DESIGN EVALUATION AND PERFORMANCE ASSESSMENT OF ROTORCRAFT TECHNOLOGY BY 2050

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Abstract

The extended Clean Sky Joint Technology Initiative (JTI) within the EU Horizon 2020 Framework Programme [Ref. 1] proposes to introduce a number of concept aircraft and rotorcraft to replace reference technology counterparts at different time scales (2020/2035/2050). This Clean Sky 2 (CS2) promotes the importance of those concept configurations and their application in the future. An increasing global demand within and outside the European Union (EU) for an efficient air mobility and transportation system (i.e. more flexible, resilient, effective and affordable), and future projected growth for its application, will lead to the requirement for development of highly optimised transportation solutions.

Within CS2, the project DEPART2050 (Design Evaluation and Performance Assessment of Rotorcraft Technology by 2050) aims to undertake the environmental and socio-economic assessments for two fast rotorcraft technologies, being the tilt rotor aircraft and the compound rotorcraft under development by the Original Equipment Manufacturers (OEMs), the NGCTR and the Racer. Such fast rotorcraft with improved capabilities (higher payload, range and speed) will have an inherent advantage. This will enable the utilisation of smaller airports (as they can operate from shorter runways) and optimally located heliports. The objectives of the project work will be to undertake at airport level and at Air Transport System (ATS) level, assessments of environmental (emissions and noise) and mobility (connectivity and productivity) improvements that may be accrued through replacement of reference helicopter technology over the designated time scales. The assessments will be made for a selected number of mission scenarios: Search and Rescue, Oil and Gas, Emergency Medical Service, Passenger Air Transport and Cargo Transport.

To widen the scope of the DEPART2050 project, additional assessments will be performed for two generic fast rotorcraft: a tilt rotor aircraft and a compound rotorcraft. These generic rotorcraft, having been defined by the DEPART2050 project partners, are different from and do not represent the ones under development by the OEMs within CS2 (NGCTR and Racer). Within the DEPART2050 project so far, the rotorcraft configurations have been defined and the models set up. The assessment metrics and missions have been further detailed. Initial assessments have been performed for fuel consumption, exhaust gas emissions, noise impact and mobility impact, showing that the set-up is viable and that results are in line with expectations. Considerable reductions have been found for fast rotorcraft relative to conventional helicopters, both in fuel consumption and CO_2 emission per passenger-kilometre, as well as in absolute travel time. But it also has become clear that more work is required to come to actual and final conclusions. The project will run till late 2021 and more results will become available in due time.

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1. PROJECT DEPART2050

1.1. General context

Strategic Research & Innovation Agenda (SRIA) goals have been set up for the European aviation industry to ensure future environmental sustainability, while meeting society’s needs for fast efficient transportation. Fast rotorcraft are set to play a key role, as an enabling technology, in achieving these ambitious objectives and goals.

Clean Sky 2 (CS2) proposes to introduce a number of concept aircraft and rotorcraft to replace reference technology counterparts at different time scales (2020/2035/2050). Therefore, in order to realize the overall objectives of the aviation industry, it is necessary to assess and evaluate the environmental and socio-economic impact of those new technologies in that time scale.

Based on the requirements of the CS2 Technology Evaluator, the project DEPART2050 (Design Evaluation and Performance Assessment of Rotorcraft Technology by 2050) is positioned as a dedicated technology evaluation platform, with a critical role of assessing the environmental impact of the technologies developed. Apart from assessing the level of success achieved by the novel technologies and their contribution to well-defined environmental goals, the TE is also tasked with establishing any societal benefits that may be accrued. Project DEPART2050 will focus on assessing and establishing the impact of introducing novel rotorcraft concepts at the airport and Air Transport System (ATS) level. The comparison will be made against a selected reference technology (conventional single main rotor / single tail rotor helicopter) in terms of impact on the environment, mobility and productivity.

The consortium is led by Cranfield University, and includes Netherlands Aerospace Centre NLR, ANOTEC Engineering and University of Padua.

1.2. Aims and objectives

The aim of project DEPART2050 is to undertake novel rotorcraft technology assessments (tilt rotor aircraft and compound rotorcraft), utilizing multi-disciplinary state-of-the-art simulation frameworks which are flexible, extensible and modular. As such it will provide a clear and objective assessment of the environmental and socio-economic impact of the introduction of the tilt rotor and compound rotorcraft configurations in the aviation industry.

The objective of the work will be to adapt and utilise a suite of ‘advanced’ rotorcraft models to undertake the required assessments. These will include tilt rotor aircraft configurations, compound rotorcraft configurations and suitable reference helicopter concepts. In order to undertake the requisite airport level assessments and ATS analysis, various missions will be simulated using the models for the novel (fast) rotorcraft and reference helicopter configurations. These will include missions specific to passenger transport utilisation, Emergency and Medical Services (EMS), Search and Rescue (SAR), ferrying to offshore Oil And Gas (OAG) rigs, cargo transport and any other missions deemed necessary.

The objective of the work in the project then is to undertake at airport level and at ATS level, assessments of environmental (emissions and noise) and mobility (connectivity and productivity) improvements that may be accrued through replacement of reference technology over the designated time scales (2020/2035/2050).

1.3. Structure of paper

This paper provides an overview of the current status of and results achieved within the DEPART2050 project. The project is about mid-way through its intended time scale and therefore all results are only preliminary.

Chapter 1 provides a brief introduction to the context of this paper. Chapter 2 gives an overview of the rotorcraft under consideration, their intended missions and the assessment criteria (metrics). Chapter 3 details the individual methodologies that have been employed. Chapter 4 provides insight into typical assessment results for generic tilt rotor aircraft and compound rotorcraft, in terms of fuel burn and gaseous emissions, and mobility impact. Chapter 5 summarizes the results and the planned future work. Chapter 6 is dedicated to acknowledgements. Chapter 7 includes all reference documents.

