

# Conceptual Design and Control Schedule Optimization for Parallel Hybrid Propulsion System of Regional Turboprop Aircraft

*Alexey Mikhailov<sup>1,\*</sup>, Elizaveta Vasilieva<sup>1</sup>, Alexandra Mikhailova<sup>1</sup>, Vladislav Eremenko<sup>1</sup>, Maxim Goryukhin<sup>1</sup> and Daniil Krasnoperov<sup>1</sup>*

<sup>1</sup>Federal State Budgetary Educational Institution of Higher Education «Ufa University of Science and Technology», Ufa, Russia

**Abstract.** Current environmental policies for the aviation industry motivate the use of cleaner propulsion systems to reduce its CO<sub>2</sub> and noise footprint in the coming years. In this context, hybrid propulsion systems have emerged as a potential solution as they have demonstrated a good trade-off between performance and low pollutant emissions. In the present work, the conceptual design and control schedule optimisation of a parallel hybrid propulsion system for the De Havilland Dash 8 regional turboprop aircraft is carried out. A parametric study of the turboprop engine with different degrees of hybridisation at design point and off-design performance analysis of the parallel hybrid propulsion system with different control schedules for an aircraft typical mission has been carried out. Overall aircraft performance parameters are used to evaluate hybrid propulsion systems with different degrees of hybridisation and control schedules. From the results, it was found that a control schedule with 10-15% hybridisation during the cruise phase is the most promising when considering the aircraft mission blocked fuel and fuel efficiency.

## 1 Introduction

Environmental impact is an increasingly important factor in the design of next-generation transport systems. The aerospace industry has begun the transition to zero-emission technologies, focusing primarily on electrification. Batteries and hydrogen have received the most attention as power sources. Companies such as magniX and Joby Aviation have successfully flown fully electric, battery-powered aircraft. Others, such as ZeroAvia, have flight-tested hydrogen fuel cell aircraft.

At low battery energy densities, which are expected in the near future, the fuel reduction potential is greater for short ranges than for longer ranges [1,2]. As a result, hybrid propulsion is considered most suitable for short range market segments such as regional aviation [2,3,4,5,6]. Following the successful flight of early CS-23 prototypes, regional turboprop applications are a likely first step towards the global electrification of commercial aviation [7].

---

\* Corresponding author: [mikhailov.ugatu@gmail.com](mailto:mikhailov.ugatu@gmail.com)

In 2022, the European Union, under the Clean Aviation Programme, launched several projects focused on the design of hybrid electric regional aircraft - Hybrid-Electric Regional Aircraft (HERA), Multi Hybrid Electric propulsion system for regional AiRcraft (HE-ART), Multi Power train InnovAtive for hyBRid-Electric Regional Application (AMBER), Thermal Management Solutions for Hybrid Electric Regional Aircraft (TheMa4HERA) etc.

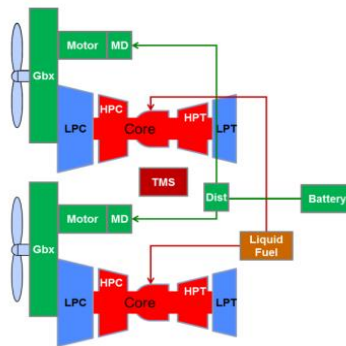
In the present work, the conceptual design and control plan optimisation of a parallel hybrid propulsion system for the De Havilland Dash 8 regional turboprop aircraft is carried out. A parametric study of the turboprop engine with different degrees of hybridisation at design time and an off-design performance analysis of the parallel hybrid propulsion system with different control schedules for a typical aircraft mission have been carried out. Overall aircraft performance parameters are used to evaluate hybrid propulsion systems with different degrees of hybridisation and control schedules.

## 2 Baseline Regional Turboprop Aircraft

The aircraft studied is a De Havilland Canada Dash 8-100, a twin-engine, medium range turboprop aircraft. The De Havilland Canada Dash 8-100 is a platform for "Project 804", a regional aircraft with a parallel hybrid propulsion system developed by Pratt & Whitney Canada and Collins Aerospace. The goal of Project 804 is to replace one of Pratt & Whitney Canada's PW100 series turboprop engines with a 2-megawatt class hybrid propulsion system.

