing mission

It is observed that for $\epsilon_{\text{HX}} < 35\%$, the improvement in range is negligible, indicating that the added pressure losses of the heat exchanger are dominant at those ranges of effectiveness. However, for $\epsilon_{\text{HX}} > 40\%$, the

improvement in average system efficiency and hence, range, becomes significant. For a fixed $\epsilon_{HX} > 40\%$, as DoH increases, the maximum range that the aircraft can fly increases until it reaches a breaking point of optimum efficiency. After this breaking point, the increase of hybridization has an adverse effect on energy efficiency and range. This is explained by the fact that the added battery weight above this value outweighs the benefit of increased total energy and powerplant efficiency.

Previous studies in the literature on recuperated cycles combined with hybrid propulsion were sizing the battery at the MCR limit [5]. It is noted however that the introduction of a larger battery, sized at the optimum efficiency line instead, may lead to better performance despite the added weight. Specifically, it is observed that for all the heat exchangers considered, the design at optimum efficiency results in better overall performance with improvements that reach up to 5.8%, 7.8%, 8.4% for ϵ_{HX} of 40%, 60% and 80%, respectively.

Figure 12 presents the effect of the design variables on the overall energy efficiency of the system (η_{ov}) averaged for the whole mission (Eq. 2). From equation 2, the propulsive energy is an integral calculated numerically based on the overall mission. Similarly, the heat input and electric energy are calculated based on the fuel and battery energy consumed throughout the mission.

$$\eta_{ov} = \frac{\text{Propulsive energy (kWh)}}{\text{Heat input (kWh)} + \text{Electric energy (kWh)}} \quad (2)$$

It is observed that the conventional tilt-rotor operates with an average efficiency of 24.4% for the sizing mission. As DoH and ϵ_{HX} increase the average energy efficiency increases reaching a maximum value of 27.2% for DoH of 5.15% and ϵ_{HX} of 80%.

The selected powerplant designs based on the two design strategies (MCR limit, optimum energy) are annotated in Figure 12. Specifically, the powerplants designed at the MCR limit correspond to DoH of 2.2%, 3% and 3.6% for heat exchangers with 40%, 60% and 80% effectiveness, respectively. Similarly, the powerplants designed for optimum efficiency correspond to DoH of 5.1%, 4.9% and 4.2% for heat exchangers with 40%, 60% and 80% effectiveness, respectively. A comparative evaluation of those designs at mission level, highlighting the respective trade-offs between fuel burn and gaseous emissions is discussed next.

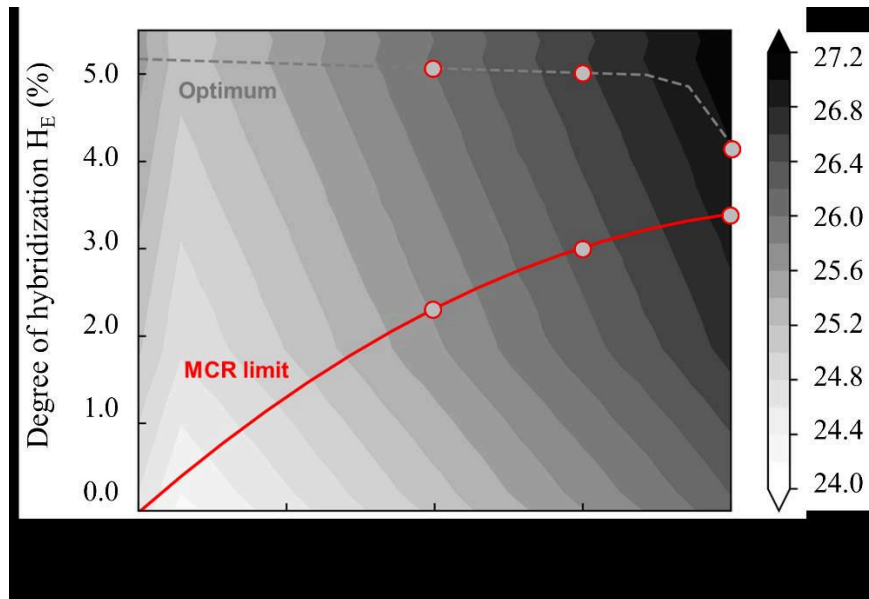


Figure 12 Effect of DoH and heat exchanger effectiveness on energy efficiency for the payload-range sizing mission

5.3 Mission analysis and environmental impact

Having explored the design space based on the payload-range sizing mission, an investigation of the selected designs at mission level provides a realistic assessment of the performance and environmental benefits. A reference mission of 180 km range is selected for this demonstration to represent two sequential UAM flights (2x90 km) [4]. The payload is assumed to be equal to 810 kg (9 PAX).