2. ROTORCRAFT, MISSIONS AND METRICS

2.1. Rotorcraft specifications

The DEPART2050 consortium has decided to widen the scope of the project, by not only undertaking assessments on conceptual Fast Rotorcraft (FRC) under development by the OEMs within CS2 (the NGCTR and RACER), but also additionally on generic fast rotorcraft designs developed by the DEPART2050 partners themselves. The latter are further explained in the following paragraphs.

2.1.1. Tilt rotor aircraft

A generic tilt rotor aircraft configuration has been designed based on existing fast rotorcraft and ones under development [Refs. 2-5]. The chosen design has a conventional layout, with a streamlined fuselage, a pressurized cabin with circular cross-section, a fixed (non-tilting) wing with large flaperons to alleviate the download in hover and low-speed flight, two tilting three-bladed proprotors with fixed (non-tilting) engines at the wing tips, and T-shaped tail planes.

The proprotors can be tilted from the vertical position for the helicopter flight mode in hover and at low speeds, to the horizontal position for the airplane flight mode. In helicopter mode the proprotors provide lift, (limited) propulsive force and control of the aircraft; in airplane mode they only provide propulsive force, whereas control is provided by conventional aerodynamic control surfaces. The proprotors have the typical control system of the helicopter main rotor, i.e. the cyclic and collective blade pitch control actuated by swashplates.

The aircraft sizing is largely derived from trend lines of other, modern tilt rotor designs. Those trend lines include rotor disk loading, rotor solidity, rotor tip speed, wing loading and power loading.

The general configuration is provided in Table 1, with proprotor and wing sizing details in Table 2.

Table 1 *Tilt rotor aircraft configuration*

Parameter		**Value**
Payload	kg	1800
Passengers	-	18
Empty weight	kg	6400
Max take-off weight	kg	10000
Engine TOP	kW	2400
Number of engines	-	2

Table 2 *Tilt rotor aircraft proprotor and wing specification*

		Proprotor
Radius	m	4.55
Chord	m	0.45
Blades per rotor	-	3
Solidity	-	0.095
Rotor speed in hover	rpm	450.12
Distance between rotor hubs	m	13.2
		Wing
Span	m	12.2
Chord	m	1.45

2.1.2. Compound rotorcraft

A generic coaxial compound rotorcraft configuration is designed based on existing fast rotorcraft [Refs. 6-10]. The chosen design consists of a stiff counter-rotating coaxial rotor system, streamlined fuselage, pusher propeller, and large horizontal stabilizer. The rotor system is heavier than conventional single rotor systems; however, it provides a number of benefits. Firstly, the opposing rotation of the rotors provides torque balance, thus a tail-rotor is not required. Secondly, due to the stiff hingeless blade design, the hub can maintain a rolling moment. This enables the advancing side of the rotor disc to generate more lift than the retreating, which is beneficial for performance at high forward speeds and alleviates retreating blade stall. Despite these advantages, the edgewise rotors are inefficient at generating the high levels of propulsive thrust that are necessary at high speed, thus, it is also necessary to utilize thrust compounding. A single high solidity six-bladed tail mounted pusher propeller is used, while the fuselage is also assumed streamlined, producing low levels of drag. To estimate the drag, historical trends are utilized which are consistent with previous conceptual studies [Ref. 11]. Finally, a large horizontal stabilizer is utilized as would be required for stability requirements, but also to offload the main rotors in cruise. The general configuration is provided in Table 3, with rotor and propeller sizing details in Table 4.

Table 3 *Compound rotorcraft configuration*

Parameter		**Value**
Payload	kg	1600
Passengers	-	16
Empty weight	kg	6136
Max take-off weight	kg	9371
Engine type	-	T700-GE-700
Number of engines	-	2

Table 4 *Compound rotorcraft rotor and propeller specification*

		Rotor	Propeller
Radius	m	7.44	2.1
Blades per rotor	-	4	6
Rotor separation	%R	13	-
Solidity	-	0.15	0.2
Blade twist (in/outboard)	deg	14 / -9	-50

2.1.3. Reference helicopter

The Year 2000 reference technology helicopter for the tilt rotor aircraft as well as for the compound rotorcraft is the Twin-Engine Medium Baseline (TEM-B) generic helicopter model developed during Clean Sky 1 [Ref. 12]. This helicopter can carry 12 passengers, employs a 5-bladed main rotor and 4-bladed tail rotor.

The simulation framework PhoeniX is employed for modelling the TEM-B helicopter. PhoeniX was developed during the Clean Sky project Green Rotorcraft [Ref. 13] and has previously been utilized for rotorcraft optimization and environmental impact studies [Ref. 14], including thorough validation.

2.2. Mission types and scenarios

This section provides an overview of the fast rotorcraft mission types that have been selected for the assessments. For each mission type a number of detailed mission scenarios have been defined in terms of the geo-location of the operations and at varying distances flown.

2.2.1. Search and rescue (SAR)

In a SAR mission, the rotorcraft is assumed to take off from the original airport/heliport and travel towards a designated area where the search and rescue needs to be executed. The rotorcraft then engages in a specific flight pattern until the victims in distress have been located and evacuated. The rotorcraft is then assumed to transfer the rescued victims to a designated hospital and returns to the original airport.

2.2.2. Oil and Gas (OAG)

In an OAG mission, the rotorcraft is assumed to take off from the original airport/heliport and transit towards a specific oil and gas platform transferring payload and personnel. Subsequently the rotorcraft returns to the original airport/heliport.