The parallel hybrid propulsion system combines an engine sized for cruise power with a similarly sized electric motor that provides additional power during take-off. The companies expect the hybrid electric propulsion system to deliver an average fuel savings of 30 per cent for a typical flight mission [8].

The architecture of a hybrid propulsion system is shown in Figure 1.



**Fig. 1.** "Project 804" parallel hybrid propulsion system architecture [8].

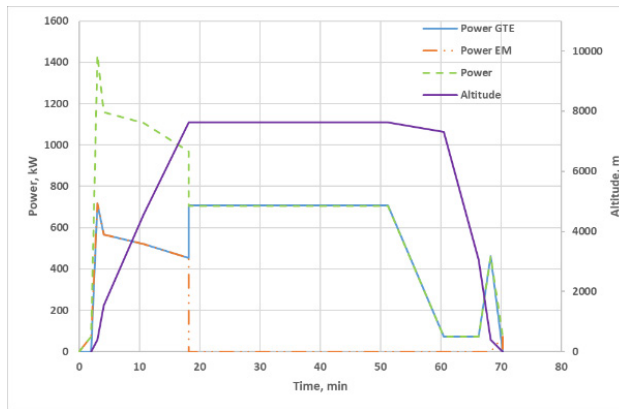
For "Project 804", the aircraft with hybrid propulsion has a limited range due to the fixed weight of the system and is limited to a 250 nm (463 km) mission. The maximum range for the De Havilland Canada Dash 8-100 is 1900 km, but still more than half of the missions flown by this aircraft class are less than 463 km. Therefore, the mission fuel burn for the baseline aircraft and aircraft with parallel hybrid propulsion systems was evaluated for a "standard mission" range of 463 km. A typical 463 km mission for the De Havilland Canada Dash 8-100 is shown in Table 1.

**Table 1.** De Havilland Canada Dash 8-100 flight mission [8]

Mission Phase	Time, sec	Power per engine, hp	Speed, knot	Altitude, m
Taxi out	120	100		0
Take-off	60	1950	115	400

Climb to FL50	63	1575–1150	150	1524
Climb to FL150	400		210	4572
Climb to FL240	450		210	7315
Cruise	1980	960	360*	7625
Descent to FL100	560	100	270	3048
Approach	348		245	400
Landing	120		121	0
Taxi in	120	100		0

Normal cruise power for the Pratt & Whitney PW 121 is ~1000 hp, a flat rated combustion core ideally sized for this application is then ~1000 hp. Such a cruise sized engine will operate at peak efficiency at cruise. To provide power required for take-off and climb, two 950hp electric motors are used. The electrical power to drive the motors is supplied by an electric power train consisting of two motor drives, feeders and a battery pack that is charged on the ground. At the propulsors, a gearbox combines the power from the electric motor and the engine core to drive the propeller. At cruise speed, the gas turbine engine runs at peak power (1000 hp) and highest efficiency, providing all the power required (no electric motor power). The power profile for both the core engine and the electric motor is shown in Figure 2.



**Fig. 2.** “Project 804” typical mission power distribution between gas turbine engine and electric motor.

### 3 Parallel hybrid propulsion system design and performance analysis

A two-spool turboprop engine is considered in the GasTurb software for design point parametric analysis. The compressor pressure ratio is varied 9..12 and the turbine inlet temperature is varied 1300..1450K for cruise conditions. A reference turboprop engine model is shown in Figure 3.

Station	W	T	P	WStd	
	kg/s	K	kPa	kg/s	
1	2,822	238,59	37,574		
2	2,822	255,80	47,932		
3	2,822	255,80	46,973	5,736	
31	2,568	531,91	422,760	0,919	
4	2,623	1300,00	401,622	1,406	
41	2,776	1261,42	401,622	1,465	
43	2,776	1022,25	144,108		
44	2,877	1006,33	144,108		
45	2,877	1006,33	141,225	3,858	
49	2,877	789,06	46,009	10,486	
5	2,877	789,06	45,089		
6	2,877	789,06	45,089		
8	2,877	789,06	45,089		
Bleed	0,000	255,80	46,973	10,700	

