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Achieving Rotorcraft Noise and Emissions Reduction for 'Clean Sky' – The Measurement of Success

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1 ABSTRACT

This paper describes the work done and strong interaction between Cranfield University as member of the Technology Evaluator (TE) team, Green Rotorcraft (GRC) Integrated Technology Demonstrator (ITD) and Sustainable and Green Engine (SAGE) ITD of the Clean Sky Joint Technology Initiative (JTI). The aim of Clean Sky is to develop and integrate new and innovative technologies that will help meeting the emission and noise reduction targets set by the Advisory Council for Aviation Research and Innovation in Europe (ACARE) for aircraft of next generation. The GRC and SAGE ITDs are responsible for developing new helicopter airframe and engine technologies respectively, whilst the TE has the distinctive role of assessing the environmental impact of these technologies at single flight (mission), airport and Air Transport System levels (ATS). Cranfield University as a member of the TE is responsible for the mission trajectory definition and for conducting the environmental performance assessments. The assessments reported herein have been performed by using a GRC-developed multi-disciplinary simulation framework called PhoeniX (Platform Hosting Operational and Environmental Investigations for Rotorcraft) that comprises various computational modules. These modules include a rotorcraft performance code (EUROPA), an engine performance and emissions simulation tool (GSP) and a noise prediction code (HELENA). PhoeniX can predict the performance of a helicopter along a prescribed 4D trajectory offering a complete helicopter mission analysis. In the context of the TE assessments reported herein, three helicopter classes are examined, namely a Twin Engine Light (TEL) configuration, for Emergency Medical Service (EMS) and Police missions, and a Single Engine Light (SEL) configuration for Passenger/Transport missions, and a Twin Engine Heavy (TEH) configuration for Oil & Gas missions. The different technologies assessed reflect three simulation points which are the 'Baseline' Year 2000 technology, 'Reference' Y2020 technology, without Clean Sky benefits, and finally the 'Conceptual', reflecting Y2020 technology with Clean Sky benefits. The results of this study illustrate the potential that incorporated technologies possess in terms of improving performance and gas emission metrics such as fuel burn, CO2, NOx as well as the noise footprint on the ground.

2 INTRODUCTION

The helicopter emerged in the first 30 years of the 20th century. Since then, the helicopter has demonstrated its diversity and versatility in terms of the operations that it can be used as a means of transportation. Helicopter operations are performed worldwide in different industries and for various purposes in order to accommodate a plethora of services. Helicopters contribute and shorten the required time for such activities as Emergency Medical Services (EMS), Search and Rescue (SAR) as well as fire fighting. Also, helicopters are used for the purposes of police enforcement as well as daily transportation of people and/or goods. An industry which is characterized by a strong presence of helicopter operations is the Oil and Gas industry. Oil and gas are extracted in isolated locations either offshore or onshore and helicopter operations play a crucial role in passenger, personnel and goods transfer. A typical amount of people transferred per year, between ships and platforms (for one helicopter operator) which constitute offshore workplaces, is more than one million [14]. As the oil and gas companies seek to go further in order to explore and produce oil and gas [15] the helicopter's crucial role in the industry will increase accordingly.

The example of the Oil and Gas industry denotes that the technological growth and evolution of modern societies has created a need for continuous and faster transportation of people and goods. However, this need has also caused the necessity of additional energy resources which are mainly petroleum based. The limitations of the current petroleum extraction technologies [1] as well as the environmental impact of the emitted pollutants have paved the way towards a global philosophy of drastically reducing the pollutants caused by fossil fuel combustion, hence creating innovative greener technologies which will be more efficient and environmentally friendly.

Thus, it can be acknowledged that the demand of transportation is increasing gradually day after day. Thus, the projected growth of helicopter activities, which reflect the rise in transportation needs, demands improvements in terms of fuel consumption, emissions as well as emitted noise. The Advisory Council for Aeronautics Research in Europe (ACARE) has established specific environmental goals to be met by the civil aviation industry (including rotorcraft and aircraft) by the year 2020. These have as an aim to sustain aviation’s present environmental impact after the expected aircraft and rotorcraft fleet growth. The ACARE goals have been defined as [2]:

- 50% reduction in CO_2 emissions by reducing the fuel consumption
- 80% reduction in NO_x emissions
- Reduction of perceived external noise by 50%
- A green product life cycle design, manufacturing, maintenance and disposal recycling

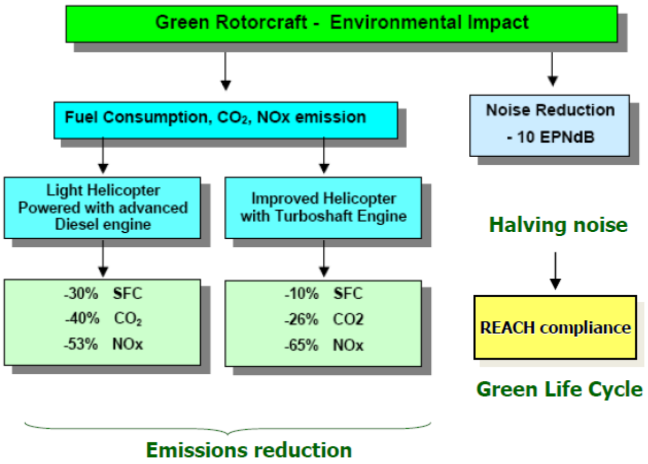


Figure 1 Expected GRC contribution with respect to the ACARE 2020 goals [2]

The Clean Sky Joint Undertaking which is a public private partnership between the European Commission and the aeronautical industry was initiated in order to deliver significant changes with regards to the environmental impact of aviation. Clean Sky will help to speed up and propagate high quality research within Europe with the ultimate goal of delivering new and more environmentally friendly technologies that will be used in future aircraft and rotorcraft.

Clean Sky consists of several ITDs which correspond to new aircraft, rotorcraft and engine technologies and each has the aim to work towards to satisfy the ACARE goals as they have been previously defined. This paper focuses only on the work done on new rotorcraft technologies and more specifically on the collaboration between the GRC and SAGE ITDs and the TE. The TE is a central body within Clean Sky responsible for carrying out all environmental impact assessments in an impartial and consistent manner. Within this paper, the TE team is represented by Cranfield

University with responsibility for the mission trajectory definition and for conducting the environmental performance assessments

The ACARE goals have set indicative milestones to be met by the aviation industry. The GRC ITD's contribution with the current new technologies, in terms of absolute figures, is illustrated in Figure 1. These goals have set the context and the necessity of researching and developing innovative green rotorcraft technologies and concepts. In response to the aforementioned, the GRC ITD is divided into 7 distinct subprojects which reflect all the different thematic areas where helicopter technologies can be improved. These areas span from external aerodynamics to the design of new electrical systems, the design and deployment of new rotorcraft blades and the implementation of concepts such as the active blade twist and Active Gurney Flap (AGF). Other activities include airframe drag reduction studies using advanced Computational Fluid Dynamics tools, as well as wind tunnel experiments. GRC7 in particular has as a main task to provide an interface between the GRC ITD and the TE as well as to ensure that rotorcraft operations and technologies are represented in a realistic manner in the TE assessments. As mentioned before, the TE has the distinctive role of assessing the environmental impact of the newly developed technologies.