2.2.3. Emergency Medical Service (EMS)

In an EMS mission, the rotorcraft is assumed to take off from the original airport/heliport and fly towards the location of a hypothetical accident and collects the casualties. After transferring the casualties to the nearest available hospital the rotorcraft returns back to the original airport/heliport.

2.2.4. Passenger Air Transport (PAT)

Three types of PAT missions have been identified based on the expected capabilities of the fast rotorcraft:

a) Door-to-door (PAT-DTD) air taxi: In a PAT-DTD mission, the rotorcraft is assumed to take off from the original airport/heliport to pick up the passengers from a designated location. It subsequently transfers them to a drop-off point and returns back to the original airport/heliport.

b) Airport hub feeder (PAT-AHF) service: In a PAT-AHF mission, the rotorcraft is assumed to transfer passengers between a base airport and a hub airport.

c) Commercial intercity transportation (PAT-CIT): In a PAT-CIT mission, the rotorcraft is assumed to transfer passengers between heliports/vertiports located in the centre of a designated city and another city centre. This mission type assumes the development of appropriate infrastructure for the operation of fast rotorcraft.

2.2.5. Cargo Transport (CGT)

In a CGT mission, the rotorcraft is assumed to transport goods from a centralized logistics centre at a major hub airport to national distribution centres, strategically located in industrial zones near motorways and railways. This mission type assumes the development of appropriate infrastructure for the operation of fast rotorcraft.

2.2.6. Mission scenarios

In consultation and after discussions with the OEMs the following mission types have been selected for the assessments: for the tilt rotor aircraft the SAR, OAG, PAT-AHF, PAT-CIT and CGT operations, and for the compound rotorcraft the SAR, EMS, PAT-DTD, PAT-AHF and PAT-CIT operations. Of course, each of the fast rotorcraft will be capable of operating a much wider range of mission types.

For each of the mission types, 5 mission scenarios at different distances flown have been detailed, with the maximum distance flown of each mission tailored to the expected capabilities of the fast rotorcraft. In this way the various mission lengths adequately represent short to long range scenarios. In doing so the capabilities of advanced rotorcraft will be holistically assessed, thereby enabling a representative ATS scenario (being an average trajectory in terms of distance flown) to be exported.

A typical mission profile is composed of a variety of mission segments, like start-up, warm-up, take-off, climb, cruise, descent, loiter/rescue, approach, landing, cool-down, shut-down. The required reserve fuel is accounted for by defining a 30 minute segment flown at holding speed.

As examples two specific missions are further detailed hereafter: for the tilt rotor aircraft an example OAG mission from Aberdeen Airport to the North Sea Magnus oil field and back, for the compound rotorcraft an example PAT-CIT mission from Paris-Issy-les-Moulineaux Heliport to London Heliport. For both missions use is made of existing airports/heliports. All rotorcraft carry their maximum number of passengers (limited by seating capacity and/or take-off mass constraints), which board at the departure airport/heliport and are flown to the destination airport/heliport. The fast rotorcraft and reference helicopter fly along the same flight route, whereas operational parameters (speeds, altitude, and climb and descent rates) are different. Cruising altitudes were chosen as follows:

- for the tilt rotor it is representative of the operating altitudes of other such aircraft
- for the compound it is the limiting altitude of unpressurised cabin operations
- for TEM-B it is an optimum altitude in terms of fuel burn and NOX emissions; due to the length of the OAG mission, TEM-B has to refuel on the rig

Typical mission parameters are shown in Tables 5 and 6.

Table 5 *Tilt rotor aircraft OAG mission*

		TEM-B	**Tilt rotor**
Mission range	km	1060	1060
Passengers	-	11	16
Contingency	min	30 (loiter)	30 (loiter)
Cruise altitude	m	2000	7620
Cruise speed	m/s	61.7	128.6
Climb speed	m/s	41.2	102.9
Climb rate	m/s	5.1	7.6
Descent speed	m/s	61.7	128.6
Descent rate	m/s	3.8	7.6

Table 6 *Compound rotorcraft PAT-CIT mission*

		TEM-B	**Compound**
Mission range	km	342	342
Passengers	-	12	16
Contingency	min	30 (loiter)	30 (loiter)
Cruise altitude	m	2000	3000
Cruise speed	m/s	61.7	105
Climb speed	m/s	41.2	95
Climb rate	m/s	5.1	5
Descent speed	m/s	61.7	105
Descent rate	m/s	3.8	5

2.3. Assessment criteria

2.3.1. Gaseous emissions

The mission definitions included cover both short and long ranges. Shorter range missions can be flown by both FRC and reference helicopter without the need of re-fuelling. This allows a direct comparison between conceptual and reference technology in terms of absolute values for fuel burn and gaseous emissions.

When compared against missions ranges typically undertaken by conventional helicopters, FRC are more efficient when operated on longer range missions. However, longer range FRC missions cannot be operated by the reference technology and hence in the course of this study, the reference helicopter missions are adapted by either scaling them down to lie within the attainable ranges, or by including auxiliary fuel, or by introducing a midway refuelling stop.

Due to the different range capabilities of the two (novel and reference technologies), the utilization of absolute impact metrics would be misleading for comparisons between different missions.

Additionally, as the FRC has a higher passenger (or payload) capacity than the reference technology, it has been deemed necessary to employ normalized metrics for the fuel burn and gaseous emissions comparisons. The proposed normalized metrics are provided in Table 7.