The improvements in performance and environmental impact stemming from the introduction of a recuperated gas turbine based hybrid-electric powerplant are illustrated in Figures 13-16 based on an 180 km mission. The

results for fuel burn, mission CO₂ and NO_x are presented as percentage differences relative to the baseline rotorcraft.

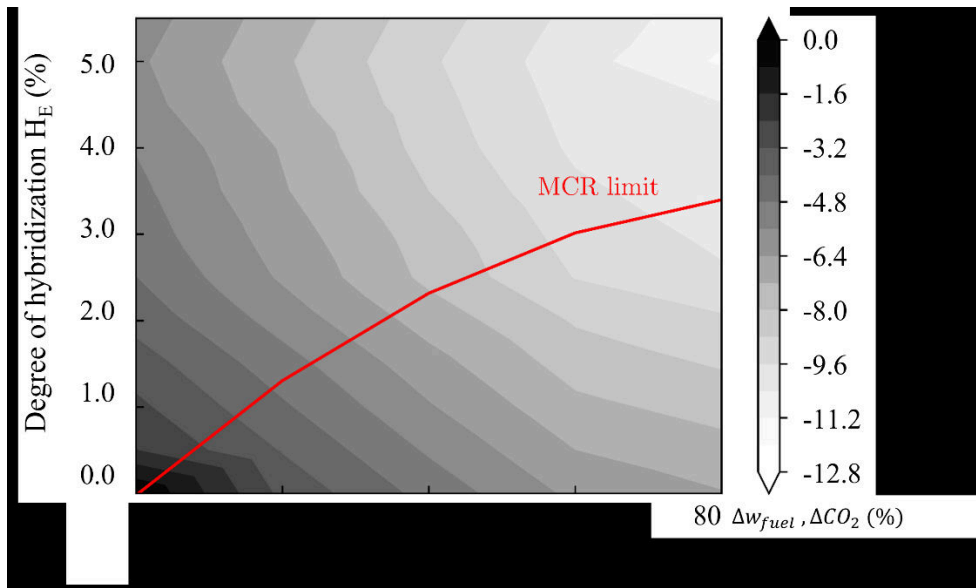


Figure 13 Effect of DoH and heat exchanger effectiveness on mission fuel burn and CO₂ relative to the baseline configuration for a representative UAM mission of 180 km range

Figure 13 illustrates the impact of H_E and ϵ_{HX} on mission fuel burn (Δw_{fuel}) and CO₂ emissions (ΔCO_2) relative to the conventional tilt-rotor. It is observed that as the ϵ_{HX} increases, mission fuel burn reduces. Specifically, for ϵ_{HX} of 40-60%, the benefit of the heat exchanger can become significant. For $\epsilon_{HX} > 60\%$, the 'rate' of improvement reduces due to the added heat exchanger weight that increases significantly for this range of effectiveness. For a fixed ϵ_{HX} , as hybridization increases, fuel burn reduces, reaching a breaking point at hybridization of 5%.

Figure 14 presents the total mission fuel and CO₂ deltas relative to the baseline aircraft for ϵ_{HX} of 40%, 60% and 80%. The present figure includes a comparison of the selected designs. It is observed that designing at optimum efficiency results in greater fuel burn improvement for every ϵ_{HX} . The greatest improvement is observed at $\epsilon_{HX} = 80\%$, where the mission fuel burn reduces by 10.5% and 12.9% for designs at MCR limit and optimum efficiency, respectively. It is noted however that the weight of the heat exchange at $\epsilon_{HX} = 80\%$ is calculated at 149 kg per engine (Fig. 7). At the same time, for a $\epsilon_{HX} = 60\%$, the HE recuperated powerplant results in almost the same benefit with approximately 10% and 11% fuel burn reduction at MCR limit and optimum efficiency, while the heat exchanger weighs 69% less than the $\epsilon_{HX} = 80\%$.

