



ASME Accepted Manuscript Repository

Institutional Repository Cover Sheet

Cranfield Collection of E-Research - CERES

ASME Paper

Title: On the effects of optimal implementation of variable rotor speed and power management on
hybrid-electric rotorcraft

Authors: Chana Anna Saias, Ioannis Goulos, Vassilios Pachidis, Marko Bacic

ASME Journal

Title: Journal of Engineering for Gas Turbines and Power

Volume/Issue: Volume 145, Issue 3, March 2023

Date of Publication (VOR* Online): 23 February 2023

ASME Digital Collection <https://asmedigitalcollection.asme.org/gasturbinespower/article/doi/10.1115/1.4056855/1156694/On-the-Effects-of-Optimal-Implementation-of>

DOI: <https://doi.org/10.1115/1.4056855>

*VOR (version of record)

On the effects of optimal implementation of variable rotor speed and power management on hybrid-electric rotorcraft

Chana Anna Saias^{a,*}, Ioannis Goulos^a, Vassilios Pachidis^a, Marko Bacic^b

^aPropulsion Engineering Centre, School of Aerospace Transport and Manufacturing, Cranfield University,
Bedfordshire, MK43 0AL, UK

^bRolls-Royce plc, P.O Box 31, Derby, United Kingdom, DE24 8BJ, UK

Abstract

The concept of Variable Rotor Speed (VRS) has been recognized as an efficient means to improve rotorcraft operational performance and environmental impact, with electrification being a potential technology to further contribute to that. This paper explores the impact of optimal implementation and scheduling of VRS and power management strategy for conventional and hybrid-electric rotorcraft on energy, fuel, and emissions footprint. A multidisciplinary simulation framework for rotorcraft performance combined with models for engine performance and gaseous emissions estimation is deployed. A holistic optimization approach is developed for the derivation of globally optimal schedules for combined rotor speed and power split targeting minimum energy consumption. Application of the derived optimal schedules at mission level resulted to a 6% improvement in range capability for the VRS tilt-rotor relative to its conventional counterpart. For the hybrid-electric tilt-rotor, combined optimization of VRS and power management leads to an increase in range to 18.4% at 40% and 25% reduced payload for current (250 Wh/kg) and future (450 Wh/kg) battery technology, respectively. For representative Urban Air Mobility (UAM) scenarios, it is demonstrated that the VRS concept resulted in up to 10% and 14% reductions in fuel burn and NO_x relative to the nominal rotor speed case, respectively. The utilization of the combined optimum VRS and power split schedules can boost performance with reductions of the order of 20% and 25% in mission fuel/CO₂ and NO_x at a reduced payload relative to the conventional tilt-rotor.

Keywords: Urban air mobility, tilt-rotor, hybrid-electric propulsion, variable rotor speed, optimization, surrogate modeling, energy-management

*Corresponding author

Email address: chana-anna.saias@cranfield.ac.uk (Chana Anna Saias)

Nomenclature

Acronyms/Abbreviations

	UAM	Urban Air Mobility
	VTOL	Vertical Take-Off and Landing
5	VRS	Variable Rotor Speed
	OEI	One Engine Inoperative
	FPT	Free-Power Turbine
	FADEC	Full Authority Digital Engine Control System
	ABT	Active Blade Twist
10	DSE	Design Space Exploration
	DP	Design Point
	HE	Hybrid-Electric
	AUM	All-Up-Mass
	SFC	Specific Fuel Consumption
15	TOW	Take-Off Weight
	RSM	Response Surface Model
	LOOCV	Leave-One-Out-Cross-Validation
	NRMSE	Normalized Root Mean Square Error
	MTOW	Maximum Take-Off Weight
20	SLS	Sea Level Static
	SOC	State of Charge
	MCR	Maximum Continuous Rating

Roman Symbols

$N_{Pearson}$	Pearson's correlation coefficient
---------------	-----------------------------------

25	Ω	Rotor speed (rad/s)
	$\bar{\Omega}$	Rotor speed ratio, $= 100 \times \frac{\Omega}{\Omega_{nom}}$ (%)
	P_{GT}	Power provided by the gas turbine (kW)
	P_{Total}	Rotor power requirement (kW)
	PS	Power split, $= 100 \times \frac{P_{GT}}{P_{Total}}$ (%)
30	h	Density altitude (m)
	W	Rotorcraft gross weight (kg)
	V	True airspeed (m/s)
	$\dot{E}_{Total}$	Total energy rate (kWh/s)
	ϕ_{tilt}	Nacelle tilt angle (deg)
35	$\Delta \dot{w}_{fuel}$	Engine fuel flow delta, $= 100 \times \frac{\dot{w}_{fuel_{opt}} - \dot{w}_{fuel_{nom}}}{\dot{w}_{fuel_{nom}}}$ (%)
	ΔSFC	Engine SFC delta relative to the nominal case, $= 100 \times \frac{SFC - SFC_{FPT=100\%}}{SFC_{FPT=100\%}}$ (%)
	$\Delta \dot{E}$	Total energy rate delta, $= 100 \times \frac{\dot{E}_{opt} - \dot{E}_{nom}}{\dot{E}_{nom}}$ (%)
	$\dot{w}_{fuel}$	Gas turbine fuel flow (kg/s)
	CO_2^{Rate}	CO_2 production rates per engine (kg/s)
40	NO_X^{Rate}	NO_X production rates per engine (kg/s)
	E_{Bat}	Battery installed energy (kWh)

Subscripts

	$()_{nom}$	Referring to the nominal rotor configuration (-)
45	$()_{opt}$	Referring to the optimal rotor configuration (-)

1. Introduction

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], have spurred the exploration of alternative configurations and propulsion systems targeting

50 sustainable solutions. UAM is a new market within the aviation industry expected to boom in the near future with a forecasted growth from \$5.3 billion in 2018 to \$9.1 billion in 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
55 in an intra-urban environment for short and frequent flights [4].

Electric propulsion is being considered for UAM VTOL due to improved flexibility of power distribution, redundancy in case of engine failure, potentially lower noise and gaseous emissions, perceived potential for lower maintenance costs and capability to reduce the need for engine over-
60 sizing [5]. However, these benefits come at a cost of increased system weight, complexity and waste heat [5, 6, 7]. According to Danis [6], a parallel hybrid-electric system for a civil tilt-rotor can provide up to 10% reductions in cruise fuel burn with a penalty of 25% increase in empty weight. The waste heat of the hybrid system was almost three times higher than the baseline [6]. Saia et al. [7] showed that for current battery technology, a parallel hybrid-electric tilt-rotor may provide up to 8% increase in maximum range relative to the conventional tilt-rotor with a penalty of 22%
65 in payload capacity. This improvement is attained through the utilization of an optimal power management strategy at mission level. Hybrid-electric systems offer great flexibility at off-design operation due to the increased number of design and control variables. These mainly relate to technology parameters and hybridization factors for the various electrical components at the design phase and control parameters for power management that must be optimized at off-design.
70 It has been recognized that optimal power and energy management at off-design can provide fuel benefits over empirical or semi-empirical strategies [7, 8, 9].

Modern helicopters operate at a constant rotor speed throughout the whole operational envelope, usually set for the maximum cruise speed at a critical altitude so that the flow at the tip region of the advancing blades does not exceed supersonic velocities [10]. Similarly, tilt-rotors are
75 designed at two rotational speeds typically high for hover and lower for transition/cruise conditions [11] and the rotors are trimmed with the pitch angle. This results in excessive rotational speeds during cruise where the rotors are tilted forward acting as propellers, which subsequently limits their performance.

The concept of VRS has been explored in the literature as a promising technology to improve

80 rotorcraft performance [10, 12, 13, 14]. Previous studies have shown that significant reductions in rotor power can be attained by appropriately varying the rotational speed depending on the flight conditions [10, 13]. Steiner et al. [13] have shown that varying the rotor speed can lead up to 17% power reduction for true airspeeds of 25-60 m/s for a UH-60 helicopter. For the same helicopter, Chi et. al [15] demonstrated that the VRS technology can improve landing performance 85 in One Engine Inoperative (OEI) conditions. Karem [11] investigated the performance benefits of a VRS tilt-rotor, showing up to 52% and 60% power reductions for hovering and cruising at low-to-moderate weights and altitudes. Modern rotorcraft are powered by simple-cycle turboshaft engines, employing a fixed gearing ratio between the Free-Power Turbine (FPT) and the main rotor [10]. The engine's Full Authority Digital Engine Control System (FADEC) is used to transiently adjust 90 the fuel injected to maintain fixed FPT speed and hence, rotor speed. Thus, the aerodynamic benefits of the VRS must be considered alongside the turboshaft engine implications associated with altering the FPT speed. This is due to the fact that the rotor aerodynamic optimum may be different from the engine thermodynamic optimum if minimum fuel burn is to be attained.

Miste et al. [10, 12] explored the impact of VRS on the integrated main rotor - engine perfor- 95 mance of a UH-60A helicopter equipped with two GE T700 turboshaft engines. Fuel flow reductions of 7-8% were attained at low-to-moderate weights and altitudes and in the vicinity of maximum endurance flight speed. The observed fuel decrease was obtained by varying the rotor speed within a $\pm 15\%$ range of nominal speed. Goulos et al. [16] investigated the concept of VRS in conjunction with Active Blade Twist (ABT) for a Bo 105 helicopter through a multidisciplinary assessment. 100 An optimization approach was deployed for the derivation of optimal schedules for rotor speed and blade twist towards minimum fuel flow. The analysis was extended to mission level, where mission fuel savings and NO_x emission reductions up to 5% and 8% were calculated for the VRS, respectively. It was concluded that the All-Up-Mass (AUM) and mission profile highly affect the potential benefits of the investigated technologies. Polyzos et al. [17] explored the impact of VRS 105 with ABT on ground noise and NO_x emitted for a twin-engine light helicopter in descending flight. Optimum schedules were derived through a multi-disciplinary genetic optimization approach that led to simultaneous reductions of NO_x up to 21% and source noise up to 8 dB. Scullion et al. [18] investigated the utilization of a VRS configuration for control redundancy on a coaxial compound rotorcraft with mission level reductions of 6.9% and 8.7% in fuel burn/ CO_2 and NO_x , respectively.