Today's latest aircraft in service (A380 and B787) and in production (A350, C-Series) show both an outstanding level of performance and a reduced impact on the environment. This is the result of a continuous improvement of the airframe and engine design in particular.

However, such performance improvements have been achieved thanks to the progressive mastering by engineers of the different interactions between systems and disciplines and a continued application of the classical iterative engineering approach, rather than by the implementation of a systematic Multidisciplinary design optimization (MDO) approach. The required step changes in performance, especially those concerning environmental impact, cannot be achieved without the development and implementation of new design methods and tools that take into consideration and exploit the various multi-disciplinary synergies in order to optimize the complete product (aircraft, rotorcraft, other) and its sub-systems according to specific criteria. MDO can provide designers with the means to further improve the performance of already mature solutions and support the exploration of innovative complex designs. However, the application of MDO to such complex cases is not feasible without the prior development of suitable methods and tools to handle high dimensional, heterogeneous product models and knowledge and provide efficient means for collaborative distributed design.

3 METHODOLOGY

For the purposes of assessing the environmental impact of the technologies that have been developed within the GRC ITD an integrated multi-disciplinary framework has been created. This framework is called PhoeniX and federates amongst others three distinct computational tools:

- **EUROPA**: A rotorcraft flight mechanics code
- **GSP**: A gas turbine engine performance simulation and gas emissions calculation tool [8]. In later assessments GSP has been replaced with the Turbomeca engine model.
- **Turbomeca Engine Model**: Engine model developed by TM providing a similar function to the GSP with exception to the conceptual model, representing in detail their innovative low NO_x combustor technology.
- **HELENA**: A rotorcraft environmental noise analysis tool.

The above three tools have been integrated into a single computational platform called OPTIMUS [9] provided by LMS Intl. and NOESIS Solutions. OPTIMUS is a process integration simulation framework and it establishes a proper workflow between the aforementioned computational tools. In addition, engine decks provided by Turbomeca through the SAGE ITD, have also been successfully integrated into PhoeniX and will be used in later assessments. An architectural overview of PhoeniX is illustrated in Figure 2.

3.1 European Rotorcraft Performance Analysis code (EUROPA)

EUROPA (EUropean ROtorcraft Performance Analysis) is a helicopter flight mechanics code, designed to calculate helicopter steady state (trim) and dynamic (manoeuvre) performance. It is ideally suited to determine (optimized) take-off and landing flight paths. The code was developed and validated in the European RESPECT project [10]. A version dedicated to tilt rotor aircraft was developed in the European NICETRIP project [7]. EUROPA utilizes the steady-state linear Blade Element Momentum Theory (BEMT) and the rotor is assumed to be an infinite thin disk (actuator disk theory). EUROPA assumes that the rotor is a rigid body thus elastic phenomena are not modeled. The flight mechanics simulation generates a helicopter's trajectory in order to analyze the performance and the environmental impact, in terms of gas emissions and noise, of existing helicopter configurations in a range of flight conditions. Its scope is to contribute to the development of new designs and to assess the feasibility of various design alternatives for the purpose of minimizing the noise and the environmental impact. The helicopter is handled dynamically during take-off and landing phases while it is assumed to be operating in trim during cruise and climb/descent segments. The code has been validated using flight test data for trim performance and dynamic response [11]. EUROPA uses a generic helicopter mission description where properties such as flight conditions, atmospheric conditions and helicopter data are defined by the user. The helicopter flight path is truncated in a number of flight segments, with each segment containing information such as position, altitude, tip path plane angles etc. as a function of time. EUROPA provides this information to the other tools for noise and gas emissions calculations along each segment of the trajectory.

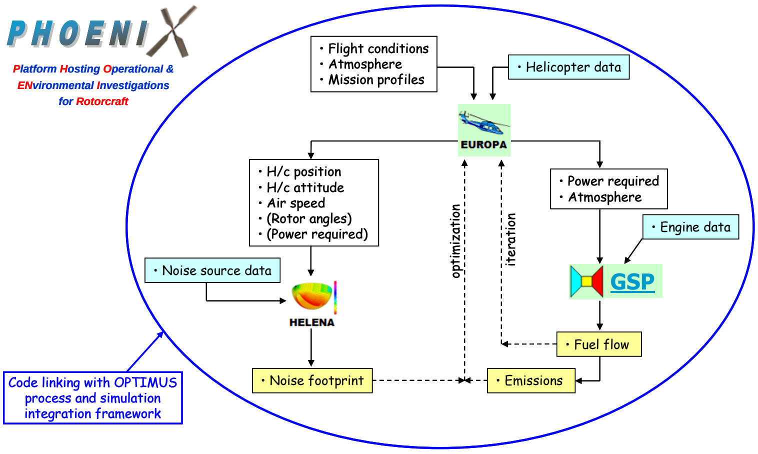


Figure 2 PhoeniX architectural overview

3.2 Gas Turbine Simulation Program (GSP)

The second tool integrated in the PhoeniX platform is the Gas turbine Simulation Program (GSP) [12]. GSP is an in-house tool developed by NLR to simulate gas turbine thermodynamic cycles for engine performance (fuel flow, power) and exhaust gas emissions. GSP implements a zero dimensional engine model (with a one dimensional combustion chamber model) and can model any type of gas turbine engine configuration. It can handle both steady state and transient calculations taking into account inlet conditions, losses and deterioration.

Within the PhoeniX framework, GSP is used to compute the gas emissions, the power available and the fuel flow for mission mass calculation in a coupled simulation with the EUROPA code. In this case, GSP retrieves the power required and the atmospheric data from EUROPA and uses also the engine data from the database. With these data at each instant in time, GSP determines the fuel consumption for mission mass calculation and generates exhaust gas emissions. For the purposes of this work the engine is assumed to be operating at steady-state conditions.

3.3 Turbomeca Engine Model

As planned, GSP was subsequently replaced by an engine model developed by Turbomeca working within SAGE5 ITD. This tool works in a similar fashion to GSP. It is used to simulate engine performance and exhaust gas emissions. However in addition, the conceptual model is enhanced by a more accurate representation of the SAGE5 innovative low NO_x combustion technology which will be introduced later.