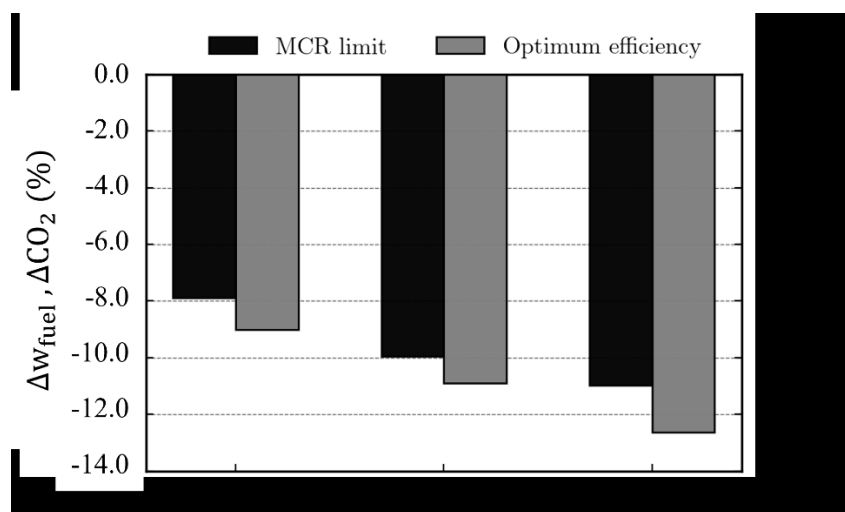


Figure 14 Mission fuel burn and CO₂ relative to the baseline tilt-rotor configuration

Figure 15 presents the impact of H_E and ϵ_{HX} on mission NO_x emissions relative to the conventional tilt-rotor (ΔNO_x). The NO_x emitted during the mission are calculated via the utilization of HEPHAESTUS software [16] (Section 2). The correlation of NO_x and fuel flow is high for simple cycle turboshafts, but their relationship is not

that straight forward for a dual-energy advanced recuperated turboshafts. This is due to the fact that, the production of NO_x is very sensitive to combustor inlet conditions and depend highly on engine fuel flow.

There are various conflicting phenomena to explain the trend in Figure 15. Through the recuperation process of exhaust waste heat utilization, the total temperature at the combustor inlet increases compared to the baseline gas turbine and thus, requiring less fuel to achieve the same turbine entry temperature resulting in lower specific fuel consumption. As illustrated in Figure 6, the benefit of the recuperator is more pronounced at lower power and therefore, the introduction of a battery as a second energy source, allows the engine to operate at lower power settings and hence, further reduce fuel burn. It is also highlighted that lower values of SFC are attained as the effectiveness increases, but this results in increased weight and combustor air inlet temperature while keeping TET constant [10].

As illustrated in this figure, for $\text{DoH} < 3.5\%$ and $\epsilon_{\text{HX}} > 50\%$, the introduction of a heat exchanger results in increased NO_x emissions relative to the baseline simple cycle turboshaft. This is explained by the fact that as the heat exchanger becomes more efficient, the total combustor air inlet temperature and pressure increases.

This trend changes for $\text{DoH} > 3.5\%$, despite the added weight of the battery and hence the increased AUM of the rotorcraft. The introduction of larger batteries allows the engine to operate at lower power settings and hence, lower fuel flow. This permits the reduction of NO_x at mission level to a minimum value of -3.8% for $\epsilon_{\text{HX}} = 40\%$. It is also noteworthy that for a simple cycle hybrid-electric powerplant ($\epsilon_{\text{HX}} = 0$), as DoH increases, NO_x emissions gradually reduce. At this point, the total energy of the aircraft is not enough to maintain payload-range capability as defined by the baseline aircraft.