***Table 7** Normalized fuel burn and gaseous emissions impact metrics*

Impact parameter	Absolute metric
Fuel burn	kg of fuel/(pax*km) or kg of fuel/(ton payload*km)
NO_x emissions	kg of NO_x/(pax*km) or kg of NO_x/(ton payload*km)
CO_2 emissions	kg of CO_2/(pax*km) or kg of CO_2/(ton payload*km)

2.3.2. Noise impact

Noise levels will be compared in terms of area above specific noise thresholds in dB LAMAX / SELA and population affected in those areas.

2.3.3. Mobility impact

For the tilt rotor aircraft, a mobility study regarding OAG mission has been carried out. The assessment will focus on the mobility benefits arising after the replacement of specific parts of the current helicopter fleet with tilt rotor aircraft. Additionally, mobility studies have been carried out regarding PAT missions, investigating the potential of replacing means of ground/air transportation with tilt rotor aircraft. Finally, PAT mobility studies have been carried out for the compound rotorcraft, compared with means of ground/air transportation.

Since the employed rotorcraft can be of different types and sizes, a weighted distance has been computed, with the weight given by the number of passengers. Hence, the passenger-distance (expressed in passenger kilometres, pkm) will be employed for comparisons. The total travel time is also employed as a mobility impact metric. The reduced travel times anticipated with FRC will lead to productivity improvements. This will be assessed in terms of man-hours lost in flight. Finally, the improvements in transport capacity will be quantified in Available Seat Kilometres (ASK).

3. METHODOLOGY

3.1. Rotorcraft performance models

3.1.1. Tilt rotor aircraft

The EUROTILT tool is a dedicated tilt rotor aircraft flight mechanics code, designed to calculate tilt rotor steady state (trim) and dynamic (manoeuvre) performance. The code was developed and validated in the European NICETRIP project [Ref. 15]. It is ideally suited to determine flight and mission performance and (optimized) take-off and landing flight paths.

EUROTILT uses a generic rotorcraft mission description where properties such as flight conditions, atmospheric conditions and rotorcraft data are defined by the user. The flight mechanics simulation generates the flight path consisting of a number of flight segments, with each segment containing information such as position, altitude, speed, etc. as a function of time. This information is forwarded to the other tools for fuel burn/gas emissions (GSP, see section 3.2.1) and noise estimations along each segment of the trajectory. The flow diagram is shown in Figure 1.

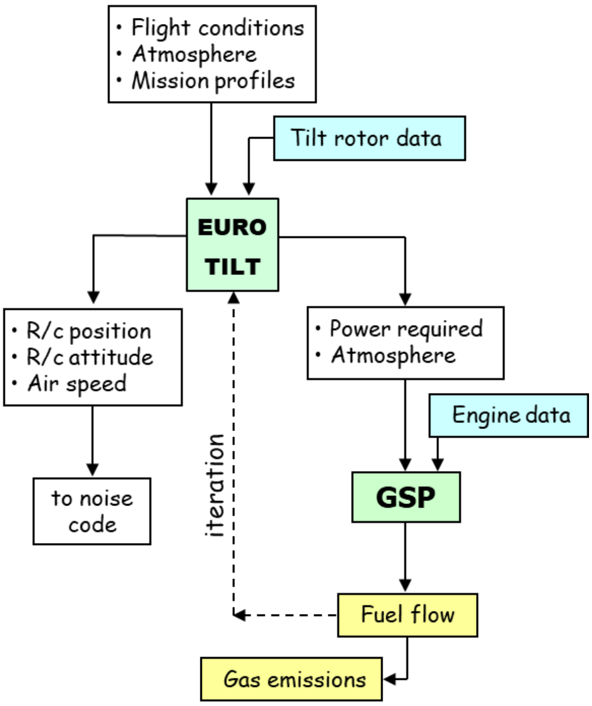

***Figure 1** Flow diagram for EUROTILT in combination with GSP and a noise code*

3.1.2. Compound rotorcraft

The integrated Coaxial Rotorcraft Performance Model (CRPM) [Refs. 16, 17] is employed in the context of this work. The CRPM utilizes the steady-state non-linear blade element momentum theory to model the rotors and propeller as infinitely thin disks. The rotor inflow utilizes first order dynamic inflow in the form of Pitt and Peters model, with the influence between rotors estimated using an analytical model [Ref. 16]. The controls required to trim the rotorcraft are obtained using a Newton-Raphson method [Ref. 16].

Turboshaft engine performance is incorporated within the CRPM framework to provide fuel flow and residual thrust modelling. The model used (Turbomatch) has been developed and extensively validated at CU for rotorcraft turboshaft applications, including the T700-GE-700 utilized for the compound rotorcraft [Ref. 18]. Turbomatch utilizes zero-dimensional aero-thermal analysis, and is capable of design and off-design point analysis.

These models are incorporated within a mission analysis framework which includes a WGS-84 flight path model to enable assessments of realistic rotorcraft operational scenarios.

3.2. Gaseous emissions models

3.2.1. Tilt rotor aircraft

The Gas turbine Simulation Program (GSP) is used to compute the fuel burn, exhaust gas emissions and power available in a coupled simulation with the EUROTILT code (Figure 1). GSP retrieves the power required and the atmospheric data from EUROTILT and uses characteristic engine data from its database.

GSP is an in-house tool developed by NLR to simulate gas turbine thermodynamic cycles for engine performance and exhaust gas emissions. It can handle any type of gas turbine engine configuration in both steady state and transient calculations, thereby taking into account inlet conditions, losses and deterioration.