As far as the integration of the models within PhoeniX is concerned, it is identical to GSP. The engine model will receive atmospheric data from EUROPA and will apply engine data provided by a database.

3.4 Helicopter Environmental Noise Analysis (HELENA)

In order to assess the noise footprint of the flown trajectory computed by EUROPA, the HELENA tool has been used. The HELENA tool was developed within the FRIENDCOPTER [6] research project and is capable of computing and generating noise footprints on the ground starting from experimental or numerical (CFD) based helicopter noise databases [13].

The noise propagation models used in HELENA have been specifically tailored for rotorcraft noise (that is very different from aircraft generated noise) and take into account also propagation distance, atmospheric absorption effects and ground reflection. HELENA has been validated with dedicated flight tests. As a result of the analysis of the trajectory data received by EUROPA, HELENA computes the noise level at the ground for each trajectory segment. For the current calculations, the noise footprints were expressed in Sound Exposure Level (SEL) (symbol - LAE). The LAE metric is the symbol abbreviation for Sound Exposure Level. It is the most common measure of cumulative noise exposure for a single rotorcraft flyover. Mathematically, is defined as the level, in decibels, of the time integral of squared 'A'- weighted sound pressure (Pa) over a given time period or event, with reference to the square of the standard reference sound pressure (P_0) of 20 μPa and a reference duration of one second. This unit is defined by the expression:

$$L_{AE} = 10\log_{10}\left[\int_{t1}^{t2}\left(\frac{P_A(t)}{P_0}\right)^2 dt\right] \ (dB) \tag{1}$$

In HELENA t2 and t1 are defined as the instances at which the A-weighted Sound Pressure Level decreases 10dB below the maximum level.

3.5 OPTIMUS Simulation Framework Toolkit

The federation of the aforementioned simulation tools has been carried out with OPTIMUS [9]. OPTIMUS is a simulation framework toolkit and a flexible design environment which can be used to create multidisciplinary simulation frameworks and to evaluate multiple design alternatives. OPTIMUS can be used to translate the logical elements and relations of a multidisciplinary simulation process into an actionable computational framework that can automatically execute a number of calculation steps without user's intervention.

Having its own integrated variety of optimization sequences ranging from single-objective local optimization to multi-objective global optimization methods, OPTIMUS can be used also for trade-off and optimization studies. The OPTIMUS implementation of the PhoeniX framework allows the execution of the multidisciplinary workflow for each helicopter mission profile and helicopter class defined. Each mission is defined by a set of flight and helicopter conditions that can be changed at every experiment and are identified by a set of values of the input parameters. A typical assessment of a rotorcraft's noise and gas emissions over a single mission and for a given set of inputs would involve the following operations:

- The EUROPA code accepts the helicopter data, the mission profile, the flight and the atmosphere conditions as input. Based on these user defined conditions, the EUROPA code then calculates a flight path divided into different segments. For each segment, the EUROPA code then returns the helicopter's position, the time to reach the position, the attitude and tip path plane angles, the power required and the atmospheric conditions.
- The GSP/TM engine code is coupled inside EUROPA: for each time segment calculated by EUROPA, the GSP code retrieves the information about the atmospheric conditions (pressure and temperature) and the power required. It uses this information to calculate the fuel burnt and the emissions' quantity of CO, CO_2, H_2O, NO_X, UHC and Smoke Number produced during every segment. Turbomeca's engine model provides only the fuel burnt, CO_2 and NO_x. After the

successful convergence of the mission fuel by EUROPA and GSP, OPTIMUS extracts these results and post processes them to produce the total quantities of fuel burnt and polluting gases generated during the entire trajectory.

- After the successful convergence of the mission fuel by EUROPA and GSP/TM, OPTIMUS also automatically reads EUROPA's trajectory output file and passes this data to HELENA in the appropriate format in order to perform the noise assessment. HELENA then determines the noise footprints for the given flight conditions. After the level of the SEL noise metrics have been calculated for each segment, OPTIMUS extracts the results and collects the data needed for further analyses.

It is worth pointing out that EUROPA, as a comprehensive rotorcraft flight mechanics code, works in a rather modular fashion. To be more specific, the performances of individual rotorcraft components such as the main rotor, tail rotor, fuselage, empennage and the engine are calculated in an integrated manner. The ultimate goal is to provide the performance of a rotorcraft during its specific mission. In PhoeniX, it is possible to define a complete mission in terms of WGS 84 coordinates. Thus, a realistic mission with a complete flight trajectory can be designed and the helicopter's performance can be assessed during all possible flight segments such as hover, take off, cruise, loiter, descent, and landing.

3.6 Helicopter Classes and Configurations

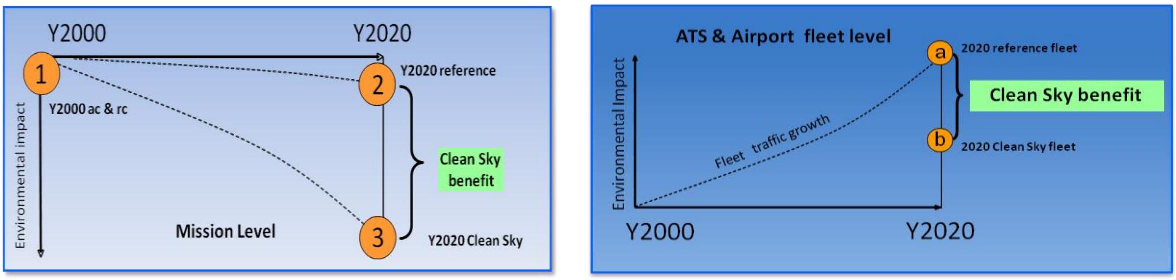
The main goal of the Clean Sky TE is to assess and compare three different helicopter technologies which are the Baseline (Year 2000), Reference (Y2020) and Conceptual Clean Sky (Y2020). The Baseline configurations correspond to existing technology and concepts which were built until the year 2000. Reference and Conceptual configurations correspond to projected technologies up until the year 2020 without and with Clean Sky benefits respectively. The technological benefits which are acquired through the research done within the GRC ITD are implicitly expressed into the specifications of the individual helicopter components. For example, a Conceptual helicopter will have a reduced profile drag coefficient compared to a Reference and Baseline configuration. These changes in such coefficients as the drag coefficient result to differences in fuel burn, CO_2, NO_x and noise emitted across the three helicopter configurations. In the context of the TE assessments the following 3 generic rotorcraft classes have been defined amongst others:

- Single Engine Light (SEL) with MTOW ≤ 4 metric tons
- Twin Engine Light (TEL) with MTOW ≤ 4 metric tons
- Twin Engine Heavy (TEH) with MTOW > 8 metric tons

3.7 TE assessment points

The TE assessments have been performed at three different levels, as depicted in Figure 3, in order to represent as realistically as possible the environmental impact of the new rotorcraft technologies. The three levels of assessments are the following:

- Mission Level: The environmental impact of the three configurations is assessed only at a single flight level which represents one mission of a helicopter on a specific day.
- Airport or Operational Level: This level represents a typical day around a specific airport or heliport where the helicopter operates i.e. it corresponds to the helicopter traffic encountered at the assessed airport/heliport. For obtaining the helicopter performance at operational level, 5 different missions have been defined around the same geographical location. It is assumed that these 5 missions represent the helicopter traffic of a whole day.
- Air Transport System (ATS) Level: The aforementioned missions at operational level are averaged in terms of range in order to derive a single 'representative' mission which will reflect the macroscopic scale to the whole amount of rotorcraft flying all around the world.