Efficiencies:	isent	polytr	hst	p/p
Compressor	0,7998	0,8500	0,534	9,000
Burner	0,9909		0,959	
HP Turbine	0,8744	0,8600	0,703	2,787
LP Turbine	0,8854	0,8700	0,321	3,070

HP Spool mech EFF	0,9900	Non Spd	30016	rpm
PT Spool mech EFF	0,9800	Non Spd	20000	rpm

eta	t-s
	0,76835

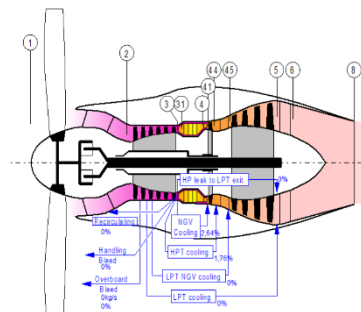
FN	=	3,33	kN
TSFC	=	16,5434	g/(kN*s)
VO	=	185,84	m/s
FN res	=	0,29	kN
MF	=	0,0533	kg/s
Therm Eff	=	0,29698	
P2/P1	=	0,38000	
TRQ	=	100,0	%
P45/P44	=	0,00000	
P6/P5	=	0,98000	
P8/Pamb	=	1,20000	
wB/w2	=	0,00000	
A8	=	0,05825	m <sup>2</sup>
wC/w2	=	0,04500	
wCR/w2	=	0,03600	
LoadInp	=	100,00	%
wCL/w2	=	0,00000	
wCLR/w2	=	0,00000	

Power	W
Pmax	= 0,00
PMSD	= 706,10
PMSD_eq	= 806,86
SFC_eq	= 0,24599
PMSFC	= 0,28109

hum	(%)	ward	F/W	Fuel
0,0	0,00000	43,124	Generic	



**Fig. 3.** Reference turboprop engine model.

A hybrid propulsion system weight, mission blocked fuel and technoeconomical analysis is performed to evaluate the performance of an aircraft with different hybrid propulsion system configurations.

Propulsion system weight prediction model, developed by Kuz'michev et al. is used [9]:

$$W_{GTE} = B(\dot{m})^{m_1} [(OPR)^{0,286} - 1]^{m_2} k_{TIT} k_{year} k_{life}, \quad (1)$$

$k_{TIT}$  shows the effect of turbine inlet temperature,  $k_{year}$  shows engine sophistication impact (changes over the years),  $k_{life}$  shows engine life impact on weight,  $\dot{m}$  – engine mass flow rate,  $OPR$  – compressor overall pressure ratio,  $B$ ,  $m_1$ ,  $m_2$  – empirical coefficients,  $W_{GTE}$  – gas turbine engine weight.

$$W_{PS} = n_{GTE} W_{GTE} k_{PS} \quad (2)$$

$n_{GTE}$  – number of gas turbine engines,  $W_{GTE}$  – gas turbine engine weight,  $k_{PS}$  – shows propulsion system components impact,  $W_{PS}$  – propulsion system weight.

Mission blocked fuel estimation:

$$W_{BF} = \sum_{i=0}^n PSFC_{ave} P_{ave} t, \quad (3)$$

$W_{BF}$  – mission blocked fuel,  $TSFC_{ave}$  – averaged power specific fuel consumption for specific mission phase,  $P_{ave}$  – averaged engine power for specific mission phase,  $t$  – duration of specific mission phase

Fuel efficiency of aircraft is blocked fuel per 1km of flight and 1kg of commercial payload

$$\eta_f = \frac{W_{BF}}{W_{pR}} \quad (4)$$

$\eta_{fuel}$  – fuel efficiency of aircraft,  $W_p$  – aircraft commercial payload,  $R$  – aircraft range.

Electric motor weight model:

$$W_{EM} = \frac{P_{EM}}{\eta_{EM}} \cdot n \cdot PW_{EM} \quad (5)$$

$W_{EM}$  – electric motor weight,  $P_{EM}$  – electric motor power,  $\eta_{EM}$  – electric motor efficiency,  $n$  – number of electric motors (2),  $SP_{EM}$  – electric motor power to weight ratio.