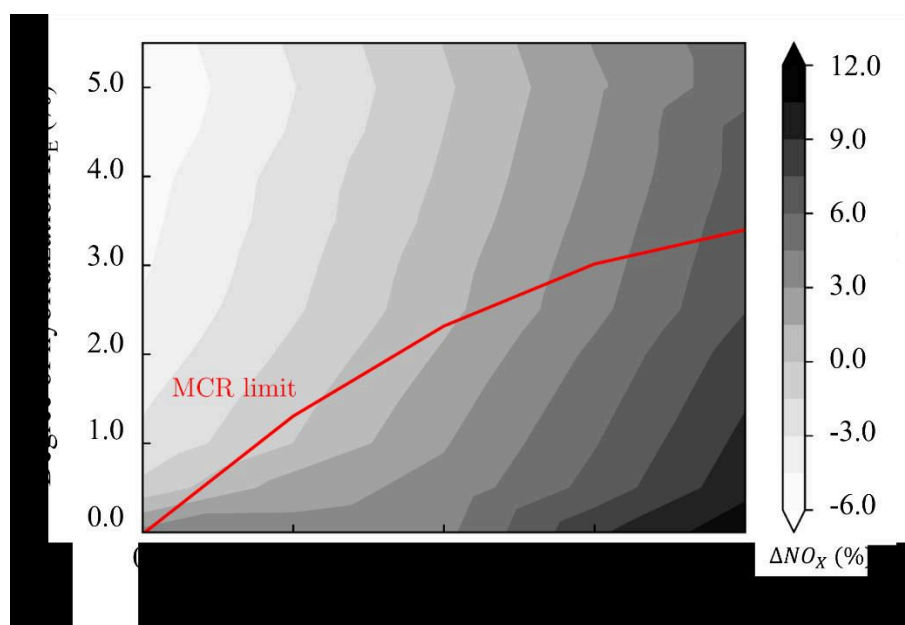


Figure 15 Effect of DoH and heat exchanger effectiveness on mission NO_x relative to the baseline configuration for a representative UAM mission of 180 km range

Figure 16 presents the impact of H_E and ϵ_{HX} on mission NO_x emissions relative to the conventional tilt-rotor (ΔNO_x) for 40, 60 and 80% ϵ_{HX} . Designing the recuperated hybrid-electric powerplant at the MCR limit results in increased NO_x for all the heat-exchangers considered, whilst designing at optimum efficiency can result in reduced NO_x emissions. Specifically, mission NO_x are reduced by 3.4% and 0.8% for ϵ_{HX} of 40% and 60%, respectively. For $\epsilon_{\text{HX}} = 80\%$, the production of NO_x is 1.95% higher than the baseline aircraft due to the added heat exchanger and battery weight.

Figure 17 illustrates the NO_x emitted during the 180 km mission for three representative designs; the baseline rotorcraft, the recuperated rotorcraft with 0% hybridization and the recuperated rotorcraft with a battery designed at the optimum efficiency ($\text{DoH} = 4.9\%$). It can be observed that the NO_x emitted for the recuperated cycle with $\text{DoH} = 0\%$ is higher than the baseline rotorcraft. It is therefore realized that although the recuperated gas turbine is more efficient and hence, the fuel at each segment is reduced, the effect of the increased total temperature at the inlet of the combustor is dominating. On the contrary, the hybrid-electric recuperated design results in reduced NO_x for all the mission segments. In this case, fuel burn is the dominating factor affecting the NO_x emitted during the mission.