(a) Mission Level (b) Operational & ATS level

Figure 3 Environmental impact of the three assessment levels

3.8 Rotorcraft Technology Assessment

In the context of this assessment four helicopter missions/categories were defined:

- An EMS mission which corresponds to the TEL helicopter class
- A Police mission which corresponds to the TEL helicopter class
- A Passenger/Transport mission which corresponds to the SEL helicopter class
- An Oil & Gas mission which corresponds to the TEH helicopter class

It is worth pointing out that the helicopter classes mentioned above were not allocated to the specified missions by means of applicability e.g. a police mission can be performed by a SEL helicopter as well. The allocated helicopter classes were chosen based on the European rotorcraft fleet distribution. For every assessed helicopter mission two scenarios were defined in order to represent in the best possible way fuel burn/emissions reductions as well as noise reductions. The two scenarios are the following:

- Fuel Economy Scenario: In this scenario the helicopter flies in straight segments in order to minimize fuel consumption.
- Population Avoidance Scenario: In this scenario the helicopter flies neighborly in order to avoid flying over densely populated areas, hence minimizing the emitted noise on residential areas. It should be noted that these are just notional trajectories and not the result of an optimization study.

4 CLEAN SKY ROTORCRAFT TECHNOLOGIES

As discussed before, the GRC ITD looks into innovative rotorcraft technologies in order to meet the ACARE goals. Each GRC sub-project has displayed advanced breakthrough technologies. In the current work contributions from GRC4 and GRC5 which account for (piston) High Compression Engine (HCE) advanced technologies and Environment Friendly Flight paths respectively were not incorporated. The estimated performance benefits which are derived from the individual technologies are applied directly into EUROPA and HELENA. The incorporated GRCi technologies as well as the advanced engine model for low NO_x combustion, as deployed in the conceptual vehicles, are briefly explained below. It must be noted that to date the Turbomeca engine model has been applied in the TEH and SEL configurations. The GSP model is applied only in the TEL configuration in which the fuel flow and exhaust gas emissions were adjusted according to Turbomeca's input.

4.1 SAGE ITD - Engine Model for low NO_x combustion

In the current version of PhoeniX an engine model developed by Turbomeca is deployed. The working principles in terms of software integration are identical as for the GSP model. The TM conceptual engine model technology was developed during several European projects and concluded in Clean Sky1. The main aim of these research programs was to develop and validate innovative lean fuel injection technologies in order to reduce NO_x emissions by 60-70%. In this engine model, the ultra-low NO_x combustor core technology is subject to the performance of the injection system. At the injection stage, a complete evaporation of the fuel before entering the combustor can offer a homogeneous air/fuel mixing at the injection exit. Thus, reduced NO_x emissions can be obtained. However, a complete evaporation at the injection stage could potentially cause auto-ignition as well as flow reversal (of the evaporated fuel in the injection system). For low OPR engine cycles, the Lean Premixed Prevaporised (LPP) injection concept is applied due to the fact that auto-ignition and flow reversal constraints are much lower. The flames produced by the LPP burners generate low gas temperatures as compared to a stoichiometric mixture of a conventional combustor technology. It is this low temperature flame which offers a drastic reduction of the NO_x emissions. At low operating conditions, the flame of the LPP burner is unstable which can cause a risk of weak extinction in case of a spontaneous reduction of engine power. This problem is alleviated by the use of a Pilot stage. In addition, the global air flow split is controlled by the geometrical dimensions, of the holes of the combustor walls and the effective area of the injection systems. The LPP injection system design is adjusted in order to optimize the air flow fraction.

Table 19 presents the differences in the NO_x predictions between the TEH baseline (TEH-B), reference (TEH-R) and conceptual (TEH-C). As well as the other GRC(i) technologies identified in Table A1 (Annex A1), the TEH-C includes the better representation of CO2/NOx reduction contribution from the engine technology improvement.

Baseline and reference configuration incorporate a linear model for NOx prediction whereas in the conceptual model a non-linear model is applied to take into account the behavior of the 2 injection systems (pilot and LPP) and the distribution of fuel flow between pilot and LPP stages.

4.2 GRC1-Innovative Rotors

GRC1 aims to develop innovative active rotor technologies. The Active Gurney Flap (AGF) selected and applied to TEH, Active Twist currently selected and applied to SEL & TEL all weight classes using a passive optimized blade as the baseline. As GRC analysis becomes more accurate future technology selections are subject to further update. The AGF can increase the maximum lift coefficient ($C_{l,max}$) of the rotor blades together with increasing the nose down pitching moment C_M and reducing the zero lift angle of attack (α_0). Thus, AGF effectively increases the airfoil camber [16] and can possibly offer a greater lift-to-drag ratio, in spite of the associated increase of the drag coefficient (C_d). AGF can offer main rotor power reduction at representative segments of the flight envelope i.e a wide range of rotor loading and advance ratios. The incorporation of these benefits, in PhoeniX, has been performed via the use of look-up tables. The Active Gurney Flap could also be used to facilitate a significant reduction in main rotor speed, with an accompanying reduction in main rotor thickness noise. The Active Twist (AT) technology is expected to apply a Higher Harmonic Control (HHC) 2 / rev variation in spanwise blade twist as an open loop input. AT is estimated to produce a significant reduction in main rotor noise by reducing Blade Vortex Interaction (BVI) as a rotorcraft is descending on approach to land. This benefit should be assumed to have no significant negative effect on shaft power requirements in this flight condition, although electrical power is required to drive the system. In level flight a slight reduction in main rotor shaft power relative to the passive rotor up to 1% is expected, dependant on the advance ratio and the blade loading.

GRC1 has also developed passive optimized blades which can offer rotor blades with improved vibration, noise and performance characteristics. It must be considered that passive blades are not actively adaptable, and the selection of operating conditions for optimisation is a dominating factor on the benefits achieved. Both optimisation of passive blade geometry and the use of laminar flow aerofoils are studied, to achieve performance and acoustic benefits, coupled with Dual Speed Rotor (DSR).