110 The concept of VRS for rotorcraft has been covered extensively in the literature from an aerodynamic [10, 13], coupled aircraft-engine [11, 12, 14], and mission level standpoint [16, 18]. However, no previous work has investigated the potential benefits of VRS concept for conventional and hybrid-electric tilt-rotor, also combined with power management optimization. Additionally, the implications of the aforementioned concepts on payload-range capacity have not been addressed
115 in the literature. Thus, the scope of this paper is to explore the environmental and performance impact of combined optimum VRS and power management schedules for hybrid-electric rotorcraft. An integrated simulation framework is deployed comprising models for tilt-rotor performance [7, 19], mission analysis, gas turbine [20] and battery-motor [21] performance and pollutant emissions prediction [22]. An efficient Design Space Exploration (DSE) and global optimization strategy is
120 employed for the evaluation of optimal controls at aircraft and mission level as reported in [16]. This consists of models for design of experiment, surrogate modeling and genetic optimization. The examined civil rotorcraft is modeled after the XV-15 tilt-rotor equipped with two turboshaft engines and later modified with a parallel hybrid-electric powerplant system.

2. Mathematical Approach

125 A multidisciplinary approach is deployed comprising a series of comprehensive modules applicable to the different aspects of rotorcraft and powerplant performance. These contain a rotorcraft performance model [7, 19] coupled with models for hybrid-electric propulsion system off-design performance analysis [20, 21], gaseous emissions estimation [22], weight estimation models [23] and an energy management module to enable analyses of hybrid-electric architectures. The different
130 simulation modules are integrated within a mission analysis model as reported by Goulos et. al [24], adapted for dual-energy systems [7]. Each model has been developed and validated independently using experimental or flight test data [7, 19]. A detailed description of the framework has been provided by Saias et al. in Refs. [7, 19]. The integration of the models resulting in the complete platform is illustrated in Figure 1.

135 2.1. Tilt-rotor performance model

The integrated modeling approach intends to incorporate the features of the first level of Padfield's hierarchical paradigm, appropriate for performance studies [25]. The rotorcraft performance module comprises models for the different aircraft components; rotor, fuselage, empennage and

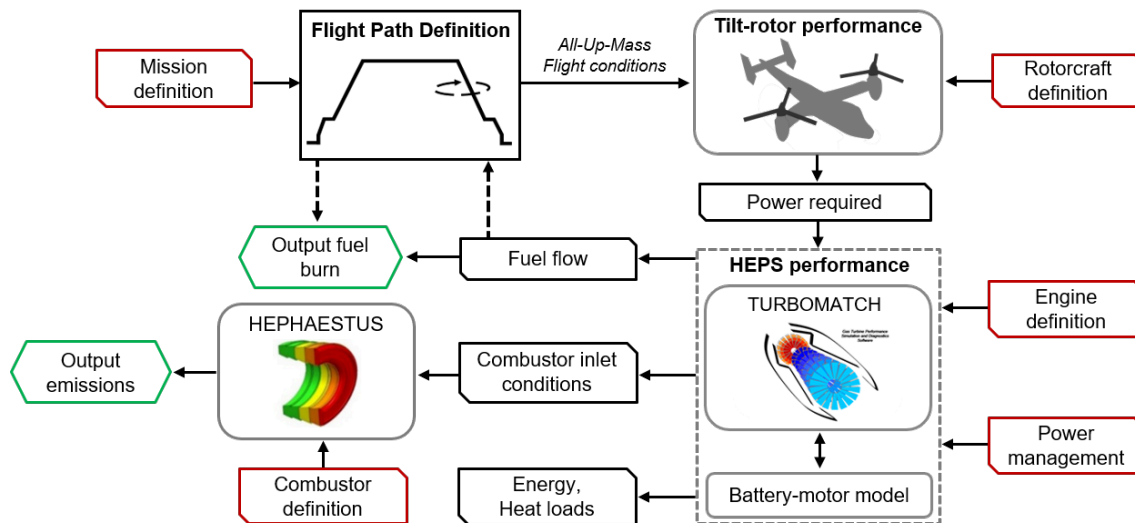


Figure 1: Tilt-rotor performance framework [7, 19]

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 edge-wise flow component [7]. The blades are assumed to be rigid bodies, with no flap deflection [26]. Look-up tables describing the steady-state aerodynamic characteristics for the two-dimensional airfoil sections are deployed.

The rotor aerodynamics model is coupled with an inflow model developed for hovering flight developed by Bhagwat [27]. For axial flight conditions corresponding to propellers in forward flight, Bhagwat’s inflow model [27] is modified to account for the free-stream inflow effect in the governing momentum equations as reported in [7]. The method caters to the inclusion of the swirl induced velocity component, which is ignored by traditional momentum theory [28]. In conversion mode, the rotor aerodynamics model is coupled with Mangler and Squire inflow model [29]. This is a potential flow-based analytical model that has found extensive application [29]. The definition of the inflow is described by Bramwell [28].

For the flight dynamics code, the tilt-rotor is a laterally symmetric vehicle that allows to decouple the roll-yaw degrees-of-freedom [30]. Experimental look-up tables expressed as functions of incidence angle are utilized for the prediction of the fuselage, wing-pylon and component interaction forces and moments of the XV-15 [31, 32, 33].

The wing is modeled separately for the portion of it in the freestream and slipstream. The area

of the wing in the rotor wake depends on the wake contraction ratio and is computed based on the nacelle angle and freestream velocity, and rotor thrust coefficient [34, 35]. A Newton-Raphson is employed to obtain the control angles for any specified operating condition. The process converges to a set of control inputs to reach equilibrium trim state. The validation of the tilt-rotor model with experimental and flight test data is presented in [7]. Good agreement of the model with flight data is reported with a NRMSE of 3.8% and 5.1% for vertical and horizontal flight, respectively.

2.2. Hybrid-electric propulsion system performance model

An integrated performance model for parallel hybrid-electric systems is developed and coupled with the rotorcraft model. This is done by combining the engine performance model (TURBOMATCH) with models for electric powertrain performance. TURBOMATCH, developed at Cranfield University [20], is a well-validated software that has been successfully deployed in several studies for turboshaft engines for rotorcraft applications [24, 36]. It utilizes zero-dimensional aerothermal analysis, employing discrete component maps. A battery simulation model for Lithium-Ion type (Li-Ion) batteries is developed based on the methodology presented in [21] and coupled with TURBOMATCH. Fixed efficiency models are assumed for the rest of the electrical components using an electric power chain approach. A flexible energy management approach is incorporated within the hybrid-electric propulsion module to allow the control of the power distribution between the two sources.

2.3. Prediction of gaseous emissions (HEPHAESTUS)

HEPHAESTUS is a combustor emissions estimation model developed by Celis [22] at Cranfield University. HEPHAESTUS is based on the stirred reactor concept and accounts for different combustor geometries in terms of primary, intermediate and dilution zone in addition to the air mass flow distribution for a given combustor design. It was originally developed for civil-aero engines and was later extended to turboshaft [37]. HEPHAESTUS has been deployed in studies for turboshaft engines and has proven to be a reliable tool for rotorcraft analysis [37, 38].

2.4. Propulsion system weight estimation

To assess hybrid-electric configurations, it is essential to include weight models for the engine and the different electric components. For a retrofitting rotorcraft, the turboshaft engines can be

185 scaled down with the introduction of a second power source. The effect of scaling on the weight of the new turboshaft is captured with ATLAS [23], a Cranfield in-house tool for component-based gas path weight estimation. The weights for the electrical components depend on technology factors. The battery weight is estimated based on the requirements for energy and power using representative values for energy and power densities. The motors and generators are sized based
 190 on the method reported in [39]. In the absence of real system data, an additional mass factor of 10% of the propulsion system is added to account for the weight of cables and mounting [5].

2.5. Integrated mission analysis

The integrated mission analysis model is based on the adoption of modular blocks corresponding to the different mission segments [24]. The rotorcraft and powerplant are assumed to operate
 195 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 (Fig. 1). The power management code is used to distribute the power of the two energy sources for hybrid-electric architectures. The engine fuel flow and battery State of Charge (SOC) are calculated subsequently, and the weight of the rotorcraft is updated based on
 200 the fuel burned at each segment. A fixed-point iteration scheme is employed to solve for mission fuel burn [24].

2.6. Design space exploration and optimization

In this work, the rotorcraft framework has been extended with an efficient optimization strategy targeting to obtain optimum rotor speed and power split schedules for any operating point in the
 205 flight envelope. This strategy is an expansion of the approach introduced by Goulos et al. [16] and later adopted in Refs. [17, 18, 40].

Figure 2 presents an overview of the method implemented in this work. The method is divided into three parts; the design of experiments, a subsequent generation of the surrogate models and global optimization. The design space comprises both operational parameters: rotorcraft AUM
 210 (W), density altitude (h), flight speed (V) and control parameters: rotor speed (Ω) and power split ($PS = P_{GT}/P_{Total}$). This enables the derivation of optimal schedules for Ω and PS for any specified operating point. The design of experiments strategically populates the five-dimensional design space via a full-factorial sampling approach to populate the sample data. The density of

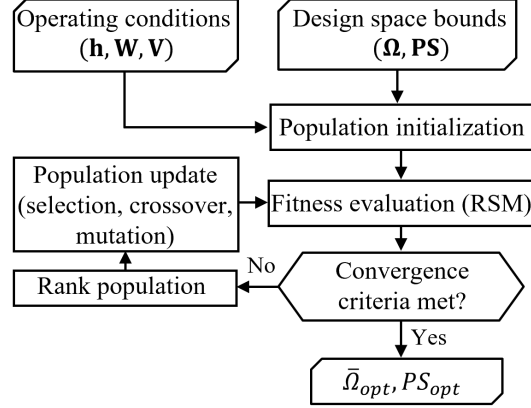


Figure 2: Optimal scheduling of rotor speed (Ω) and power split (PS) towards minimization of total energy rate ($\dot{E}_{Total}$)

points for each variable in the design space is selected based on a sensitivity analysis conducted
 215 for rotor power and fuel flow.

Having populated the design space, a trim point analysis is conducted for each sample point to compute the power requirement, fuel flow and emission rates. A Response Surface Model (RSM) is then derived using Gaussian Processes Regression (Kriging-based) interpolation [41]. This is done through a generic function $y(x)$ approximated with $\tilde{y}(x)$ in the form of $\tilde{y}(x) = \mu - z(x)$. This
 220 combines a regression model μ and a correlation model $z(x)$ [41], where an exponential function is employed [16, 17].