Motor drive weight model:

$$W_{MD} = \frac{P_{MD}}{\eta_{MD}} \cdot n \cdot PW_{MD} \quad (6)$$

$W_{MD}$  – motor drive weight,  $\eta_{MD}$  – motor drive efficiency,  $n$  – number of motor drives,  $PW_{MD}$  – motor drive power to weight ratio.

Feeders weight model:

$$W_{feeder} = \frac{P_{feeder}}{\eta_{feeder}} \cdot n \cdot PW_{feeder} \quad (7)$$

$W_{feeder}$  – feeder weight,  $P_{feeder}$  – feeder power,  $\eta_{feeder}$  – feeder efficiency,  $n$  – number of feeders,  $PW_{feeder}$  – feeder power to weight ratio.

$$W_{bat} = \frac{n \cdot k \cdot SC_{bat} \cdot C}{\eta_{bat}} \quad (8)$$

$W_{bat}$  – battery weight,  $n$  – number of electric motors,  $SC_{bat}$  – battery specific capacity,  $C$  – battery capacity,  $\eta_{bat}$  – battery efficiency.

$$C = P_{EM} t \quad (9)$$

$C$  – battery capacity,  $P_{EM}$  – electric motor power,  $t$  – flight duration.

Hybrid propulsion system weight model:

$$W_{HPS} = W_{PS} + W_{EM} + W_{MD} + W_{feeder} + W_{bat} \quad (10)$$

Hybrid propulsion system and blocked fuel total weight:

$$W_{BF+HPS} = W_{BF} + W_{HPS}$$

The fuel efficiency of the aircraft, hybrid propulsion system and blocked fuel total weight are considered as figures of merit for hybrid propulsion system design point parametric analysis and control schedule optimization.

State-of-the-art hybrid propulsion system component performance parameters are shown on fig. 4.

	Power to Weight (kW/kg)	Performance	Notes
Motor	13	0.97 eff	NASA support motor development
Motor Drive	20	0.98 eff	NASA supported inverter dev
Feeders	100	0.99 eff	Estimate
Battery	355 Whr/kg packaged	500 Whr/kg cell, 0.95 eff, 90% max discharge, 15% back burden	Parameter targets laid out by Battery 500 consortium

**Fig. 4.** State-of-the-art electric components performance parameters [8].

Each hybrid propulsion system control schedule is denoted AA-BB-CC-DD-EE, where AA is take-off hybridisation, BB-CC-DD is hybridisation for three consecutive climb phases, and DD is cruise hybridisation. For each hybrid propulsion system control schedule, a set of design points with different compressor pressure ratio and turbine inlet temperature is considered. The results of the design point parametric analysis and control schedule optimisation are shown in Table 2.

In table 2  $\Delta W_{PW}$  is the difference the total weight of the hybrid propulsion system and the blocked fuel and PW121 and blocked fuel; and  $\Delta \eta_{fPW}$  is the difference between the fuel efficiency of the hybrid propulsion system and the fuel efficiency of the PW121;  $\Delta W_{0\%}$  is the difference between the total weight of the hybrid propulsion system and the blocked fuel and the reference engine with 0% hybridisation;  $\Delta \eta_{f0\%}$  is the difference between the fuel efficiency of the hybrid propulsion system and the reference engine with 0% hybridisation;  $R_{max}$  is the maximum range of the aircraft with the specific hybrid propulsion system; -PAX s the possible difference in PAX number due to the increased weight of the propulsion system.

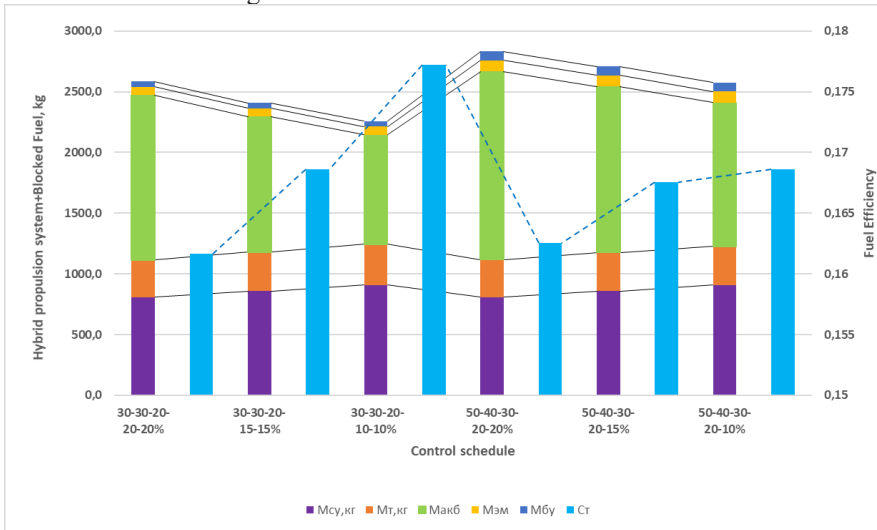
**Table 2.** Hybrid propulsion system design parametric analysis and control schedule optimization results