4.3 GRC2-Drag Reduction of Airframe and Non-lifting Rotating Systems

GRC2 aims to develop, through extensive numerical analysis by means of CFD, wind tunnel experiments and flight testing, innovative rotorcraft configurations, which will display fuselage drag reduction. Particularly, in the TEH configuration the rotor hub cap and mast fairing have been optimized for low drag. This is due to the effective reduction of parasitic drag which is obtained by

more streamlined bodies. A reduced parasitic drag translates to reduced power requirements, hence reduced fuel consumption and the associated NO_x emissions. In addition, GRC2 vehicle configurations benefit from a passive shape optimization approach [[17]] / vortex generators [[18]] on blunt aft body. Another objective of GRC2 is to increase the available power by improving engine installation. A novel air intake for the TEL helicopter has been designed via numerical analysis and wind tunnel tests. The benefit of this new technology will be assessed in flight in 2015. The ERICA tilt rotor has been aerodynamically optimised too. The addressed components are the fuselage and the engine installation in the nacelles [[18]].
The benefits of the GRC technologies have been integrated in PhoeniX through the adjustment of the individual drag coefficients of the fuselage and the non-lifting surfaces.

4.4 GRC3-Integration of Innovative Electrical Systems

GRC3 aims to develop innovative electrical systems which will result to greener rotorcraft configurations. More precisely, the new technologies aim to replace the hydraulic systems on rotorcraft by electrically powered systems along with reducing the weight of the whole on-board energy system. In addition, a main objective is also to reduce the CO_2 emissions and improve the overall electrical power system energy efficiency. In the TEH, the GRC3 applied technologies account for new brushless started generators, storage techniques and development of novel converter technologies. In addition, energy recovery and management tools have been developed as well as an electric rotor brake technology. In terms of actuators, innovative electromechanical actuators (main rotor control, brakes, landing gears and utility actuators) have been developed. The impact of these technologies have been accounted for in EUROPA by applying a mass saving to the conceptual operating empty weight and where applicable a delta to the accessory power.

4.5 GRC4-Integration of a High Compression Engine on a Light Helicopter

GRC4 aims to modify, assemble and test a flightworthy helicopter with a light High Compression Engine. The objective is to take advantage of the extremely low specific fuel consumption which can be obtained thanks to High Compression Engine technology developed in the automotive industry in order to integrate this technology on helicopters and drastically reduce their gas emission level. The assessment of the HCE (Diesel) on a single engine light rotorcraft was performed. The Phoenix platform conceptual TM engine model of the Single Engine Light (SEL) was replaced by a HCE model representing the environmental benefits predicted by the program.

4.6 GRC5-Environment Friendly Flight Paths

GRC5 aims to develop optimized flight paths and pilot guidance systems. The benefits of the optimized trajectories have not yet been incorporated in the current version of PhoeniX and the assessments performed to date. The first GRC5 integration into the Twin Engine Medium platform is expected in the TE's 4th Assessment planned in late 2014

4.7 GRC6-Eco Demonstrators for Rotorcraft

GRC6 aims to develop eco-friendly life cycle processes in the phases of manufacturing, maintenance and disposal of specific helicopter components. To be more specific, GRC 6 will demonstrate the possibility, on actual rotorcraft specific parts, to substitute hazardous substances and environmentally harmful processes with materials and industrial methods which can correct these problems. This includes work towards improving the dismantling capability and recyclability. GRC6 also aims to investigate innovative methodologies in order to reduce emissions and energy consumption in manufacturing, maintenance and dismantling. The benefits, derived from the work done within GRC6, were applied in PhoeniX in terms of weight saving i.e. reduction of the helicopter empty mass

5 RESULTS

The assessment work reported here focused on three different geographical locations. These geographical locations were identified by the TE and account for typical (busy) airports/heliports in

Europe where the helicopter traffic was assessed. The missions were defined in such a way in order to capture a radius of 40 km from the airport/heliport of interest. The selection of the locations was done using public domain information and under the assumption that helicopters can use the specified heliports as a permanent or temporary base. The trajectories between the three helicopter classes are fixed and ATC constraints were not applied. It must be noted that the trajectories have not been optimized e.g. by using an optimization algorithm or by varying the speed and/or the altitude of the helicopter. Annex A1 consists of 3 tables which summarise, for each of the following weight classes assessed, the mission, mission type, GRC(i) technology benefits included into the Y2020+ Conceptual platforms and the constituent part of Phoenix impacted as a result.

5.1 EMS Mission (TEL helicopter class)

For the EMS mission illustrated in Figure 5 the helicopter starts from its base and cruises at high speed towards a hypothetical accident location. In this case a motorway traffic accident was considered and a helicopter is utilised in order to transfer the injured civilians to the nearest hospital. The helicopter then returns to its base after the delivery of the injured civilians. A typical EMS mission (as simulated in this study) comprises the following operations:

1. The helicopter starts both engines and rotors on the helipad
2. The helicopter remains in idle for 5 minutes
3. The helicopter lifts into the hover
4. The helicopter climbs to 1500 ft AGL at 80 knots
5. The helicopter transits at 120 knots to the rescue zone
6. The helicopter lands at the rescue area where an accident has occurred
7. The helicopter collects the civilians in distress, rotors running on ground for 1 minute
8. The helicopter climbs to 1500 ft AGL at 80 knots
9. The helicopter transits at 120 knots to the nearest accessible hospital with a landing pad
10. The helicopter lands at the hospital's helideck
11. The helicopter sits for 1 minute with rotors turning on the ground while the patients are unloaded
12. The helicopter lifts into the hover
13. The helicopter climbs to 1500 ft AGL at 80 knots
14. The helicopter transits at 120 knots to the original helipad
15. The helicopter lands at the original helipad
16. The helicopter sits for 1 minute with rotors turning on the ground

(a) (b)

Figure 4 Reference EMS mission (a) Fuel Economy (b) Population Avoidance

It must be noted, that the first two segments of each scenario are identical. This has been done due to the fact that during EMS helicopter operations the helicopter will typically follow the shortest route to the accident point in order not to lose crucial time. Thus, only in the last segment from the hospital back to the heliport a diversion around the city centre can be seen.