The purpose of utilizing RSMs instead of direct integrated rotorcraft-hybrid-electric trim runs is to mitigate the high computational overhead, which is essential for the optimization task. Once derived, the RSMs are assessed using the Leave-One-Out-Cross-Validation (LOOCV) method [42]
 225 for their predictive accuracy using appropriate statistical metrics: Pearson's correlation $N_{Pearson}$, regression line gradient as well as NRMSE and standard deviation of the model error.

The derived RSMs are combined with a global optimization algorithm to systematically explore for potential optimum schedules for Ω and PS targeting the minimization of energy rate, which is defined as the heat input rate of the fuel injected in the engine and the battery energy rate
 230 driving the motor ($\dot{E}[kWh/s] = LHV[kWh/kg] \times \dot{w}_{fuel}[kg/s] + SOC[\%/s] \times E_{Bat}[kWh]$). In presence of economic data, the optimization formulation could be replaced with the minimization of the net economic impact or a weighted function of the energy rate objective as reported in

[43]. The global optimization algorithm selected is the Non-dominated Sorting Genetic Algorithm II (NSGAI) [44] on account of avoiding solutions being trapped at local optimal points [16].

As discussed, the utilization of surrogate models allows for instantaneous derivation of combined optimal schedules for Ω and PS for any designated flight condition (h, W, V). Next, the method is adapted for assessments at payload-range and mission level to evaluate the effect of those using realistic flight profiles. This is done by utilizing the rotorcraft model combined with the derived optimal schedules for Ω and PS at each discrete way-point along the mission profile.

2.7. Tilt-rotor and powerplant model configuration

The configuration selected for this study is a civil rotorcraft representative of the XV-15 tilt-rotor. The XV-15 is equipped with two nacelle-mounted turboshaft engines [32] and has been extensively documented in [31, 32, 33]. Table 1 presents the rotorcraft main design parameters. The rotorcraft performance model for XV-15 has been validated using experimental and flight test data [7]. An engine based on the General Electric T700-GE-700 that was developed and validated by Ortiz-Carretero et al. [45] is used as baseline. The Maximum Continuous Rating (MCR) setting is set as the Design Point (DP) of the engine (Table 2).

Design parameter	Value	Units
Empty Weight	4116	kg
MTOW	6803	kg
Disk loading	13.2	lb/ft ²
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	-

Table 1: Tilt-rotor main design parameters [32, 33].

The conceptual tilt-rotor is designed to carry up to 9 passengers for eight sequential UAM flights of 93 km. A parallel hybrid propulsion architecture is selected as illustrated in Figure 3, on account of high flexibility and reduced complexity with respect to potential other Hybrid-Electric (HE) configurations [7]. The present powerplant comprises two energy sources: fossil fuel and battery, providing energy to the gas turbine and motor respectively. A DC electrical bus allows

Design parameter	Value	Units
Design mass flow	4.17	kg/s
Axial compressor PR	5.3	-
Centrifugal compressor PR	2.8	-
TET	1440	K
Fuel flow	0.0807	kg/s
Shaft power	987	kW

Table 2: Turboshaft engine design point data at SLS-ISA conditions [45].

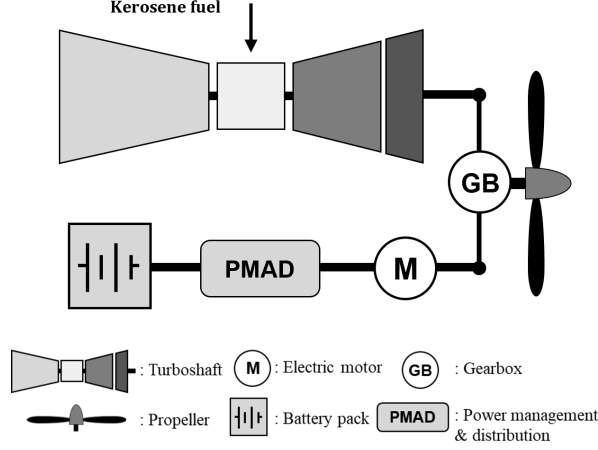


Figure 3: Conceptual hybrid-electric powerplant architecture

eliminating the mechanical cross-shafting of the baseline tilt-rotor [6]. Table 3 presents the main assumption for the electric propulsion components. The batteries are assumed to discharge to a minimum value of SOC=20% to avoid severe reduction in battery life [6]. The HE configuration is designed to comply with the baseline tilt-rotor power ratings, Maximum Take-Off Weight (MTOW) limit and OEI capability. A fixed gearing ratio is kept in this work on account of reduced weight and complexity.

Parameter	Value	Units
Battery weight per engine	280	kg
Battery specific energy	250	Wh/kg
Battery specific power	900	W/kg
Motor specific power	8	kW/kg
Motor efficiency	0.97	-

Table 3: Propulsion component current technology level assumptions [7].

3. Results and discussion

3.1. DSE, surrogate modeling and cross-validation

A DSE activity is carried out to evaluate the impact of variable rotor speed and power split on overall performance and carbon footprint of the tilt-rotor. The five-dimensional design space comprises a combination of key operating conditions (W, h, V) and control parameters ($\bar{\Omega}, PS$). The tilt-rotor operates at two modes for the majority of the flight, them being helicopter and aeroplane mode. In helicopter mode, the rotors are tilted to a vertical position ($\phi_{tilt}=90^\circ$) and in aeroplane mode, the rotors tilt to a horizontal position ($\phi_{tilt}=0^\circ$) acting as propellers producing forward thrust and lift is generated by the wings. For this reason, the DSE was separated in two parts to account for both operating modes. Transition flight mode only consumes small part of the mission and hence, is disregarded. The prescribed design space was discretized using 4200 and 5880 points for the aeroplane (1) and helicopter mode (2) DSE, respectively. The selected bounds are presented in Table 4. It is highlighted that in-flight re-charging ($PS>100\%$) is not considered in this paper due to the relatively short missions considered for this application and low charging times for Li-Ion batteries.

Parameter	Symbol	Units	DSE bounds	
			1	2
Gross weight	W	kg	4500-6800 (3)	4500-6800 (3)
Flight speed	V	m/s	0-40 (5)	60-120 (7)
Altitude	h	m	0-3048 (5)	0-3048 (5)
Rotor speed ratio	$\bar{\Omega}$	%	75-115 (7)	75-115 (7)
Power split	PS	%	30-100 (8)	30-100 (8)

Table 4: Design space definition and bounds. Sampling density levels annotated in parentheses and bold font.

With the samples generated, a trim point analysis is carried out at each point using the developed framework. The resulting data are used to generate Kriging-based RSMs of shaft power requirement (P_{Total}), fuel flow ($\dot{w}_{fuel}$), SFC and gaseous emissions rates (CO_2^{Rate} , NO_X^{Rate}). Having structured the surrogate models, a LOOCV [42] approach was utilized to assess their predictive accuracy. This method is based on creating a unique RSM based on the design of experiments population excluding a single sample point. The sample point that is excluded is then compared against predictions made with the RSM and the process is repeated for every sample point. The results of the LOOCV for the engine fuel flow $\dot{w}_{fuel}$ are computed and illustrated in Figure 4. The NRMSE of the RSM fuel predictions with the direct trim simulations are of the order of 1.24% and

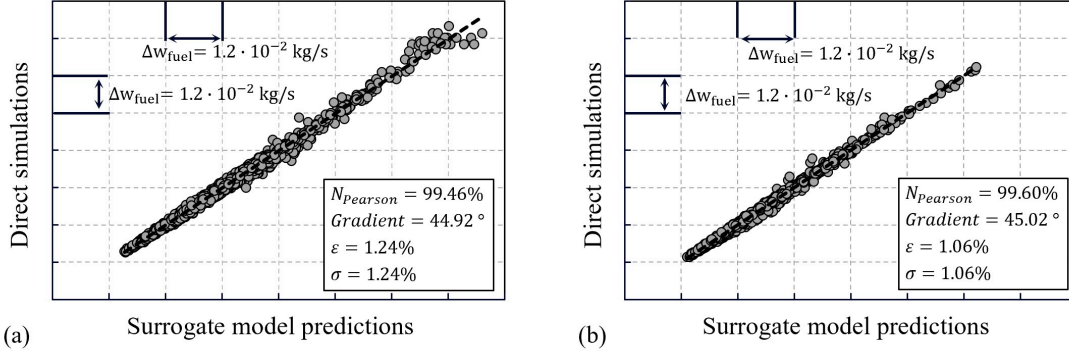


Figure 4: Leave-one-out-cross-validation for the engine fuel flow RSM models: a) DSE 1, b) DSE 2

1.06% for the DSE 1 and 2. For DSE 1, the associated values of $N_{Pearson}$ and line gradient are 99.46% and 44.92° , respectively. For DSE 2, the same values are calculated as 99.6% and 45.02° . Similar values are computed for CO_2^{Rate} and NO_X^{Rate} indicating a good predictive accuracy of the RSMs.

3.2. Optimized rotor speed and power split

Having developed surrogate models that accurately predict the impact of variable rotor speed (Ω) combined with power split (PS) on the overall performance of the tilt-rotor, it is possible to derive optimum schedules for any specified operating point. A global optimization algorithm (NSGA II [44]) is used targeting the minimization of the total energy rate ($\dot{E}_{Total}$) for any operating conditions using the derived surrogate models as drivers. A population size of 40 individuals per generation and 40 generations were selected as they were sufficient to converge to the optimum Ω and PS within a 10^{-10} per generation.

The optimum schedules for Ω and PS are computed at prescribed operating conditions (W , h , V) which encompass the flight envelope of the tilt-rotor. The resulting engine fuel flow and energy rate are calculated and deltas relative to the baseline architecture are subsequently obtained. Figures 5, 7, 9 illustrate the derived optimum schedules of rotor speed and power split as functions of density altitude and flight speed for three weights $W=4500$ kg, 5650 kg, and 6800 kg. To understand the impact of each control and the combined effect of those on overall performance, three separate optimizations are carried out: a) variable Ω and fixed $PS = PS_{nom}$, b) fixed $\Omega=\Omega_{nom}$ and variable PS and c) variable Ω and PS . The optimum prop-rotor speed (Ω_{opt}) is

expressed as a percentage difference relative to the nominal values of rotor speed and the power split ($PS=P_{GT}/P_{Total}$) defines the amount of power provided by the gas turbine and battery.

305 The associated energy benefits are shown as percentage differences relative to the nominal gas-turbine-based configuration ($\Delta\dot{E}_{opt} (\%) = 100 \times \frac{\dot{E}_{opt}-\dot{E}_{nom}}{\dot{E}_{nom}}$). For the case of the kerosene-fueled configuration, the energy delta is equal to the fuel delta ($\Delta\dot{E}=\Delta\dot{w}_{fuel}$).