	$\Delta W_{PW}$ , kg	$\Delta \eta_{fPW}$ , %	$\Delta W_{0\%}$ , kg	$\Delta \eta_{f0\%}$ , %	$R_{max}$	-PAX
PW121					2014,5	
0%	316,7	6,6			2716,9	
	267,7	13,0			2785,0	
10-10-10-10-0%	7,1	14,9	323,8	8,86	2201,0	0,1
	33,8	21,1	350,5	15,56	2279,4	0,3
30-30-30-30-0%	512,6	22,2	829,3	16,72	1347,1	5
	374,8	29,2	691,5	24,15	1684,1	4
50-50-50-50-0%	1062	27,4	1378,8	22,32	399,6	10
	925,3	34,2	1242,0	29,53	650,7	9
70-70-70-70-0%	2768	32,6	3085,0	27,80	-2542,4	26
	2543	36,0	2859,7	31,48	-2386,0	24
30-30-20-10-0%	207,0	18,4	523,7	12,66	1874,0	2
	73,4	25,3	390,1	20,01	2249,9	1
30-30-30-30-10%	736,6	27,8	1053,3	22,69	643,0	7
	616,2	34,2	932,9	29,55	729,7	6
30-30-20-20-20%	745,6	29,9	1062,3	24,97	576,3	7
	639,7	36,1	956,4	31,59	623,0	6
30-30-20-15-15%	576,9	26,9	893,6	21,71	683,0	5
	463,1	33,4	779,8	28,65	749,7	4
30-30-20-10-10%	436,7	20,2	753,4	14,59	843,0	4
	312,9	29,9	629,6	25,00	1003,0	3
	530,0	21,7	846,7	16,12	777,8	5

50-40-30-20-0%	391,9	28,7	708,6	23,65	1629,8	4
50-40-30-20-10%	757,1	26,8	1073,8	21,63	656,3	7
	636,0	33,4	952,7	28,65	763,0	6

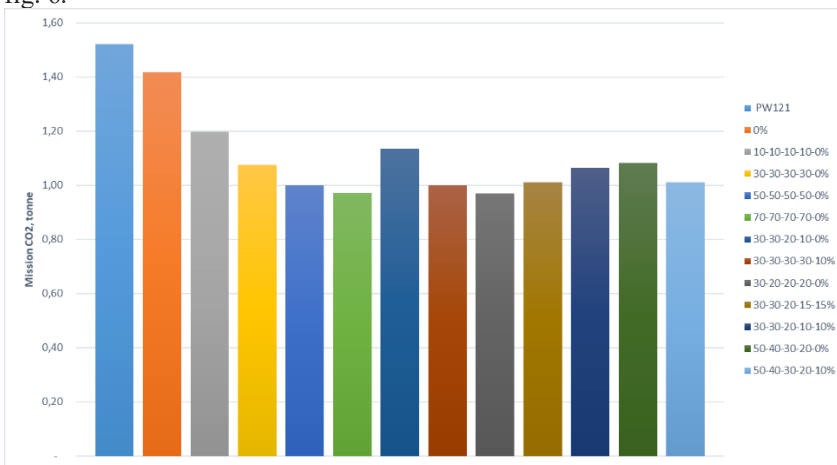
For each control schedule in Table 2, two rows can be seen indicating the engine with maximum and minimum compressor pressure ratio and turbine inlet temperature.

The effect of the hybrid propulsion system control schedule on the optimisation figures of merit is shown in Figure 5.