5.1.1 EMS Fuel Burn & Emissions Results

EMS F	R vs B %Δ	C vs B %Δ	C vs R %Δ
Fuel Burn	-11.8	-25.7	-15.7
CO_2	-11.8	-25.6	-15.7
NO_x	-17.7	-73.9	-68.3

Table 1 Percentage differences in Fuel Burn, CO2 and NOx (EMS-TEL-Fuel Economy)

EMS P	R vs B %Δ	C vs B %Δ	C vs R %Δ
Fuel Burn	-11.9	-25.9	-15.9
CO_2	-11.9	-25.9	-15.9
NO_x	-18.0	-74.1	-68.4

Table 2 Percentage differences in Fuel Burn, CO_2 and NO_x (EMS-TEL-Population Avoidance)

The trends observed in the obtainable fuel burn, CO_2 and NO_x percentage reduction have been shown to be quite similar for both missions. It has been shown that the deployment of the Conceptual TEL helicopter configuration may result in a percentage reduction in CO_2 of the order of 25% and about 70% for NO_x relative to the Y2000 Baseline.

5.1.2 EMS Noise Results

Representative noise contours for the EMS mission are provided in Annex A1. The following tables illustrate the percentage differences in assessed noise level areas between each configuration. It is to be noted that there are clear differences in noise levels between the two missions, as expected.

EMS F	R vs B %Δ	C vs B %Δ	C vs R %Δ
> 55 dB(A)	-5.6	-16.2	-11.2
> 60 dB(A)	-10.9	-29.0	-20.3
> 65 dB(A)	-14.5	-47.0	-38.1
> 70 dB(A)	-25.8	-71.6	-61.8
> 75 dB(A)	-44.6	-78.8	-61.8
> 80 dB(A)	-28.9	-74.0	-63.5
Average	-21.7	-52.8	-42.8

Table 3 Percentage differences in assessed noise level areas (EMS-TEL-Fuel Economy)

EMS P	R vs B %Δ	C vs B %Δ	C vs R %Δ
> 55 dB(A)	-3.4	-9.7	-6.6
> 60 dB(A)	-8.7	-29.2	-22.4
> 65 dB(A)	-18.9	-52.2	-41.0
> 70 dB(A)	-25.4	-74.4	-65.7
> 75 dB(A)	-47.9	-80.2	-62.0
> 80 dB(A)	-29.0	-74.0	-63.4
Average	-22.2	-53.3	-43.5

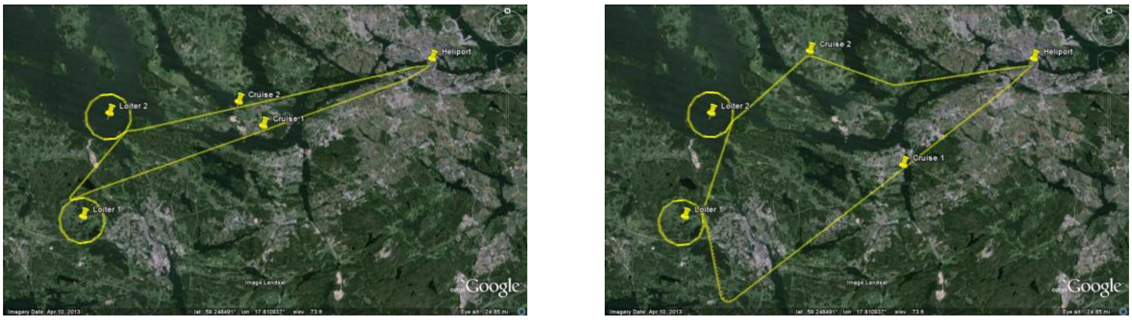
Table 4 Percentage differences in assessed noise level areas (EMS-TEL-Population Avoidance)

5.2 Police Mission (TEL helicopter class)

In the Police mission shown in Figure 6, the helicopter starts from its base and will cruise towards two distinct loiter points. ATC constraints were not applied in this mission. A typical Police mission (as simulated in this study) comprises the following operations:

1. The helicopter starts both engine(s) and rotors on the ground at the helipad
2. The helicopter remains in idle for 5 minutes
3. The helicopter will taxi to the main runway and await take off clearance
4. The helicopter lifts into hover

5. The helicopter climbs to 1500 ft AGL at 80 knots
6. The helicopter transits at 120 knots to the searching /tracing area
7. The helicopter descends to 1000 ft AGL and loiters at about 60 knots
8. Once the searching/tracking is completed, the helicopter transits at 120 knots back to the police helipad
9. The helicopter lands at the original helipad
10. The helicopter sits for 1 minute with rotors turning on the ground
11. The helicopter will taxi according to the directions provided by the ATC of the helipad



(a) (b)

Figure 5 Reference Police mission (a) Fuel Economy (b) Population Avoidance

5.2.1 *Police Fuel Burn & Emissions Results*

Police F	R vs B %Δ	C vs B %Δ	C vs R %Δ
Fuel Burn	-12.2	-26.5	-16.3
CO_2	-12.2	-26.1	-15.8
NO_x	-18.3	-74.5	-68.8

Table 5 Percentage differences in Fuel Burn, CO2 and NOx (Police-TEL-Fuel Economy)

Police P	R vs B %Δ	C vs B %Δ	C vs R %Δ
Fuel Burn	-12.3	-26.7	-16.4
CO_2	-12.3	-26.6	-16.3
NO_x	-18.5	-74.6	-68.9

Table 6 Percentage differences in Fuel Burn, CO2 and NOx (Police-TEL-Population Avoidance)

The trends observed in the obtainable fuel burn, CO_2 and NO_x percentage reduction have been shown to be quite similar for both missions. It has been shown that the deployment of the Conceptual TEL helicopter configuration may result in a percentage reduction in CO_2 of the order of 25% and about 75% for NO_x relative to the Y2000 Baseline.

5.2.2 *Police Noise Results*

The following tables illustrate the percentage differences in assessed noise level areas between each configuration. It is to be noted that there are clear differences in noise levels between the two missions, as expected.

Police F	R vs B %Δ	C vs B %Δ	C vs R %Δ
> 55 dB(A)	-4.4	-12.7	-8.7
> 60 dB(A)	-7.9	-26.4	-20.1
> 65 dB(A)	-15.0	-41.3	-31.0
> 70 dB(A)	-20.8	-52.4	-39.8
> 75 dB(A)	-39.5	-61.6	-36.5
> 80 dB(A)	-26.0	-68.1	-56.8
Average	-18.9	-43.7	-32.1

Table 7 Percentage differences in assessed noise level areas (Police-TEL- Fuel Economy)

Police P	R vs B %Δ	C vs B %Δ	C vs R %Δ
> 55 dB(A)	-1.6	-14.6	-13.1
> 60 dB(A)	-7.8	-26.5	-20.3
> 65 dB(A)	-17.2	-43.5	-31.7
> 70 dB(A)	-24.2	-62.1	-50.1
> 75 dB(A)	-42.0	-63.2	-36.5
> 80 dB(A)	-26.0	-67.7	-56.4
Average	-19.8	-46.3	-34.7