Basically GSP implements a zero dimensional engine model (with a one dimensional combustion chamber model). To enable calculations for low NO_x combustion chambers a so-called multi-reactor combustion model can be used, in which the combustion chamber liner volume is divided into an array of reactors. Each reactor can comprise the gas flow coming from the previous reactor, fuel flow, oxidizer flow and (injected) water/steam flow. These flows are assumed to mix instantaneously and reach equilibrium at reactor exit. Both instantaneous emission formation in the flame and gradual emission formation throughout the combustion chamber are accounted for in the emissions model. Equilibrium temperature, composition and actual emission concentration at every reactor exit are numerically integrated to obtain the emission formation rates.

For helicopter engines GSP has been validated against the Swiss Federal Office of Civil Aviation (FOCA) database [Ref. 19], demonstrating a good level of accuracy.

3.2.2. Compound rotorcraft

Hephaestus is a gaseous emission prediction software developed for civil aero-engines, and extended for turboshaft engines [Refs. 20, 21]. The model is based on a stirred reactor concept combined with simplified chemical reaction equations. The specific combustor geometry is accounted for and must be defined in terms of primary, intermediate, and dilution zone volumes, in addition to the air mass-flow fractions. The emission indices may therefore be calculated for any given operating conditions.

Although this model differs from GSP, which is used for both the tilt rotor aircraft and reference helicopter simulations, similar physics-based modelling is used, involving arrays of stirred reactors to represent the combustion chamber. In addition, both models have been validated against the Swiss FOCA database [Ref. 19], demonstrating similar levels of accuracy and therefore their fidelity is considered equivalent. The engine selected for the compound rotorcraft is the T700-GE-700 and previous validations of Hephaestus predictions for this engine are presented in [Ref. 21].

3.3. Noise impact models

Under an EU DG-MOVE contract a state-of-the-art methodology to model noise emissions of helicopter operations was developed by NLR and Anotec. This new model NORAH (NOise of Rotorcraft Assessed by a Hemisphere-approach) is aimed at filling the gap that existed in the European aviation environmental noise modelling suite. A detailed overview of NORAH is given in [Ref. 22]. It leverages the knowledge obtained during the development of the HELENA model in the FRIENDCOPTER project and its subsequent application in the CS-TE PhoeniX platform. NORAH contains a database of measured helicopter noise levels representative for those classes of helicopters covering around 80% of the European rotorcraft operations. For each class a source noise description based on hemispheres is provided for a range of operational conditions, which allows the model to calculate the noise for real-life operations.

Since the source description is on a (1/3 octave) spectral basis, more realistic propagation effects can be calculated. For a given heliport/helipad, flight profiles can be constructed by means of segments, each with an assigned state, corresponding to one of the flight conditions for which noise hemispheres are available. These flight profiles are then mapped on user defined ground tracks, thus obtaining a full 3D description of the flight path. Based on this input the model calculates the noise on a user defined observer grid. Since spectral information is available at the observer position, a wide variety of noise metrics can be calculated. This output can then be combined with population maps to determine the number of people affected by different noise levels.

For DEPART2050, NORAH has been adapted to be able to handle the specific characteristics of tilt rotor aircraft and compound rotorcraft. Noise hemispheres will be provided by the OEMs for their aircraft, while capabilities for hemisphere generation for the alternative (generic) concepts will be developed for future assessments.

For the ATS noise assessment the NENA model will be used. This model was originally developed by Anotec within the FP7 NINHA project, with the objective to assess the noise impact of open-rotor aircraft, in the en-route phase of flight [Ref. 23]. This model allows for wide area noise impact assessments within a reasonable calculation time. It calculates the population exposed to noise for a variety of noise metrics. The input to NENA mainly consists of 3D flight tracks for the cruise phase and a database with overall noise (e.g. Sound Exposure Level, SEL) as a function of distance. NENA will be adapted to the specifics of rotorcraft noise, by adding directivity in the noise database. This database will be generated by a dedicated use of NORAH for the specific cruise conditions.

3.4. Mobility impact models

OAG Missions. Helicopter air traffic data related to a particular operational zone (in a specified time period) is retrieved from the FlightRadar24 online platform. Data on the number of flights and helicopter flight trajectories is used to simulate a typical business day. In order to compare conventional helicopter and FRC performance from a mobility standpoint, it is necessary to simulate FRC missions in the same operational scenario. A flight path model is thus used for the estimation of the FRC travel time for each mission. In the FRC flight simulations, each mission has one or more legs (more than one oil platform may be served by a single flight). Each leg is modelled with five segments (Figure 2): take-off, climb, cruise, descent and landing. In this way it is possible to predict how a partial or total replacement of conventional helicopter fleets with FRC fleets will change the operating scenario.

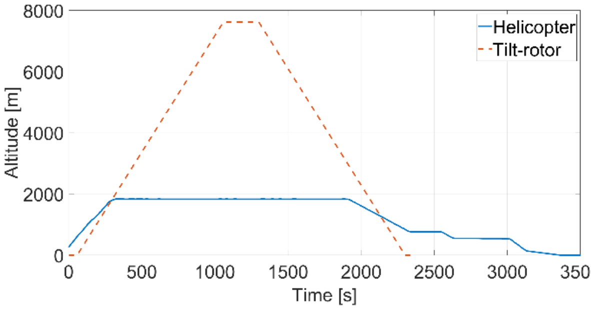

***Figure 2** Real helicopter mission vs tilt rotor simulated mission*

PAT Missions. The goal of passenger transport modelling is to compare both compound and tilt rotor with different transport modes and to identify the most convenient mode depending on the mission type. The modes chosen for comparison with both FRCs are car, airplane and ground public transport. A travel time model was developed to estimate the total duration of a passenger’s journey from origin to destination. The following journey components are used to calculate total journey travel time:

Airport/Heliport waiting time: the time a passenger has to wait inside origin and destination airports/heliports;

Airport/Heliport access time: the time a passenger spends going to or coming from the airport/heliport by car or by taxi. This time is calculated case by case using Google Maps API (Application Programming Interface) services;

FRC flight time: the time a passenger spends in an FRC flight (computed through simulation);

Airplane flight time: the time a passenger spends in a commercial scheduled flight. A database developed by DLR has been used as source for the flight schedules. The DLR database includes travel time matrices for different combinations of means of transportation within the European region [Ref. 24];

Connection time: the time a passenger needs to get to the gate of his next flight after landing of his previous flight;

Car travel time: the time needed to get to the destination by car. It is calculated by using Google

Maps API services. The quickest path travelled during low traffic hours is chosen;

Public transport travel time: the time needed to get to the destination by public transport. It is again calculated by using Google Maps API services.