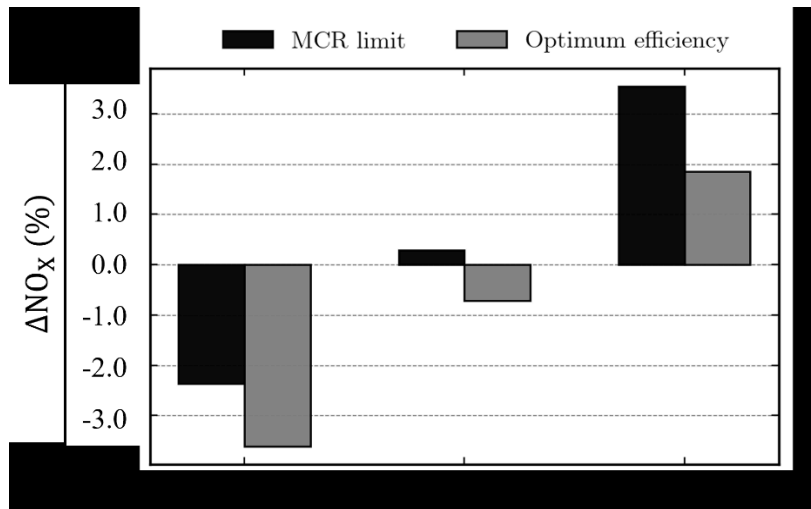


Figure 16 Mission NO_x relative to the baseline tilt-rotor configuration

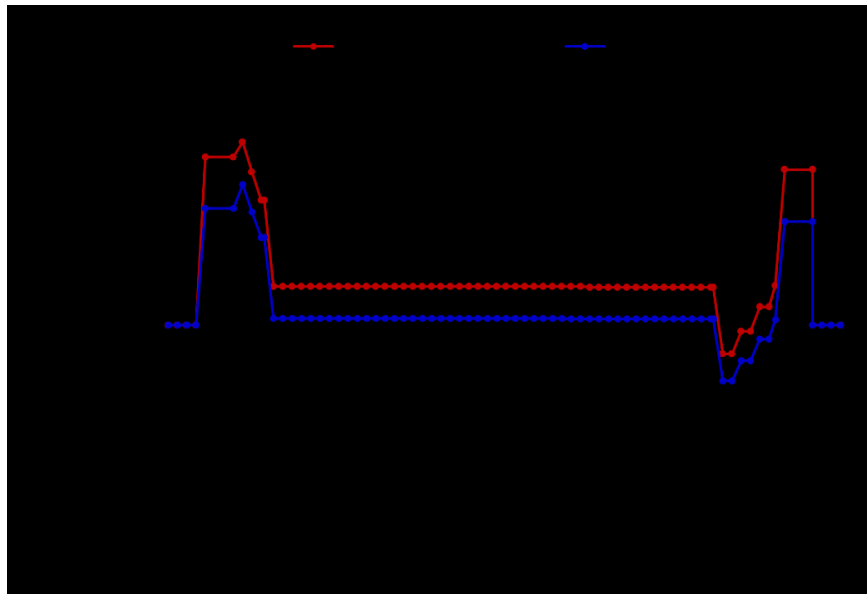


Figure 17 NO_x emitted for the reference 180 km range mission, Comparison of baseline - simple cycle, recuperated - DoH=0%, recuperated - DoH=4.9%

It is however realized that the benefit of the HE recuperated powerplant is mainly associated with the introduction of the heat exchanger. Figure 18 presents a comparison of three recuperated designs; at DoH=0%, at the MCR limit and optimum efficiency. This evaluation aims to break-down the benefit of the recuperated HE powerplant to the heat exchanger and the electric system. It is highlighted that for this comparison, a fixed AUM at take-off is assumed. This is done in order to compare the powerplants at the same power demand throughout the mission. It is observed that the recuperated cycle with 0% hybridization leads to improvements in fuel by 6%, 7.8% and 8.2% for ϵ_{HX} of 40, 60 and 80% respectively. Albeit this design does not comply with the baseline power ratings and hence, is not feasible, it allows to understand the benefit of the heat exchanger without the electric system. By introducing a second energy source, this benefit increases to 11.7% and 12.5% at MCR limit and optimum efficiency for an indicative heat exchanger of 60%.