Table 8 Percentage differences in assessed noise level areas (Police-TEL-Population Avoidance)

5.3 Passenger/Transport Mission (SEL helicopter class)

For the Passenger/Transport mission illustrated in Figure 6 the helicopter starts from its base and will cruise towards a hypothetical location where it will collect a certain amount of passengers. After transferring the passengers to the destination location it will subsequently return to its base. ATC constraints were not applied in this mission. A typical Passenger/Transport mission comprises the following operations:

1. The helicopter starts engine and rotors on the helipad
2. The helicopter remains in idle for 5 minutes
3. The helicopter lifts into the hover
4. The helicopter climbs to 1500 ft AGL at 80 knots
5. The helicopter transits to the location of the passenger- pick up point at 120 knots
6. The helicopter hovers whilst pilot positions for landing
7. The helicopter lands at the passenger pick up point and the passenger(s) get on board
8. The helicopter awaits for takeoff clearance
9. The helicopter lifts into hover
10. The helicopter climbs to 1500 ft AGL at 80 knots and heads towards the designated drop-off zone at 120 knots
11. The helicopter lands at the designated drop off zone and the passengers exit the aircraft
12. The helicopter lifts into hover
13. The helicopter climbs to 1000 ft AGL at 80 knots and heads towards the originating heliport at 120 knots
14. The helicopter lands at the original heliport
15. The helicopter sits for 1 minute with rotors turning on the ground

(a) (b)

Figure 6 Reference Passenger/Transport mission (a) Fuel Economy (b) Population Avoidance

5.3.1 Passenger/Transport Fuel Burn & Emissions Results

Passenger/Transport F	R vs B %Δ	C vs B %Δ	C vs R %Δ
Fuel Burn	-5.0	-19.2	-14.9
CO_2	-5.0	-19.2	-14.9
NO_x	-8	-55.1	-51.2

Table 9 Percentage differences in Fuel Burn, CO2 and NOx (Passenger/Transport-SEL_U1-Fuel Economy)

Passenger/Transport P	R vs B %Δ	C vs B %Δ	C vs R %Δ
Fuel Burn	-4.8	-20.0	-15.9
CO_2	-4.8	-20.0	-15.9
NO_x	-7.4	-58.0	-54.6

Table 10 Percentage differences in Fuel Burn, CO2 and NOx (Passenger/Transport-SEL_U1-Population Avoidance)

The trends observed in the obtainable fuel burn, CO_2 and NO_x percentage reduction have been shown to be quite similar for both missions. It has been shown that the deployment of the Conceptual SEL helicopter configuration may result in a percentage reduction in CO_2 of the order of 20% and about 55% for NO_x relative to the Y2000 Baseline.

5.3.2 Passenger/Transport Noise Results

The following tables illustrate the percentage differences in assessed noise level areas between each configuration. It is to be noted that there are clear differences in noise levels between the two missions, as expected.

Passenger/Transport F	R vs B %Δ	C vs B %Δ	C vs R %Δ
> 55 dB(A)	-4.25	-22.65	-19.22
> 60 dB(A)	-5.89	-33.71	-29.56
> 65 dB(A)	-9.40	-54.25	-49.50
> 70 dB(A)	-13.88	-57.42	-50.56
> 75 dB(A)	-1.92	-28.85	-27.45
> 80 dB(A)	-7.14	0.00	7.69
Average	-7.08	-32.81	-28.10

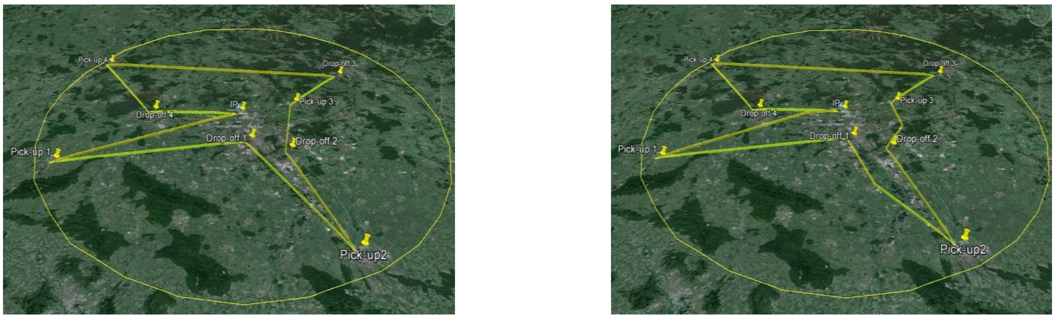
Table 11 Percentage differences in assessed noise level areas (Passenger/Transport-SEL_U1-Fuel Economy)

Passenger/Transport P	R vs B %Δ	C vs B %Δ	C vs R %Δ
> 55 dB(A)	-3.71	-25.22	-22.34
> 60 dB(A)	-11.67	-50.19	-43.61
> 65 dB(A)	-18.99	-66.73	-58.93
> 70 dB(A)	-12.41	-42.07	-33.86
> 75 dB(A)	0.00	-6.98	-6.98
> 80 dB(A)	41.67	41.67	0.00
Average	-0.85	-24.92	-27.62

Table 12 Percentage differences in assessed noise level areas (Passenger/Transport-SEL_U1-Population Avoidance)

5.4 Passenger Mission for HCE (HCE helicopter class)

For the Passenger mission illustrated in Figure 7, the helicopter takes off from Hannover Airport to pick up the designated passenger(s) from a secondary location. It subsequently transfers them to a drop-off point. This procedure is repeated for a total of 4 pick-up and drop-off points. There are two scenarios to the mission, one restrained by Population Avoidance procedures and one without them.



(a) (b)

Figure 7 Passenger mission for HCE (a) Fuel Economy (b) Population Avoidance

5.4.1 Passenger Fuel Burn & Emissions Results

In order to compare the emissions of the HCE in relation to the SEL_U1 Y2020R and Y2020C configurations, three approaches can be used as follows.

Approach 1:

The same Passenger mission profile is applied across all three rotorcraft. In this way, a direct comparison in terms of mass of emitted pollutants is obtained. The mission profiles chosen are the Fuel Economy and Population Avoidance scenarios for the HCE Passenger mission.