4. ASSESSMENT RESULTS

Due to the current status of the project the assessment results in this chapter are to be considered as preliminary data and the amount of results is limited. The values may change when the designs and models mature in the coming years, and more results, especially under various operational conditions, will become available then.

4.1. Gaseous emissions

4.1.1. Tilt rotor aircraft

As an example some preliminary results obtained for TEM-B and the tilt rotor aircraft conducting the OAG mission are shown in Table 8 (total fuel consumption, CO_2, and NO_X emissions, along with their normalized metrics) and Figure 3 (flight altitude and fuel flow during the mission).

***Table 8** Tilt rotor aircraft OAG results*

		TEM-B	**Tilt rotor**
Distance	km	1060	1060
Passengers	-	11	16
V_{Cruise}	m/s	62	129
Mission time	minutes	325	160
Total fuel	Kg	1329	1539
Total CO_2	Kg	4156	4896
Total NO_X	Kg	8.352	(22.347)
Fuel	kg/pax*km	0.114	0.091
CO2	kg/pax*km	0.356	0.289
NO_X	g/pax*km	0.716	(1.318)

Table 8 provides total fuel consumption, CO_2 and NO_X emissions, plus their normalized metrics. Each rotorcraft is carrying the maximum possible payload for the specific mission. To transport the same amount of payload, more than one TEM-B will be needed, resulting in equally increased total fuel burn, and total CO_2 and NO_X output. The normalized assessment metrics are not influenced by the number of rotorcraft involved. All results are to be considered as preliminary data that may change in the coming years. This is especially true for the tilt rotor NO_X results for which an improved model, reflecting the expected technology level with a low NO_X combustion chamber, is still under development.

Figure 3a demonstrates a clear benefit in mission time (about 51%) for the generic tilt rotor aircraft due to its higher flight speed. As is illustrated in Figure 3b the tilt rotor fuel flow is considerably higher (more than doubled in cruise conditions), but due to the shorter mission time and higher payload the normalized fuel burned and CO_2 emissions are lower (about 20%). The normalized NO_X emissions show an adverse effect for the tilt rotor aircraft, which is due to the engine model. This will change in future assessments when the improved NO_X emissions simulation model will become available.

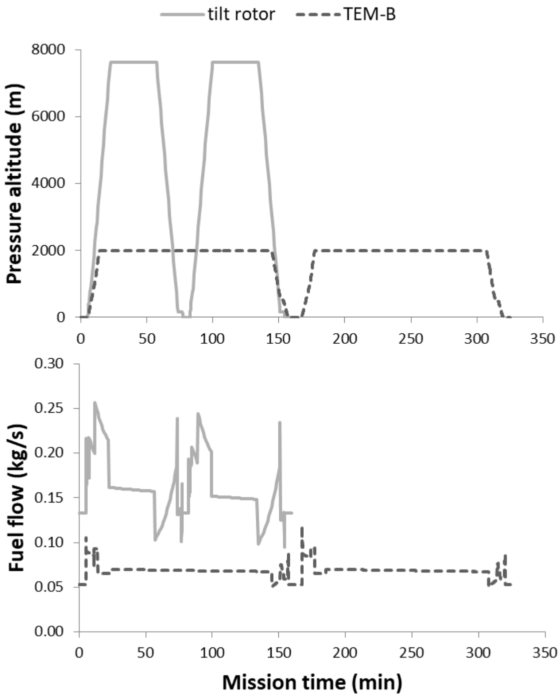

***Figure 3** Tilt rotor and TEM-B OAG mission pressure altitude and fuel flow*

4.1.2. Compound rotorcraft

The results obtained for TEM-B and the compound rotorcraft conducting the PAT-CIT mission are shown in Table 9 and Figure 4. Table 9 presents total fuel consumption, CO_2, and NO_X emissions, along with their normalized metrics, while Figure 4 illustrates the fuel flow and NO_X production rates during the mission.

Figure 4a demonstrates that the fuel flow of the coaxial compound is significantly higher throughout the mission, however, due to the decrease in overall mission time the cumulative fuel consumption increases by only 19%. This is expected due to the increase in flight speed and payload capacity, which is reflected in the normalized metric demonstrating an 11% improvement.