Figure 5 demonstrates the optimum rotor speed variation $\overline{\Omega_{opt}}$ (Fig. 5(a)) and the resultant fuel/energy rate deltas relative to the baseline (Fig. 5(b)). From this figure, it can be observed
 310 that a reduction in rotational speed is more beneficial at low rotorcraft weights and hence, low blade loadings. For low operating weights ($W=4500$ kg), the optimal values for rotor speed range between $75\% \leq \overline{\Omega_{opt}} \leq 85\%$ throughout most of the flight envelope. At the same time, the associated fuel burn benefits at this weight are significantly greater than highly loaded conditions, with a maximum fuel reduction of -21% noted for $V=10-20$ m/s and $h<1400$ m at $\overline{\Omega_{opt}} = 75\%$.
 315 As the rotorcraft weight increases, the optimal rotor speed shifts to higher values ($\overline{\Omega_{opt}} > 75\%$) and the associated fuel flow benefits are shown to reduce. Specifically, the energy benefit at hover at Sea Level Static (SLS) conditions is $\Delta\dot{w}_{fuelopt} = -4\%, -0.9\%, -0.1\%$ at $\overline{\Omega_{opt}} = 84\%, 97\%, 101\%$ for $W=4500$ kg, 5650 kg, 6800 kg. This is due to the fact that the optimal rotor speed for higher gross weights and hence, higher loadings, is found to be very close to the design point resulting in
 320 negligible improvements at this regime ($W=6800$ kg) (Fig. 5(b)). For cruise conditions at speeds of $100 \text{ m/s} \leq V \leq 115 \text{ m/s}$ and altitudes of $1000 \text{ m} \leq h \leq 2000 \text{ m}$, the fuel burn benefits reach a maximum of $\Delta\dot{w}_{fuelopt}=11.3\%, 10.2\%, 2.4\%$ at $\overline{\Omega_{opt}}=75\%, 76\%, 84\%$ for $W=4500$ kg, 5650 kg, 6800 kg. For these operating regions, the optimum rotational speed $\overline{\Omega_{opt}}$ is less sensitive to changes in airspeed and altitude. It is concluded that the benefits of VRS become more pronounced far
 325 from the design point.

The impact of the variation of main rotor speed on fuel flow observed in Figure 5 is primarily affected by the prop-rotor and turboshaft engine coupling. It is therefore realized that the potential fuel savings are governed by two fundamental aspects: (a) the effect of rotor speed on the rotor aerodynamics and (b) the effect of FPT speed on engine thermodynamics. With respect to rotor
 330 aerodynamics, reducing the rotor speed at specific flight regimes may allow to produce the required thrust at a reduced power level. This is explained by the fact that by reducing the rotor speed, the local dynamic head encountered by the blades reduces, leading to an overall blade profile drag

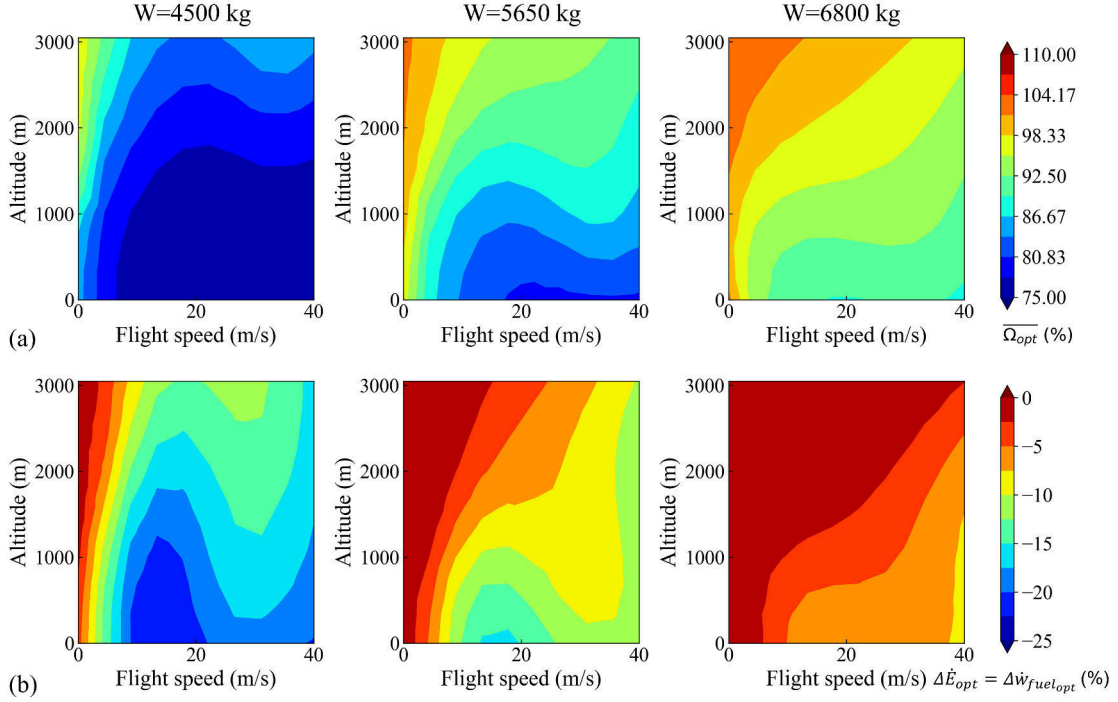


Figure 5: Optimized control schedule for variable Ω and $PS = PS_{nom}$ at $\phi_{tilt}=90^\circ$ as function of gross weight W , altitude h and rotorcraft speed V : (a) optimum rotor speed variation Ω_{opt} (%) and (b) resultant energy rate relative to nominal configuration $\Delta \dot{E}_{opt}$ (%)

power reduction. At the same time, this reduction will also reduce the lift capabilities of the blade and hence, a simultaneous increase in blade collective pitch is essential to maintain the required thrust levels. For highly loaded rotors, an excessive rise in collective pitch may have a detrimental effect on rotor performance. This is due to the fact that very high collective pitch angles lead to higher local incidence angles and hence, increased aerodynamic loading. At these conditions, the blade stall margin is low and hence, excessive values of blade loading may result in blade stall. Thus, from an aerodynamic perspective, the optimal rotor speed is determined by the trade-off of local dynamic head reduction and blade loading increase [16].

Concerning the engine performance, state-of-the-art rotorcraft typically employ a fixed gearing ratio between the main rotor and FPT. Thus, the variation in FPT speed is directly dependent on the prop-rotor rotational speed. FPTs nominally operate at narrow speed ranges and high variation in FPT speed may have a positive or adverse effect on turboshaft engine efficiency [12]. At part power operation, studies have demonstrated that reductions in FPT speed may lead to

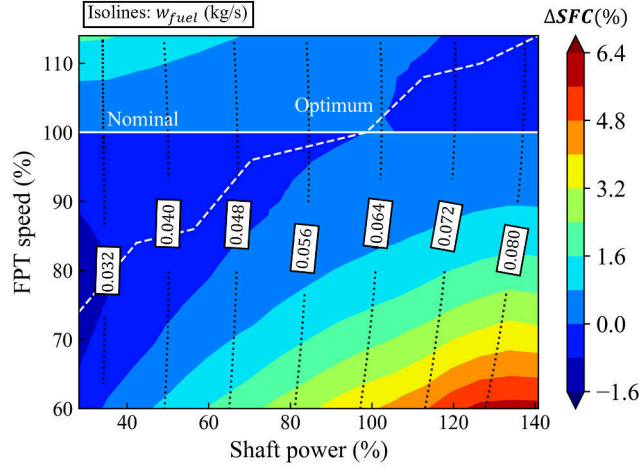


Figure 6: Design space behavior: Impact of FPT speed with normalized shaft power on ΔSFC and fuel flow at SLS conditions.

improvements in engine SFC [12]. This is explained by the fact that at each gas generator speed, there is a unique optimum FPT speed [16, 46]. Figure 6 presents the simulation results of the T700-GE-700 engine at SLS conditions highlighting the impact of normalized FPT speed on ΔSFC_{opt} (%) ($= 100 \times \frac{SFC - SFC_{FPT=100\%}}{SFC_{FPT=100\%}}$) and fuel flow ($\dot{w}_{fuel}$) for various power settings. It is observed that at a normalized shaft power of 100% which corresponds to the MCR, the thermodynamic optimal line intersects the nominal FPT=100%. Furthermore, it can be noted that as the engine power setting reduces, the optimal FPT speed shifts to lower values than the nominal. Thus, at power requirements below the MCR, reducing rotor speed and hence, the FPT speed given a fixed gearing ratio, will allow for reduction in SFC and hence, fuel flow. At higher power settings, the optimal FPT speed increases to a maximum of $FPT_{opt} = 115\%$.

It is highlighted that for specific flight conditions, it might be impossible to optimize both subsystems (rotor and engine) as the theoretical aerodynamic optimum for Ω may diverge from the thermodynamic optimum for FPT speed. Therefore, due to the inter-dependency of the rotor and FPT speed, the rotational speed that minimizes fuel burn is the best compromise between the engine and rotor performance.

A HE system will introduce extra degrees of freedom due to the power management strategy flexibility. Figure 7 demonstrates the optimum control schedules for power split PS_{opt} with fixed rotor speed ($\Omega = \Omega_{nom}$) (Fig. 7(a)) and the associated energy rate deltas $\Delta \dot{E}_{opt}$ (Fig. 7(b)). The results are presented as a function of the operating conditions (W, h, V) of the rotorcraft

through the whole operational envelope. Significantly reduced values of PS_{opt} are observed for low gross weight $W=4500$ kg with $PS_{opt}=30\%$ being the optimal power ratio throughout most of this operating region. The resultant fuel savings at $W=4500$ kg range from 40-48%. However, due to the increased contribution of the battery on the system, these translate in energy savings of the order of 30-39%. It is highlighted that the maximum energy benefits at this weight are attained at near endurance flight conditions and altitudes $h > 600$ m.