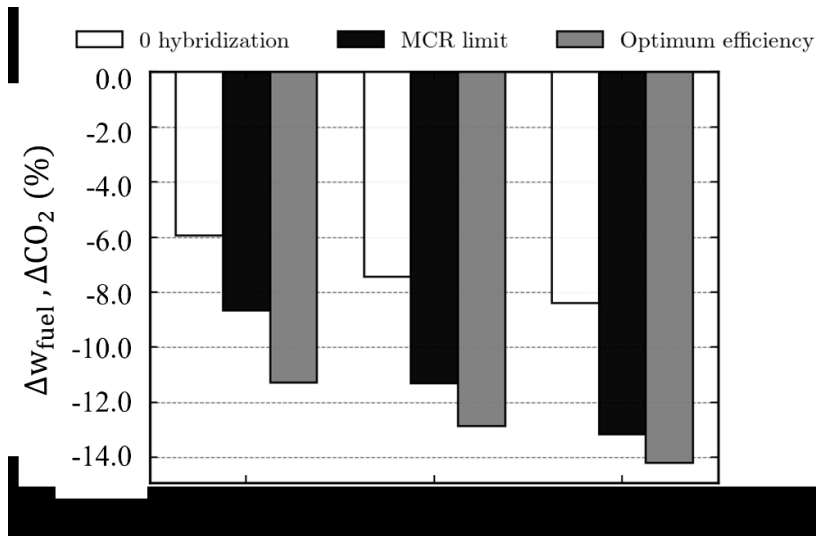


Figure 18 Mission fuel burn and CO₂ relative to the baseline tilt-rotor configuration – fixed AUM = 6700 kg for all designs

5.4 Mission analysis and environmental impact for different mission ranges

UAM vehicles will perform passenger transport missions in intra-urban environments [3,4]. Thus, the mission range for this application depends on the market demands as well as the infrastructure. For this reason, a comparative assessment is conducted for the two design strategies for various mission ranges. The reference mission selected for this comparison starts with a 5-min idle period where all the power is produced by the gas turbine, continues with a take-off and climb segment up to 1200 m and a subsequent descent and land segment. The payload is assumed to be equal to 810 kg.

Figures 19-20 present the mission results for different mission ranges as a function of heat exchanger effectiveness. Each point in the trend plot represents a unique powerplant sized at the MCR limit. For each unique powerplant, a mission analysis is carried out. Figure 19 presents the mission fuel burn and CO₂ relative to the conventional tilt-rotor. Greater improvement is observed at low range missions. Specifically, for a 100 km mission range, the benefit rises to 9.1%, 11.3% and 12.1% for ϵ_{HX} of 40, 60 and 80% respectively.

For short missions, the battery energy is enough to boost the gas turbine including parts of the cruise segment and hence, operate at a relatively low SFC. As the mission range increases, the benefit in fuel burn reduces. For a mission of 500 km, the maximum fuel reduction that can be attained is 7% for ϵ_{HX} =80%. While the recuperated configuration improves fuel burn, it has an adverse effect on mission NO_x emissions. From Figure 20, it is observed that for ϵ_{HX} =80%, the NO_x emitted during the mission exceed the NO_x of the baseline model with a maximum increase of 7% for a mission range of 500 km. This adverse effect on NO_x emissions is less pronounced at lower ϵ_{HX} values. For missions below 400 km, ϵ_{HX} =40% leads to improvements in NO_x emissions.

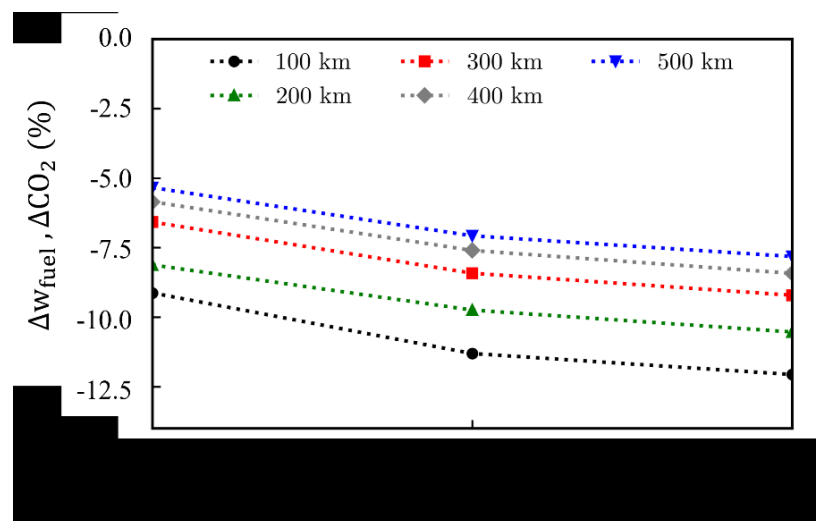


Figure 19 Effect of mission range on mission fuel burn and CO₂ relative to the conventional aircraft designed at MCR limit