Table 9 *Compound rotorcraft PAT-CIT results*

		TEM-B	Compound
Distance	km	342	342
Passengers	-	12	16
V_{Cruise}	m/s	62	105
Mission time	minutes	102	64
Total fuel	kg	415	492
Total CO_2	kg	1297	1550
Total NO_X	kg	2.585	2.298
Fuel	kg/pax*km	0.101	0.090
CO2	kg/pax*km	0.316	0.283
NO_X	g/pax*km	0.630	0.420

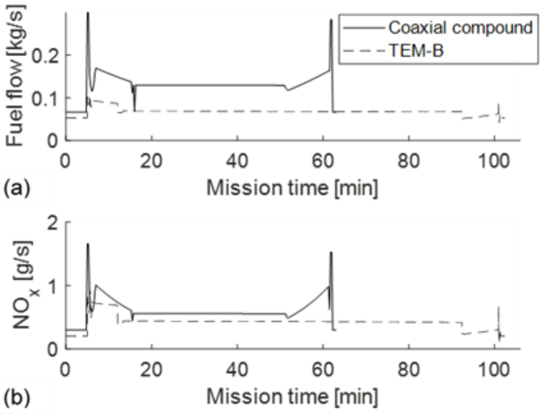

Figure 4 *Compound and TEM-B PAT-CIT mission fuel and NO_X rates*

The compound rotorcraft NO_X rate illustrated in Figure 4b is only slightly higher than the TEM-B during cruise. This is apparent in the total NO_X emissions reducing by 11%, with a 33% improvement in the normalized metric. These improvements are notably higher than for fuel consumption, but may be attributed to the increase in cruise altitude. As altitude increases the ambient air temperature, air density and pressure reduce. This leads to aerodynamic benefits, predominantly through reduced parasitic drag, but also engine performance benefits resulting from reduced combustor inlet temperature, pressure and air flow. These effects have been examined in detail with Turbomatch and Hephaestus for the T700-GE-700 [Ref. 18], demonstrating considerable reductions in NO_X production rates with increasing altitude.

4.2. Noise impact

At this stage of the project no noise hemispheres are available for the fast rotorcraft considered in this project. Therefore no results for the noise impact are yet available.

4.3. Mobility impact

4.3.1. Tilt rotor aircraft

In order to understand tilt rotor potential in improving mobility performance, comparisons have been made between conventional transport modes (car, public transport, and airplane) and tilt rotor mode for different mission types.

OAG Missions. Two reference heliports in the North Sea have been chosen for the analysis: Aberdeen and Stavanger. For each of the two locations the objective of the study is to estimate helicopter traffic, obtain route data related to each single flight, simulate the same flights with a tilt rotor as operating aircraft and, finally, compare the two types of rotorcraft in terms of travel time. The simulated helicopter routes are plotted in Figure 5.

Figure 5 *Simulated helicopter traffic*

Multiplying travel time by passenger number makes it possible to obtain the total man-hours spent in flight during one business day. These are reported in Table 10 for both the helicopter case (employing real observed data) and the tilt rotor case (using simulated data). The tilt rotor travel times are consistently lower than the conventional helicopter ones and time benefits become higher for longer missions. This translates into flight productivity improvements: the total man-hour gains are 37.6% for Aberdeen and 37.1% for Stavanger.

Table 10 *Total Man-hours lost in flight (1 day)*

Location	Total man-hours lost in flight (helicopter)	Total man-hours lost in flight (tilt rotor)	Man-hours gained
Aberdeen	940.8	586.8	-354.0 (-37.6%)
Stavanger	631.4	397.0	-234.4 (-37.1%)

PAT-AHF Missions. Another possible use of the tilt rotor is to operate as a hub feeder, therefore easing congestion and freeing up slots at crowded airports. Figure 6 illustrates travel time benefits given by the tilt rotor for some typical AHF missions.

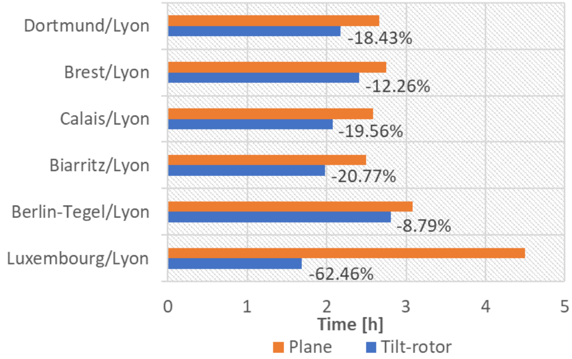

Figure 6 *Travel time comparison tilt rotor vs other air transport modes for PAT-AHF missions*

The numbers demonstrate that all tilt rotor missions present an advantage with respect to traditional aviation. AHF missions operated by a tilt rotor will be useful primarily for those city pairs which are not already served by a direct airplane connection.

PAT-CIT Missions. One of the possible uses of the tilt rotor is to operate as an alternative in medium range distance intercity transport, where traditional aviation and public transport may have similar or higher total travel times. As illustrated in Figure 7, in all the mission simulations the tilt rotor aircraft always gets a large reduction in total travel time, compared to all the other means of transport.

The least reduction is observed for the Monaco-Frankfurt city pair, which is about 30%. It has to be noted that the ACARE mobility goal for 2050 (max 4h duration for a travel inside the EU) is attained in tilt rotor mode for all city pairs, whereas with conventional aviation 4 out of 6 city pairs do not reach the target.

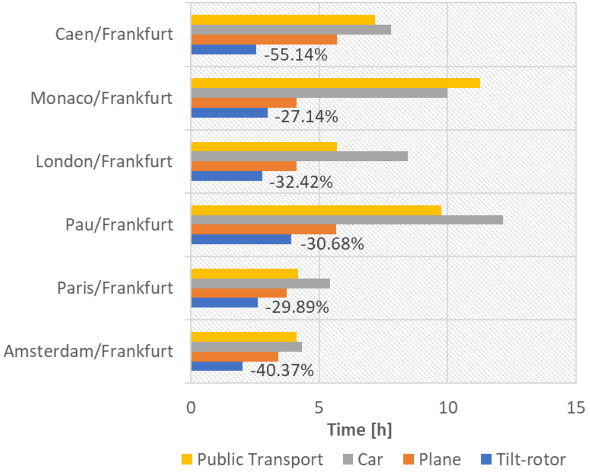

Figure 7 *Travel time comparison tilt rotor vs other transport modes for PAT-CIT missions*

4.3.2. Compound rotorcraft

Compound rotorcraft can be useful in reducing travel time with respect to other conventional transport modes. The assessment has been carried out on different PAT missions.