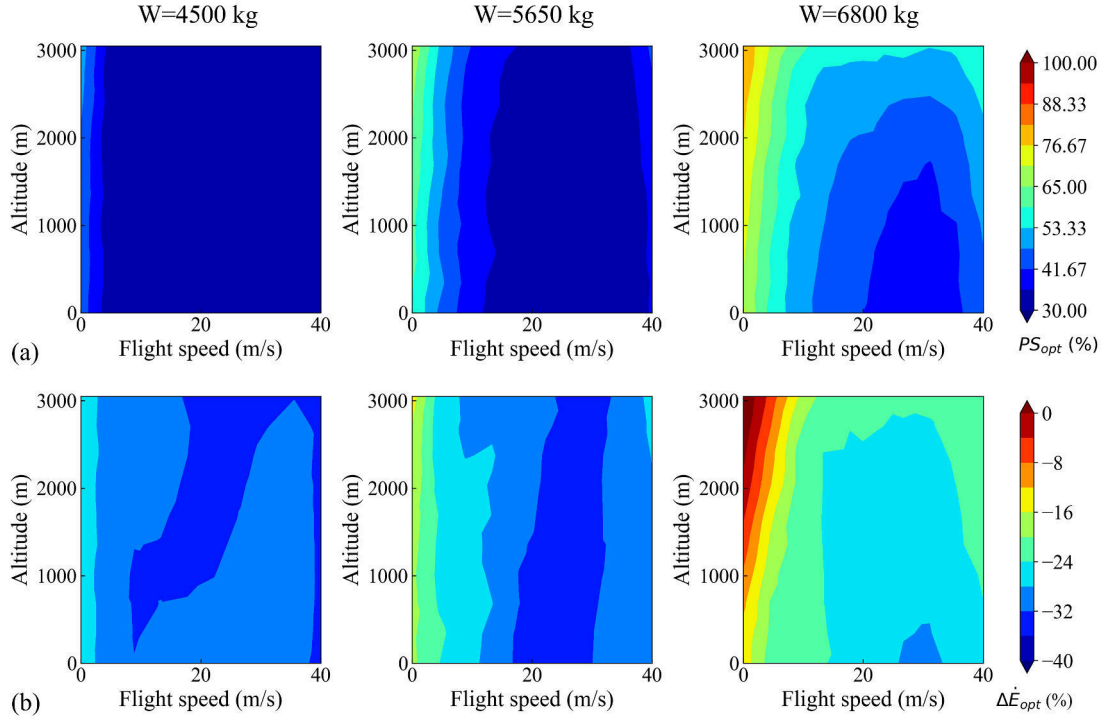


Figure 7: Optimized control schedule for variable PS and $\Omega = \Omega_{nom}$ at $\phi_{tilt}=90^\circ$ as function of gross weight W , altitude h and rotorcraft speed V : (a) optimum power split PS_{opt} (%) and (b) resultant energy rate relative to nominal configuration $\Delta \dot{E}_{opt}$ (%)

As the weight of the rotorcraft increases, the optimal PS increases and the benefit reduces. Specifically, the energy benefit at hover at SLS conditions is $\Delta \dot{E}_{opt} = -24\%$, -19% , -14% at $PS_{opt} = 30\%$, 59% , 71% for $W=4500$ kg, 5650 kg, 6800 kg respectively. At the same condition, the resultant changes in fuel of $\Delta \dot{w}_{fuelopt} = -39\%$, -30% , -22% . This is because at higher gross weights, the engine power requirement increases and exceeds the maximum power that the electric system can supply resulting in greater optimal power split values ($PS_{opt} > 40\%$) at this regime ($W=6800$ kg) (Fig. 7(a)). At this weight, the maximum computed change in $\Delta \dot{E}_{opt}$ is of the order of -28% and is

observed at low-density altitudes ($h < 1016$ m) and flight speeds between 20-35 m/s. It is therefore realized that the magnitudes observed in Fig. 7(b) for low-to-moderate weights are dominated by the battery efficiency rather than the gas turbine SFC penalty presented in Fig. 6. Overall, the energy benefits attained by varying the PS appear to be consistently higher than the variation of rotor speed shown in Fig. 5(b). It is noted however that, the mission fuel benefits will be highly influenced by the battery energy, SOC at take-off, take-off weight, mission profile and range.

For a hybrid-electric rotorcraft featuring a VRS rotor, three fundamental aspects govern the behavior observed: (a) rotor aerodynamic performance, (b) turboshaft thermodynamic performance and (c) battery-motor performance. As regards to the first two, their inter-dependency has been covered earlier in this section. Isolating the turboshaft under variable power split (PS) conditions while maintaining fixed rotor speed provides insight into the dependence of the last two. Figure 8 presents the simulation results of a hybrid-electric system coupled with the the T700-GE-700 turboshaft in a parallel arrangement. It highlights the impact of PS and normalized shaft power on ΔSFC and fuel flow. At low power settings, a low power split may provide significant reductions in fuel burn and hence, this could further improve overall performance if combined with reduced rotor speed. It is however noted that at low PS values, the engine operates far from the design point, which deteriorates its performance leading to higher SFC. Furthermore, as shaft power increases, the battery becomes insufficient to supply the required power for most of the operating points and the power split is shifted to higher values $PS > 60\%$ for power settings higher than MCR. It is concluded that the optimum operating point for the hybrid system is the best compromise between engine thermal efficiency and battery efficiency.

Having investigated the impact of optimized schedules for rotor speed and power split on energy and fuel separately, it is essential to expand the analysis towards the combined optimization of the two systems. Figure 9 presents the combined optimization schedules for variable Ω (Fig. 9(a)) and PS (Fig. 9(b)) as function of the gross weight W , density altitude h and flight speed V . The presented optimized schedules present the effect in fuel and energy that is reflected by both the introduction of the hybrid-electric technology and simultaneous optimization of its power management strategy combined with VRS.

It is observed that the optimal scheduling patterns are similar with the ones computed for the individual cases. Additionally, the combined optimized controls allow to for greater improvements

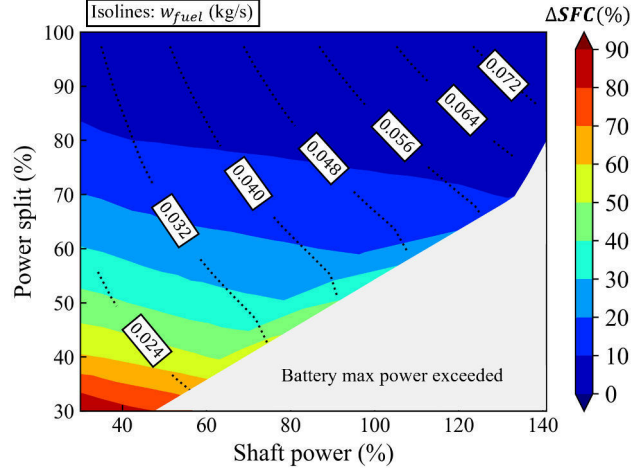


Figure 8: Design space behavior: Impact of power split on ΔSFC and fuel flow at SLS conditions. The grey area has been removed based on the maximum battery power exceeded.

in performance with the greatest fuel reduction being of the order of 50% observed at $V=10\text{-}25$ m/s at low altitudes $h < 2100$ m and $W=4500$ kg, whereas at the same operating condition the
410 greatest energy reduction is of the order of 35%. For the heaviest take-off case ($W=6800$ kg), a rotor over-speed region near hovering conditions at low altitudes ($h < 1500$ m) is noted. This is explained by the fact that at this power setting and a $PS=78\%$, the rotor moves to higher rotational speeds for the engine to operate close to the DP and hence, at high thermal efficiency. For horizontal flight, at speeds of $100 \text{ m/s} \leq V \leq 115 \text{ m/s}$ and altitudes of $1000 \text{ m} \leq h \leq 2000 \text{ m}$,
415 the fuel savings reach a maximum of $\Delta \dot{w}_{fuel opt} = -54.9\%$, -54.7% , -45.2% at $\overline{\Omega}_{opt} = 76\%$, 78% , 85% for $W=4500$ kg, 5650 kg, 6800 kg.

3.3. Payload-range capacity

The potential benefits stemming from the optimum implementation of variable rotor speed and power split are assessed at payload-range level. Figure 10 illustrates the payload-range diagram for
420 the baseline tilt-rotor (nominal RPM) and the optimum architectures. The payload-range diagram is constructed based on the sizing mission that consists of a 5-min idle period, a take-off and climb segment up to 2000 m and a subsequent descent and land segment with 20% reserves. The fuel capacity (without the reserves) is annotated in bold at each point of the payload-range diagram.

It can be observed that the VRS tilt-rotor results in 6.2% increase in maximum range relative to
425 the baseline rotorcraft at a maximum payload capacity. On the other hand, for the HE tilt-rotor,