**Fig. 5.** Effect of hybrid propulsion system control schedule on optimization figures of merit.

Effect of hybrid propulsion system control schedule on flight mission CO<sub>2</sub> is shown on fig. 6.



**Fig. 6.** Effect of hybrid propulsion system control schedule on flight mission CO<sub>2</sub>.

In Project 804, the degree of hybridisation is 50% at take-off and decreases linearly as the aircraft climbs. In fact, Pratt&Whitney and Collins Aerospace are aiming to develop a technology demonstrator of a hybrid propulsion system with a MW-class electric motor.

Considering the fuel efficiency of the aircraft, the total weight of the hybrid propulsion system and the mission blocked fuel, it can be seen that the hybrid propulsion system control plan with 50% at take-off and linear decrease of hybridisation is not optimal.

The best fuel efficiency is obtained by considering a low hybridisation of 10-20% in the cruise phase, Figures 5 and 6. The most promising control schedules are 30-30-20-15-15%, 30-30-20-10-10% and 50-40-30-20-10%. As expected, the control schedule with cruise hybridisation has a great effect on the battery weight and consequently on the maximum range of the aircraft.

Considering the weight of the hybrid propulsion system, the most promising control schedule is 30-30-20-10-0%.

The maximum fuel efficiency gain is 36.1% for the PW121 and 31.59% for the reference engine with 0% hybridisation when we use a 30-30-20-20-20% control schedule.

## 4 Conclusion

The authors considered the problem of conceptual design and control program optimisation for a parallel hybrid propulsion system of a regional turboprop aircraft. Parametric analysis and control program optimisation were carried out for the hybrid propulsion system of the De Havilland Canada Dash 8-100 aircraft. The aircraft fuel efficiency and the total mass of the hybrid propulsion system and blocked fuel were considered as the optimisation parameters.

Based on the results obtained, the effect of the control program on the integral performance parameters of the hybrid propulsion system is shown. It is shown that the parallel hybrid propulsion system with moderate hybridisation at take-off and minimal hybridisation at cruise has the highest efficiency. Considering the weight of the hybrid propulsion system, the best solution is the propulsion system with moderate hybridisation at take-off and linear decrease at climb with no hybridisation at cruise.

The authors also gratefully acknowledge the helpful comments and suggestions of the reviewers, which have improved the presentation.

## References

1. A.T. Isikveren, A. Seitz, P.C. Vratny, C. Pomet, K.O. Ploetner, M. Hornung, Conceptual Studies of Universally-Electric Systems Architectures Suitable for Transport Aircraft. In 61. Deutscher Luft- und Raumfahrtkongress (DLRK) (2012)
2. C. Pomet, A.T. Isikveren, Conceptual design of hybrid-electric transport aircraft. *Prog. Aerosp. Sci.*, **79** (2015)
3. R. Thomson, M. Baum, T. Kirschstein, N. Martinez, N. Sachdeva, P.L. Lepine, N. Bailly, Aircraft Electrical Propulsion—Onwards and Upwards. In *Think: Act* (2018)
4. B.J. Brelje, J.R. Martins, Electric, hybrid, and turboelectric fixed-wing aircraft: A review of concepts, models, and design approaches. *Prog. Aerosp. Sci.*, (2019)
5. S. Sahoo, X. Zhao, K. Kyprianidis, A Review of Concepts, Benefits, and Challenges for Future Electrical Propulsion-Based Aircraft. *Aerospace* **7**, 44 (2020)
6. M. Voskuijl, J. van Bogaert, A.G. Rao, Analysis and design of hybrid electric regional turboprop aircraft. *CEAS Aeronaut. J.* **9**, (2018)
7. F. Orefice, F. Nicolosi, S. Corcione, P. Della Vecchia, Hybridization and Mission Analysis of a regional turboprop. In *AIAA Aviation 2021 Forum* (2021)

8. T. Spierling, C. Lents, Parallel Hybrid Propulsion System for a Regional Turboprop: Conceptual Design and Benefits Analysis AIAA/IEEE Electric Aircraft Technologies Symposium (EATS) (2019)
9. V. Kuz'Michev, I.N. Krupenich, E. Filinov, Comparative Analysis of Mathematical Models for Turbofan Engine Weight Estimation. MATEC Web of Conferences (2018)