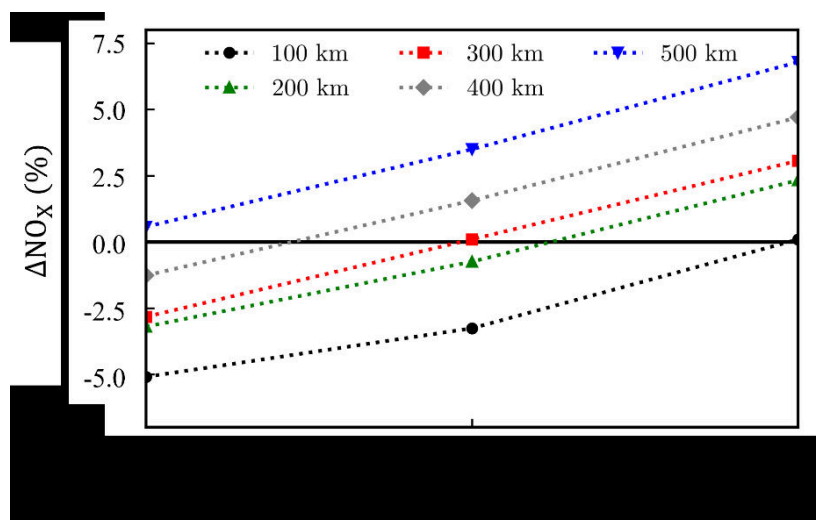


Figure 20 Effect of mission range on mission NO_x relative to the conventional aircraft designed at MCR limit

Figure 21 presents the mission results for different mission ranges as a function of heat exchanger effectiveness. Each point in the trend plot represents a unique powerplant sized at the DoH for optimum efficiency. It is observed that the benefit in fuel economy, CO_2 and NO_x emissions are greater than the designs at the MCR limit (Figs. 19-20). The greatest reduction in mission fuel is observed for 100 km mission range, rising to 10.4%, 11.8% and 12.8% for ϵ_{HX} of 40%, 60% and 80%, respectively.

Figure 22 illustrates the mission NO_x relative to the conventional tilt-rotor (ΔNO_x). The adverse effect on NO_x emissions is still present for this design strategy, as also observed in Fig. 20. However, the introduction of a larger battery can improve environmental impact. Specifically, for $\epsilon_{HX}=80\%$, the NO_x emissions are higher than the baseline aircraft for missions above 200 km. For $\epsilon_{HX}=60\%$, missions with range above 300 km exceed the baseline NO_x emissions. It is noted however that at $\epsilon_{HX}=40\%$, NO_x emissions are reduced relative to the baseline for mission ranges <450 km. The heat exchanger at this level of effectiveness provides improved thermal efficiency while maintaining a lower weight compared to the designs with higher effectiveness. From this analysis, we can conclude that the most beneficial design is the recuperated turboshaft with $\epsilon_{HX}=40\%$ and $\epsilon_{HX}=60\%$ and a battery sized at DoH for optimum efficiency.

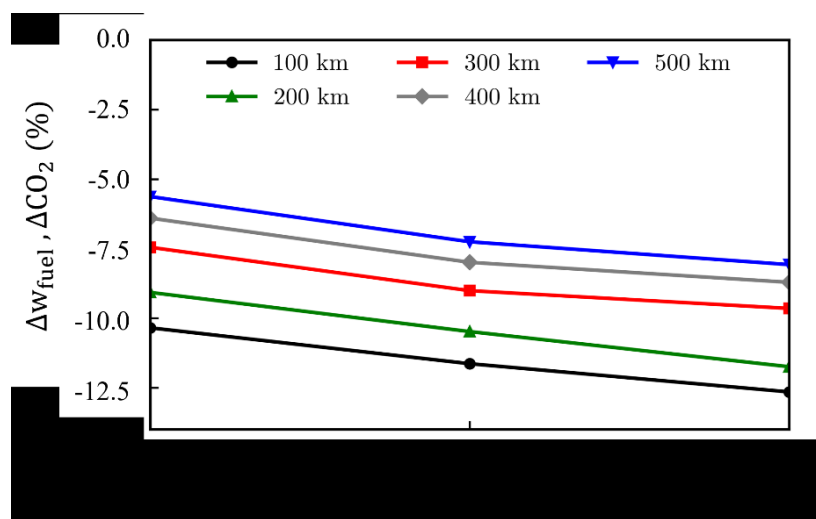


Figure 21 Effect of mission range on mission fuel burn and CO_2 relative to the conventional aircraft designed at optimum range