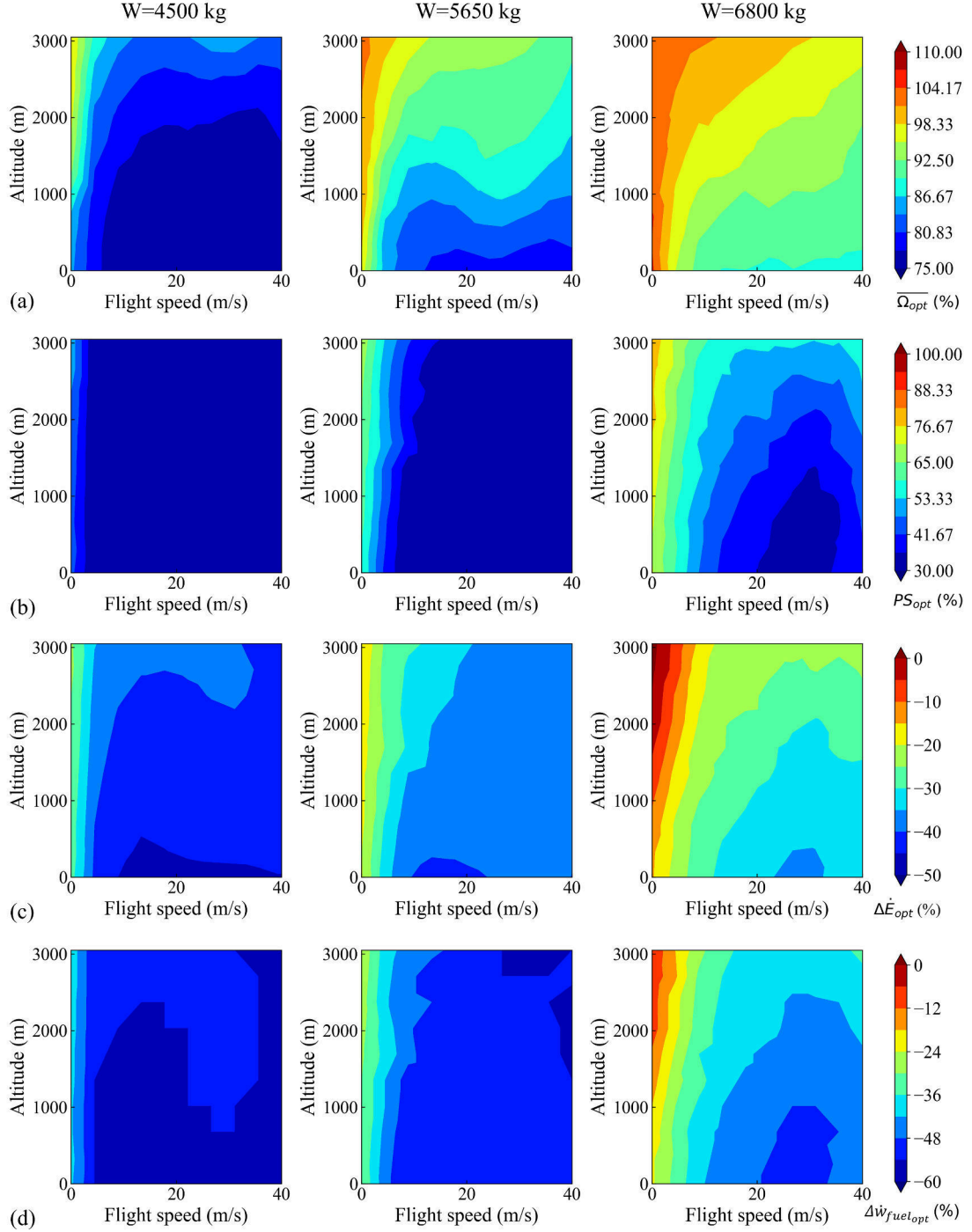


Figure 9: Optimized control schedule for variable Ω and PS at $\phi_{tilt}=90^\circ$ as function of gross weight W , altitude h and rotorcraft speed V : (a) optimum rotor speed variation $\overline{\Omega}_{opt}$ (%), (b) optimum power split PS_{opt} (%), (c) resultant energy rate relative to the nominal configuration $\Delta \dot{E}_{opt}$ (%) and (d) resultant fuel flow relative to nominal configuration $\Delta \dot{w}_{fuel_{opt}}$ (%)

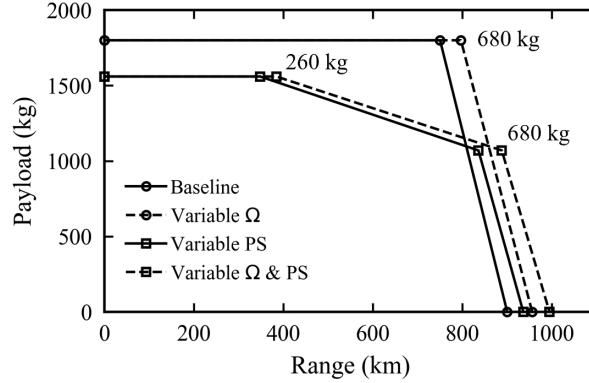


Figure 10: Impact of optimum Ω and PS scheduling on payload-range. Fuel capacity annotated in bold font.

the additional weight of the electrical components heavily penalizes the payload-range capability of the rotorcraft if current battery energy densities (250 Wh/kg) are assumed. The system can be designed at reduced payload or reduced range. Specifically, for a design at maximum fuel capacity (680 kg), the optimum PS configuration leads to an increase of 11.4% in range at a penalty of 40% reduction in payload. The combined optimization of Ω and PS allows to increase the range capability by 18.4% at 40% payload relative to the baseline. For a reduced fuel capacity of 260 kg, the rotorcraft can fly at 49% of the original range carrying 88% payload at a 14% reduced fuel per payload-range relative to the baseline if the combined optimum strategy is implemented.

It is therefore realized that the VRS architecture can provide significant improvements in range capability while maintaining fixed payload capability. Clearly, the hybrid-electric tilt-rotor suffers from severe reductions in payload capacity with respect to the kerosene counterpart irrespective of the rotor speed strategy. It is also noted that for the hybrid-electric tilt-rotor the benefits of the combined optimization strategy for rotor speed and power split will become greater at lower ranges, where the battery energy contribution is higher.

3.4. Mission analysis and environmental impact

To evaluate the full impact of optimized Ω and PS on overall performance and environmental impact, the architectures are assessed within a mission analysis environment. Three missions are selected targeting to cover a wide range of representative UAM scenarios. Figure 12 illustrates the mission profiles for each mission considered. In mission 1, Fig. 12(a), the rotorcraft takes off with AUM=5500 kg and flies for 300 km at a cruise altitude of 2000 m and at 110 m/s cruise speed.

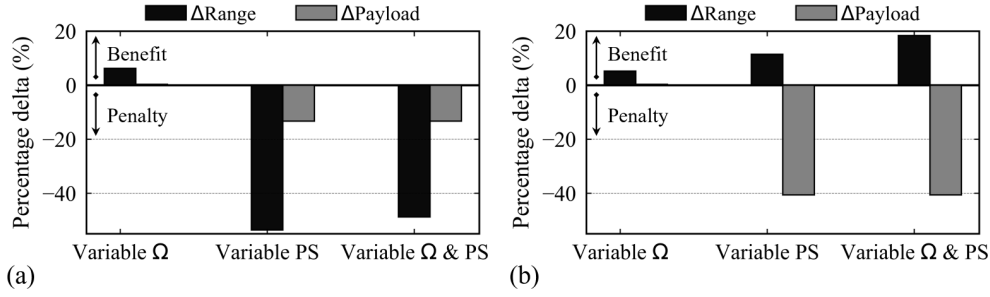


Figure 11: Impact of optimum Ω and PS scheduling on maximum payload and range - expressed as percentage delta relative to the baseline tilt-rotor a) design at reduced range, b) design at reduced payload

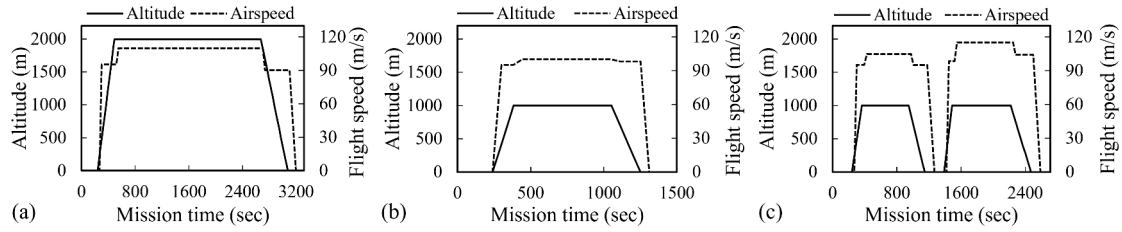


Figure 12: Mission altitude and flight speed profiles: (a) Mission 1: 300 km range operating with TOW=5500 kg, (b) Mission 2: 100 km range operating with TOW=6600 kg, and (c) Mission 3: 212 km operating with TOW=6000 kg

Next, in mission 2, Fig. 12(b), the rotorcraft takes off with a higher AUM=6600 kg, close to the MTOW=6800 kg, cruises at 1000 m with $V=105$ m/s. For mission 3, Fig. 12(c), the rotorcraft starts with AUM=6000 kg and flies for 90 km and 110 km in the first and second cruise leg, respectively. For the three missions, three control strategies are considered: a) variable Ω and fixed $PS = PS_{nom}$, b) fixed $\Omega = \Omega_{nom}$ and variable PS and c) variable Ω and PS .

As discussed in Section 2, the optimum control schedules (Ω and PS) were derived based on surrogate models applicable to straight and level flight for the tilt-rotor in helicopter or aeroplane mode. In a similar manner, for climb and descent phases, optimum schedules for Ω and PS are computed as functions of gross weight (W) for a $V=90$ m/s and a rate of ± 6 m/s. Transition phases from vertical to horizontal flight are ignored.

Figure 13 illustrates the impact of optimal rotor speed and power split schedules on fuel burn and gaseous emissions (NO_x , CO_2). The results are expressed as percentage differences relative to missions carried out for the nominal case. The nominal case represents the baseline fixed rotor speed tilt-rotor equipped with two turboshaft engines ($\Omega = \Omega_{nom}$ and $PS = PS_{nom}$). For the

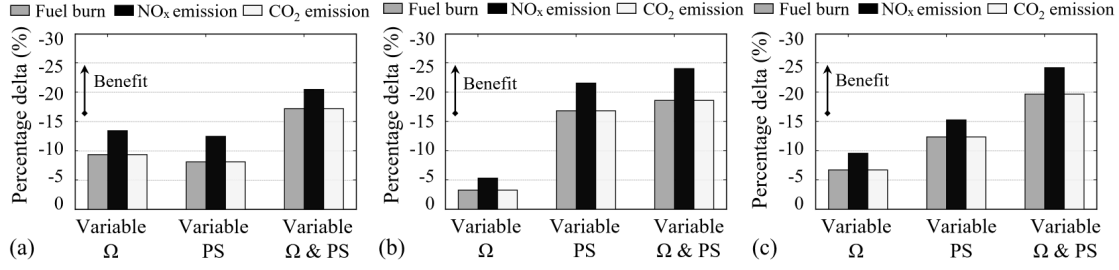


Figure 13: Impact of optimum Ω and PS scheduling on mission fuel burn, NO_x , CO_2 emissions relative to the baseline tilt-rotor: (a) Mission 1: 300 km range operating with TOW=5500 kg, (b) Mission 2: 100 km range operating with TOW=6600 kg, and (c) Mission 3: 212 km range operating with TOW=6000 kg

first mission, the utilization of a variable rotor speed mechanism provides a reduction of 9.4% and 13.5% in fuel burn and NO_x emissions (Figure 13(a)). If combined with a HE system with optimized PS , the overall benefits in fuel/ CO_2 and NO_x raise up to 17.2% and 20.5% relative to the nominal case, respectively. The emission rates for the HE tilt-rotor are computed based on the assumption that the electric energy is produced by renewable sources and hence, the gas turbine is the only contributor to the resultant emissions. It is highlighted however that based on 2016 data, 66% of the world grid power comes from fossil fuels [47]. Thus, the tilt-rotor CO_2 consumption will be highly dependent on the adoption of renewables for land-based grid and is expected to vary with respect to the geographical region of operation and renewable sources availability.