PAT-AHF Missions. The potential of utilization of compound rotorcraft for airport hub feeder missions is investigated: the chosen hub airport is Manchester airport. Figure 8 presents the time benefits for the compound rotorcraft: time benefits between 27% and 61% are observed.

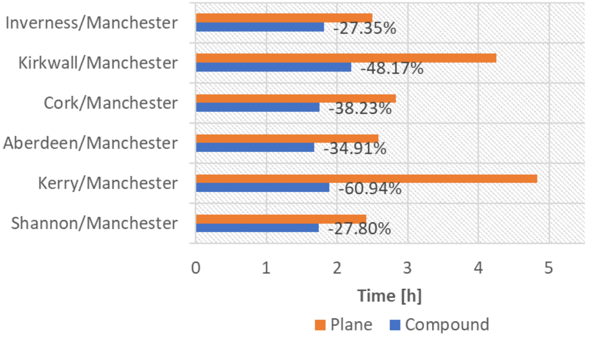

Figure 8 *Travel time comparison compound vs other air transport modes for PAT-AHF missions*

PAT-CIT Missions. The goal of the analysis is to estimate the possible travel benefits arising from the connection of medium to large Italian cities with Rome. It is noted that half of the city pairs have a good train connection, which makes ground public transport a good alternative to air transport. In all the city pairs the compound rotorcraft represents the best choice in terms of travel time, with time reductions between 18% and 42% as shown in Figure 9.

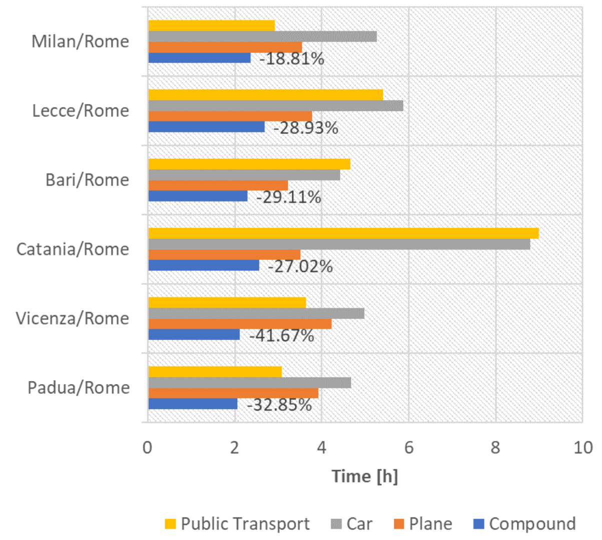

***Figure 9** Travel time comparison compound vs other transport modes for PAT-CIT missions*

PAT-DTD Missions. The compound door-to-door missions represent a possible air-taxi service able to improve the accessibility of remote locations. The goal of the analysis is to find how regional and trans-regional connections can be improved. Due to the short range of the defined missions (235 km max), the compound rotorcraft missions are compared with car and public transport only. Considerable time reductions occur when the compound rotorcraft competes directly with ground transportation: all the missions are operated in about one hour, whereas the other two modes usually need 2.5-3 hours. The relative time reductions lie within 56% and 67%, as shown in Figure 10.

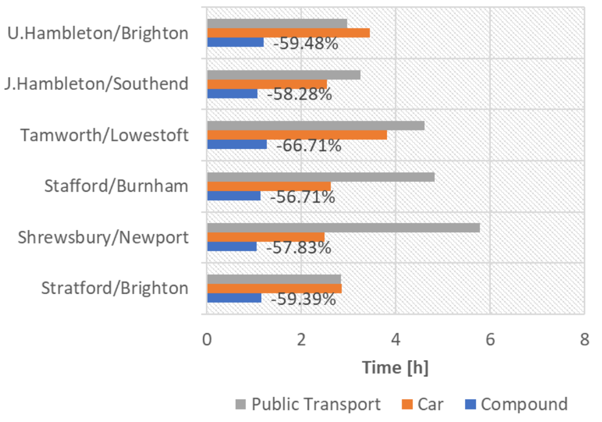

***Figure 10** Travel time comparison compound vs other transport modes for PAT-DTD missions*

5. RESULTS AND WAY FORWARD

Within the DEPART2050 project, two generic fast rotorcraft configurations (tilt rotor aircraft and compound rotorcraft) have been defined and the models set up. Assessment metrics and a range of representative mission scenarios have been established.

Initial assessments for fuel consumption and exhaust gas emissions show that the set-up is viable and that initial results are in line with expectations. Considerable reductions in time and normalized CO_2 emission can be found for fast rotorcraft relative to conventional helicopters. More work is required to come to actual and final conclusions.

Assessments have also been performed for mobility impact. The results clearly show time benefits due to the higher cruise speeds of the fast rotorcraft. But also large reductions in total travel time are apparent when compared to other means of transportation.

As noise hemispheres are not available in this phase of the project, noise impact assessments have not been performed yet.

The project will run till late 2021 and additional results will become available in due time. Future work will include the development of an engine model featuring a low NOx combustor for the tilt rotor aircraft, the enhancement of capabilities of the fast rotorcraft models, and the development of noise hemispheres. The adaption of NENA noise impact model to the NORAH standard will also be carried out in order to speed up the calculation of noise footprints and include affected population.

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