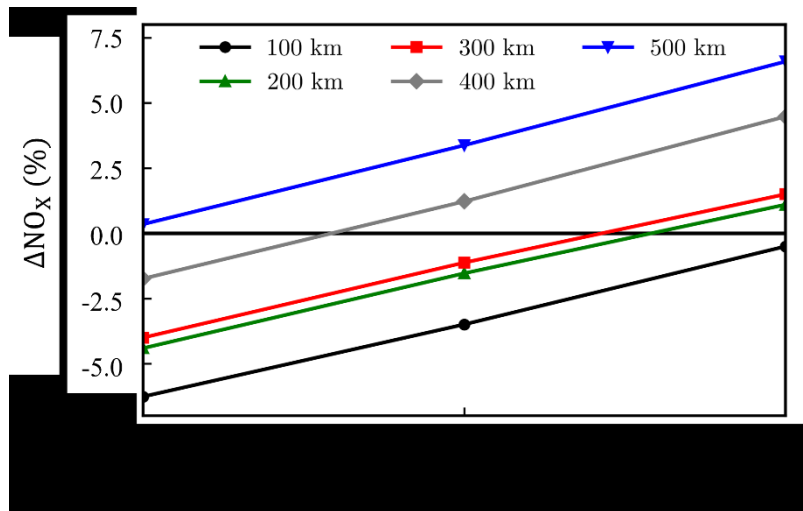


Figure 22 Effect of mission range on mission NO_x relative to the conventional aircraft designed at MCR limit

6. CONCLUSION

This work presented a comprehensive preliminary design exploration and assessment of HE architectures utilizing simple and advanced cycles for a civil tilt-rotor rotorcraft. The design space exploration was conducted using two fundamental parameters; the hybridization of energy and heat exchanger effectiveness. This analysis was done to quantify corresponding trade-offs between fuel economy, energy efficiency, engine weight, rotorcraft weight and environmental impact. A multidisciplinary approach for rotorcraft performance, HEPS performance, mission analysis has been developed and validated. A conventional tilt-rotor configuration and its HE variant equipped with a novel parallel HEPS were developed to enable this assessment.

It has been demonstrated that the hybrid-electric recuperated powerplant may result in improvements in fuel economy and environmental impact. Two different design strategies have been considered for the hybrid recuperated powerplant. Despite the additional weight of larger batteries, designing at optimum efficiency is superior to the MCR limit. Additionally, energy management plays an important role for the NO_x emitted at each mission segment. It has been shown that improvements up to 4% in energy efficiency and 6% in maximum range capability can be attained with the introduction of a heat exchanger with $\epsilon_{\text{HX}}=40\%$ and a $\text{DoH}=5.1\%$ for a fixed sizing mission under the simulated design space, constraints and operational requirements. At mission level, the aforementioned configuration can result in reductions of the order of 12.9% in fuel burn/ CO_2 emissions and 5.2% in NO_x emissions.

The recuperated designs are based on an existing simple cycle engine targeting to investigate the enhancement of overall performance of already existing engine designs targeting reduced development cost. Additionally, advancements in battery specific energy will enable the potential to increase hybridization without further increasing battery weight and improve performance by utilizing a larger fraction of the installed battery energy. At the same time, it will allow the engine to operate at more favourable conditions targeting reduced NO_x emissions. This work has provided new insight into the design, performance and operability characteristics of a hybrid-electric recuperated gas turbine based powerplant for rotorcraft applications.

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Design exploration and performance assessment of advanced recuperated hybrid-electric UAM rotorcraft

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