For the HE tilt-rotor, a hybrid powerplant is integrated into the rotorcraft, which penalizes its payload capability. Figure 14 presents the component weight breakdown for the three missions for current battery technology. It is observed that the overall performance benefits of the combined Ω and PS strategy come at a cost of high payload penalty if a fixed mission Take-Off Weight (TOW) is assumed. Specifically, the tilt-rotor can carry 57% of the baseline tilt-rotor payload if current batteries are considered (Fig. 14(a)). According to Epstein et al. [47], advanced battery chemistries will be in the range of 200-600 Wh/kg. Thus, for advanced technology (450 Wh/kg), the penalty in the payload will reduce to 26%. At both technology levels, the combined optimum tilt-rotor is dominated by the added weight leading to an increase in fuel and NO_x per passenger-km relative to the nominal configuration. The evident increase in heat generated by the hybrid-electric system as well as the high difference in heat loads between helicopter and aeroplane mode operation will require design and integration of an efficient thermal management system [6]. This is expected to come at a cost of increased system weight and drag, which are not quantified in this paper.

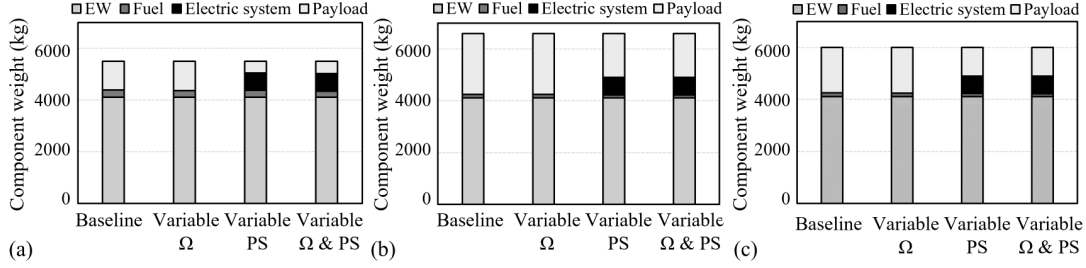


Figure 14: All-up-mass breakdown for: (a) Mission 1:300 km range operating with TOW=5500 kg, (b) Mission 2: 100 km range operating with TOW=6600 kg, and (c) Mission 3: 212 km operating with TOW=6000 kg. Battery density = 250 Wh/kg.

For the second mission, optimizing the rotor speed led to a 3.3% improvement in fuel burn and CO_2 and a 5.3% reduction in NO_X . The large variability observed in block fuel benefits of the VRS architecture for mission 2 and mission 1 is attributed to the large difference in TOW ($TOW_1 = 5500 \text{ kg} \ll TOW_2 = 6600 \text{ kg}$). It has been demonstrated that the performance benefits of VRS are greater for low gross weights as also illustrated in Figure 7. The implementation of a combined optimization strategy for Ω and PS leads to reductions of 18.6% and 24% for fuel burn and NO_X , respectively. At the same time, the added weight of the electric system imposes a 27% penalty in payload capacity for current battery technology, leading to an increase in fuel per passenger-km relative to the conventional tilt-rotor. For advanced battery technology (450 Wh/kg), the payload capacity penalty reduces to 13%. This translates into reductions of 6.1% and 18.5% in fuel and NO_X per passenger-km relative to the conventional tilt-rotor, respectively.

Finally, for the mission 3 (Fig. 13(c)), the delta in fuel burn is of the order of -6.8%, -12.4% and -19.7% for a variable Ω , variable PS and combined variable Ω and PS strategy, respectively. The associated deltas in mission NO_X reach -9.6%, -15.3%, -24.1%. The impact of PS appears to be highly dependent on mission range and the benefits become significant for short ranges, where the battery energy is enough to power the whole mission. The impact of VRS appears to be highly dependent on TOW. From Figure 14(c), it is observed that the added weight of the electric system will reduce the payload capability of the vehicle of 37%, 18% for battery densities of 250 Wh/kg, 450 Wh/kg, respectively. For this mission, the penalty imposed by the 250 Wh/kg battery dominates resulting in an increase in fuel and NO_X per passenger-km relative to the baseline. On the contrary, with a 450 Wh/kg battery, a 2.2% reduction in fuel and 12.6% for NO_X per passenger-km relative to the nominal case can be attained. Thus, it is highlighted that for batteries of 450

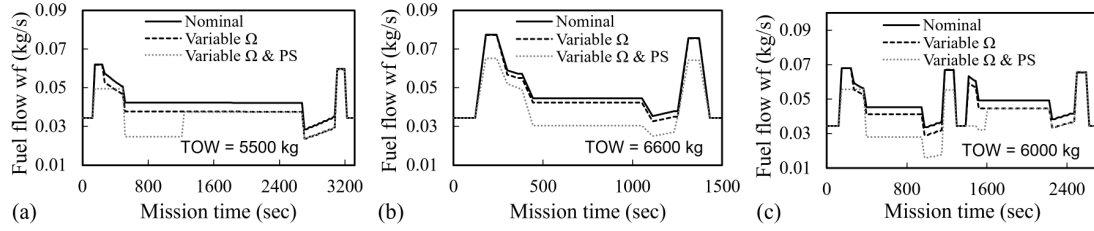


Figure 15: Comparison of mission fuel flow for nominal and optimal control schedules (a) Mission 1: 300 km range operating with TOW=5500 kg, (b) Mission 2: 100 km range operating with TOW=6600 kg, and (c) Mission 3: 212 km operating with TOW=6000 kg

Wh/kg and short mission ranges, the combined optimal strategy is superior to the VRS strategy of the conventional tilt-rotor.

The fuel flow rate consumed throughout the missions is illustrated in Figure 15 for the nominal, variable Ω and combined variable Ω and PS strategy. It is observed that for the VRS strategy, greater improvements are attained during climb, cruise and descent segments. Additionally, the benefits are more pronounced for low gross weights (Fig. 15 (a)) and less obvious at higher weights $W=6000-6600$ kg (Fig. 15 (b-c)). It is also noted that installed battery energy is enough to power the whole flight for mission 2 only (Fig. 15(b)). On the contrary, for missions 1 and 3, the battery is depleted at approximately the middle of the cruise leg and at the beginning of the second cruise leg, respectively.

4. Conclusions

This paper assessed the potential and quantified the benefits on overall performance and chemical emissions stemming from the optimum implementation of VRS for a conventional tilt-rotor and combined VRS with power management for a parallel hybrid-electric tilt-rotor. A multidisciplinary framework comprising models for rotorcraft performance, hybrid-electric propulsion performance, mission analysis and power management has been deployed. The framework was extended with a holistic DSE, surrogate modeling and global optimization approach used to compute optimal schedules for Ω and PS applied on a conventional and a hybrid-electric tilt-rotor. Generalized RSM-assisted optimal schedules have been derived as function of operating conditions across the flight envelope. The developed computational framework allowed for productionized rapid trade-off analyses of VTOL configurations.

525 At aircraft level, it has been demonstrated that optimizing the rotor speed across the operational envelope can lead to reductions in fuel flow of the order of 21% relative to the nominal rotor speed tilt-rotor, which are more pronounced for low gross weight, low altitude and low flight speed close to hovering conditions. The introduction of an electric system leads to greater reductions in fuel flow of the order of 48% at low loading conditions, where the battery is sufficient to power a high 530 fraction of the total power requirement. It is realized however that this benefit is predicated on the battery technology level and size that restricts both its mass, volume and maximum power output.

At payload-range level, it was demonstrated that the utilization of a VRS strategy allows to extend range capacity by 6.2% relative to the baseline tilt-rotor at maximum payload. Combining 535 VRS with power split for the hybrid-electric tilt-rotor variant resulted in two potential designs. The first one is designed at maximum payload resulting in a 52% of the original range and the second is designed at 60% reduced payload to maintain full range capability. The energy and fuel benefits for the hybrid-electric tilt-rotor is primarily influenced by the proximity of the mission operating conditions and battery technology.

540 At mission level, for three representative UAM scenarios, fuel burn/ CO_2 benefits of 3.3% to 9.4% were reported for the VRS tilt-rotor. The associated benefit in NO_x emissions varies from 5.3% to 13.9%. The significance of those benefits strongly depends on the AUM as well as proximity and time spent at each operating condition during the mission. The integration of a hybrid-electric system and hence, an optimized control strategy for both rotor speed and power split leads to 545 higher fuel and emission benefits. Specifically, mission fuel/ CO_2 deltas ranging from -17.2% to -20% and NO_x ranging from -20.5% to -24.1% relative to the nominal architecture were reported. These benefits come at a cost of reduced payload by 37% for current batteries (250 Wh/kg) that translates in higher fuel/ NO_x per passenger-km relative to the VRS strategy.

For battery with 450 Wh/kg and mission ranges up to 250 km, the combined VRS and *PS* 550 tilt-rotor performs (fuel/ NO_x per passenger-km) better than the VRS tilt-rotor without electrical boosting. For higher ranges, the benefits are outweighed by the payload penalty highlighting that the main driver for this architecture is the battery energy density. Concluding, this paper provided new insight into the impact of optimal implementation of VRS combined with power management for tilt-rotor at aircraft, payload-range and mission level for current and future battery technology.

References

- [1] International Air Transport Association (IATA), Aircraft Technology Roadmap to 2050, Technical Report ARC R & M 2642 (2019).
- [2] M. Bradley, C. Droney, D. Paisley, B. Roth, S. Gowda, M. Kirby, NASA N+3 Subsonic Ultra
560 Green Aircraft Research SUGAR Final Review, Boeing Research and Technology 01 (2012).
- [3] Urban Air Mobility Market, Markets and Markets, Report Code:
AS 695, [https://www.marketsandmarkets.com/Market-Reports/
urban-air-mobility-market-251142860.html?gclid=Cj0KCQjw060TBhC_
ARIsAAU1y0V90-M0Gd2Xl1ULeFUGh12Q4QYZwnYe6pu9xTCk0AiAzi0lZyU7oCIaAt45EALw_wcB](https://www.marketsandmarkets.com/Market-Reports/urban-air-mobility-market-251142860.html?gclid=Cj0KCQjw060TBhC_ARIsAAU1y0V90-M0Gd2Xl1ULeFUGh12Q4QYZwnYe6pu9xTCk0AiAzi0lZyU7oCIaAt45EALw_wcB),
565 Published Date: Feb 2021.
- [4] J. Holden, N. Goel, Fast-Forwarding to a Future of On-Demand Urban Air Transportation, White Paper, Uber (2016).
- [5] I. Roumeliotis, C. Mourouzidis, M. Zafferetti, D. Unlu, O. Broca, V. Pachidis, Assessment
of Thermo-Electric Power Plants for Rotorcraft Application, Journal of Engineering for Gas
570 Turbines and Power 142 (2020). 051003.
- [6] R. A. Danis, M. W. Green, J. L. Freeman, D. W. Hall, Examining the Conceptual Design Process for Future Hybrid-Electric Rotorcraft, Technical Report NASA/CR-2018-219897 (2018).
- [7] C. A. Saias, I. Goulos, I. Roumeliotis, V. Pachidis, M. Basic, Preliminary Design of Hybrid-
575 Electric Propulsion Systems for Emerging Urban Air Mobility Rotorcraft Architectures, Journal of Engineering for Gas Turbines and Power 143 (2021). 111015.
- [8] M. Doff-Sotta, M. Cannon, M. Basic, Optimal energy management for hybrid electric aircraft, IFAC 53 (2020) 6043–6049. 21st IFAC World Congress.
- [9] T. Donateo, C. L. De Pascalis, L. Strafella, A. Ficarella, Off-line and on-line optimization
580 of the energy management strategy in a hybrid electric helicopter for urban air-mobility, Aerospace Science and Technology 113 (2021) 106677.

- [10] G. A. Misté, E. Benini, Variable-speed rotor helicopters: Performance comparison between continuously variable and fixed-ratio transmissions, *Journal of Aircraft* 53 (2016) 1189–1200.
- [11] A. E. Karem, Optimum speed tilt rotor, US Patent 6,641,365 B2, 2003.
- 585 [12] G. A. Misté, E. Benini, G. Andre, G.-A. Maria, A methodology for determining the optimal rotational speed of a variable rpm main rotor/turboshaft engine system, *Journal of the American Helicopter Society* 60 (2015) 1–11.
- [13] J. H. Steiner, An Investigation of Performance Benefits and Trim Requirements of a Variable Speed Helicopter Rotor, Master’s Thesis, Pennsylvania State University, 2008.
- 590 [14] D. Han, V. Patrikakis, G. N. Barakos, Helicopter performance improvement by variable rotor speed and variable blade twist, *Aerospace Science and Technology* 54 (2016) 164–173.
- [15] C. Chi, X. Yan, R. Chen, P. Li, Analysis of low-speed height-velocity diagram of a variable-speed-rotor helicopter in one-engine-failure, *Aerospace Science and Technology* 91 (2019) 310–320.
- 595 [16] I. Goulos, M. Bonesso, Variable rotor speed and active blade twist for civil rotorcraft: Optimum scheduling, mission analysis, and environmental impact, *Aerospace Science and Technology* 88 (2019) 444 – 456.
- [17] N. D. Polyzos, S. Vouros, I. Goulos, V. Pachidis, Multi-disciplinary optimization of variable rotor speed and active blade twist rotorcraft: Trade-off between noise and emissions, 600 *Aerospace Science and Technology* 107 (2020) 106356.
- [18] C. Scullion, S. Vouros, I. Goulos, D. Nalianda, V. Pachidis, Optimal Control of a Compound Rotorcraft for Engine Performance Enhancement, *Journal of Engineering for Gas Turbines and Power* 143 (2021). 021005.
- [19] C. A. Saias, I. Roumeliotis, I. Goulos, V. Pachidis, M. Bacic, Design Exploration and Performance Assessment of Advanced Recuperated Hybrid-Electric Urban Air Mobility Rotorcraft, 605 *Journal of Engineering for Gas Turbines and Power* 144 (2022). 031023.
- [20] W. L. MacMillan, Development of a Modular Type Computer Program for the Calculation of Gas Turbine, PhD Thesis, Cranfield University, 1974.

- [21] P. Vratny, C. Gologan, C. Pornet, A. Isikveren, M. Hornung, Battery Pack Modeling Methods
610 for Universally-Electric Aircraft, in: 4th CEAS, Air and Space Conference, Sweden, 2013.
- [22] C. Celis, Evaluation and Optimisation of Environmentally Friendly Aircraft Propulsion Systems, PhD Thesis, Cranfield University, 2010.
- [23] P. Lolis, Development of a Novel Preliminary Aero Engine Weight Estimation Method, PhD Thesis, Cranfield University, 2014.
- [24] I. Goulos, P. Giannakakis, V. Pachidis, P. Pilidis, Mission Performance Simulation of Integrated Helicopter-Engine Systems Using an Aeroelastic Rotor Model, Journal of Engineering
615 for Gas Turbines and Power 135 (2013). 091201.
- [25] G. D. Padfield, Helicopter Flight Dynamics - The Theory and Application of Flying Qualities and Simulation Modelling, John Wiley and Sons, Chichester, UK, 2007.
- [26] J. G. Leishman, Principles of Helicopter Aerodynamics , second ed., Cambridge Aerospace
620 Series, New York, USA, 2006.
- [27] M. J. Bhagwat, Optimum Loading and Induced Swirl Effects in Hover, Journal of the American Helicopter Society 60 (2015).
- [28] A. Bramwell, G. Done, D. Balmford, Bramwell's Helicopter Dynamics, second edition ed., Butterworth-Heinemann, Oxford, UK, 2000. doi:<https://doi.org/10.1016/B978-075065075-5/50005-1>.
625
- [29] K. W. Mangler, Calculation of The Induced Velocity Field of a Rotor, Royal Aircraft Establishment, Report Aero 2247 (1948).
- [30] M. E. Dreier, Introduction to Helicopter and Tiltrotor Flight Simulation, 2007. doi:10.2514/
630 4.862083.
- [31] P. B. Harendra, M. J. Joglekar, T. M. Gaffey, R. L. Marr, V/STOL Tilt Rotor Study - Volume V: A Mathematical Model For Real Time Flight Simulation of the Bell Model 301 Tilt Rotor Research Aircraft, NASA Contract NAS 2-6599 (1973).
- [32] S. W. Ferguson, A Mathematical Model for Real Time Flight Simulation of a Generic Tilt-Rotor Aircraft, NASA Contractor Report (1988).
635

- [33] M. D. Maisel, D. J. Giulianetti, D. C. Dugan, The History of the XV-15 Tilt Rotor Research Aircraft: From Concept to Flight, NASA/SP-2000-4517, NASA Ames Research Center (1980).
- [34] E. B. Carlson, Y. J. Zhao, Optimal Short Takeoff of Tiltrotor Aircraft in One Engine Failure, *Journal of Aircraft* 39 (2002).
- 640 [35] E. B. Carlson, Y. J. Zhao, Prediction of Tiltrotor Height-Velocity Diagrams Using Optimal Control Theory, *Journal of Aircraft* 40 (2003).
- [36] I. Goulos, F. Hempert, V. Sethi, V. Pachidis, R. d'Ippolito, M. d'Auria, Rotorcraft Engine Cycle Optimization at Mission Level, *Journal of Engineering for Gas Turbines and Power* 135 (2013). 091202.
- 645 [37] C. Celis, B. Moss, P. Pilidis, Emissions Modelling for the Optimization of Greener Aircraft Operations, volume Volume 2: Combustion, Fuels and Emissions of *Turbo Expo: Power for Land, Sea, and Air*, 2009, pp. 167–178. doi:10.1115/GT2009-59211.
- [38] I. Goulos, F. Ali, K. Tzanidakis, V. Pachidis, R. d'Ippolito, A Multidisciplinary Approach for the Comprehensive Assessment of Integrated Rotorcraft–Powerplant Systems at Mission
650 Level, *Journal of Engineering for Gas Turbines and Power* 137 (2014). 012603.
- [39] P. Vratny, P. Forsbach, A. Seitz, M. Hornung, Investigation of universally electric propulsion systems for transport aircraft, in: 29th Congress of the International Council of the Aeronautical Sciences, ICAS, 2014.
- [40] S. Vouros, N. D. Polyzos, I. Goulos, V. Pachidis, Impact of optimized variable rotor speed
655 and active blade twist control on helicopter blade–vortex interaction noise and environmental impact, *Journal of Fluids and Structures* 104 (2021) 103285.
- [41] H. Bayraktar, F. S. Turalioglu, A Kriging-based approach for locating a sampling site—in the assessment of air quality, *Journal of Stochastic Environmental Research and Risk Assessment* 19 (2005).
- 660 [42] R. Kohavi, A study of cross-validation and bootstrap for accuracy estimation and model selection, in: Proceedings of the 14th International Joint Conference on Artificial Intelligence - Volume 2, Morgan Kaufmann Publishers Inc., San Francisco, USA, 1995, p. 1137–1143.

- [43] H. Richter, J. W. Connolly, D. L. Simon, Optimal Control and Energy Management for Hybrid Gas-Electric Propulsion, *Journal of Engineering for Gas Turbines and Power* 142 (2020). 091009.
- [44] K. Deb, A. Pratap, S. Agarwal, T. Meyarivan, A fast and elitist multiobjective genetic algorithm: NSGA-II, *IEEE Transactions on Evolutionary Computation* 6 (2002) 182–197.
- [45] J. Ortiz-Carretero, A. Castillo Pardo, I. Goulos, V. Pachidis, Impact of Adverse Environmental Conditions on Rotorcraft Operational Performance and Pollutant Emissions, *Journal of Engineering for Gas Turbines and Power* 140 (2017). 021201.
- [46] P. P. Walsh, P. Fletcher, *Gas Turbine Performance*, John Wiley & Sons, Ltd, 2004. doi:<https://doi.org/10.1002/9780470774533.ch1>.
- [47] A. H. Epstein, S. M. O’Flarity, Considerations for Reducing Aviation’s CO₂ with Aircraft Electric Propulsion, *Journal of Propulsion and Power* 35 (2019) 572–582.



DSPACE

<https://dspace.org/>

On the effects of optimal implementation of variable rotor speed and power management on hybrid-electric rotorcraft

Saias, Chana Anna; Goulos, Ioannis; Pachidis, Vassilios; Bacic, Marko

2023-02-08

American Society of Mechanical Engineers (ASME)

<https://doi.org/10.1115/1.4056855>

Saias CA, Goulos I, Pachidis V, Bacic M. (2023) On the effects of optimal implementation of variable rotor speed and power management on hybrid-electric rotorcraft. Journal of Engineering for Gas Turbines and Power, Volume 145, Issue 3, March 2023, Article number 031028, Paper number GTP-22-1245