Passenger/Transport F	HCE C vs SEL R %Δ	HCE C vs SEL C %Δ
Fuel Burn	-58.5	-49.9
CO_2	-58.5	-49.9
NO_x	-64.3	-11.5

Table 13 Percentage differences in Fuel Burn, CO2 and NOx (Passenger/Transport-SEL-Fuel Economy)

Passenger/Transport P	HCE C vs SEL R %Δ	HCE C vs SEL C %Δ
Fuel Burn	-58.3	-49.8
CO_2	-58.3	-49.8
NO_x	-64.1	-11.0

Table 14 Percentage differences in Fuel Burn, CO2 and NOx (Passenger/Transport-SEL_U1-Population Avoidance)

Approach 2:

Mission level results are normalised with respect to payload and distance. Results in this case are taken from different mission profiles assessed before (for HCE and SEL_U1 respectively). Distances are 44 km and 55 km for SEL_U1-Passenger-Fuel Economy and SEL_U1-Passenger-Population Avoidance respectively, and 250 km and 255 km for HCE-Passenger-Fuel Economy and HCE-Passenger-Population respectively.

Passenger/Transport F	HCE C vs SEL R %Δ	HCE C vs SEL C %Δ
Fuel Burn	-67.7	-62.1
CO_2	-67.7	-62.1
NO_x	-68.0	-34.2

Table 15 Percentage differences in Fuel Burn, CO2 and NOx (Passenger/Transport-SEL_U1-Fuel Economy)

Passenger/Transport P	HCE C vs SEL R %Δ	HCE C vs SEL C %Δ
Fuel Burn	-65.6	-59.2
CO_2	-65.6	-59.2
NO_x	-67.5	-28.6

Table 16 Percentage differences in Fuel Burn, CO2 and NOx (Passenger/Transport-SEL_U1-Population Avoidance)

Approach 3:
Mission level results are normalised with respect to payload and duration. Results in this case are taken from different mission profiles assessed before (for HCE and SEL_U1 respectively). Durations are 0.48 hrs and 0.54 hrs for SEL_U1-Passenger-Fuel Economy and SEL_U1-Passenger-Population Avoidance respectively, and 1.85 hrs and 1.86 hrs for HCE-Passenger-Fuel Economy and HCE-Passenger-Population respectively.

Passenger/Transport F	HCE C vs SEL R %Δ	HCE C vs SEL C %Δ
Fuel Burn	-52.3	-44.0
CO_2	-52.3	-44.0
NO_x	-52.8	-2.8

Table 17 Percentage differences in Fuel Burn, CO2 and NOx (Passenger/Transport-SEL-Fuel Economy)

Passenger/Transport P	HCE C vs SEL R %Δ	HCE C vs SEL C %Δ
Fuel Burn	-54.0	-45.4
CO_2	-54.0	-45.4
NO_x	-56.5	-4.5

Table 18 Percentage differences in Fuel Burn, CO2 and NOx (Passenger/Transport-SEL-Population Avoidance)

The results obtained for the Passenger mission demonstrate that the deployment of the Conceptual HCE helicopter configuration may result in a percentage reduction in CO2 between 54 and-67% and between 56 to 68% for NOx relative to the SELU1 Y2020 Reference.

5.5 Oil & Gas Mission (TEH helicopter class)

For the Oil & Gas mission, which is shown in Figure 8 only the fuel economy scenario was performed due to the geographic location (North Sea) of the mission. The hypothetical scenario of the mission accounts for a TEH helicopter operated from Den Helder Airport. The helicopter transits towards two specific oil and gas platforms transferring personnel. Subsequently the helicopter returns back to its base. ATC constraints were not applied in this mission. A typical Oil & Gas mission comprises the following operations:

1. The helicopter starts both engine(s) and rotors on the helipad
2. The helicopter remains in idle for 5 minutes
3. The helicopter lifts into hover
4. The helicopter climbs to 3000 ft AGL at 80 knots.
5. The helicopter transits at 120 knots towards the first oil off-shore platform
6. The helicopter hovers over the oil platform, lands and unloads its payload/personnel
7. The helicopter sits for 10 minutes on the deck during passenger and baggage off-loading and loading
8. The helicopter lifts into hover with 10 passengers and baggage
9. The helicopter climbs to 1000 ft AGL at 70 knots towards the second oil off-shore platform
10. The helicopter hovers over the oil platform where it lands and unloads its payload/personnel
11. The helicopter sits for 10 minutes on the deck during passenger and baggage offloading and loading
12. The helicopter lifts into hover with 5 passengers and baggage

13. The helicopter climbs to 3000 ft AGL at 80 knots and heads towards the original heliport at 120 knots
14. The helicopter lands at the original helipad
15. The helicopter sits for 10 minute with rotors turning on the ground during unloading
16. The helicopter taxis according to the directions provided by the ATC of the airport

Figure 8 Reference Oil & Gas mission Fuel Economy

5.5.1 Oil & Gas Fuel Burn & Emissions Results

Oil & Gas F	R vs B %Δ	C vs B %Δ	C vs R %Δ
Fuel Burn	-10.3	-20.6	-11.5
CO_2	-10.3	-20.6	-11.5
NO_x	-16.1	-55.4	-46.8

Table 19 Percentage differences in Fuel Burn, CO2 and NOx (Oil & Gas-TEH-U1 Fuel Economy)

The results obtained for the Oil & Gas mission demonstrate that the deployment of the Conceptual TEH helicopter configuration may result in a percentage reduction in CO_2 of the order of 21% and about 55% for NO_x relative to the Y2000 Baseline.

6 CONCLUSIONS

The main conclusion that can be drawn from the above exercise is that the deployed new technologies show a great potential of reducing important performance and gas emission metrics such as fuel burn, CO_2 and NO_x. Specifically, it has been illustrated that there is approximately a 74% and 47%, for the TEL/SEL and TEH helicopter configurations respectively, reduction in NO_x. A contributing factor to the reduction of NOx identified between the platforms is the more accurate representation of the SAGE ITD low combustion engine technology by TM integrated in the later TEH Conceptual platform. The reduction in fuel burn and CO_2 is around 22-30 %. In addition, the new technologies illustrate a significant reduction in the acoustic footprint area. The reductions can vary between 50% and 80% approximately compared to the year 2000 Baseline. Acoustic footprint area deltas seem to be consistent in all acoustic ranges for both Fuel Economy and Population Avoidance missions. The noise reduction obtained by the Y2020 Reference rotorcraft is due to the reduced main rotor tip speed, reduced maximum take-off mass and increased performances (flyover, take-off and approach speeds) compared to the Y2000 Baseline. The benefits in noise reduction for the Y2020 Cleansky rotorcraft are due to the Dual Speed Rotor (DSR) Technology as well as to the Active Twist noise technology which reduces blade vortex interaction in approach segments.

The above tables (for Fuel Economy and Population Avoidance) must not be compared directly on the grounds that the lower values of the corresponding surfaces in the fuel economy mission are due to the type of the mission (direct point to point helicopter trajectory). In addition, it is acknowledged that the 55 to 60 dB noise levels should be taken with caution as they are subject to undesirable effects (such as background noise) in a realistic environment. It is advised not to consider these noise levels for assessing the achievement towards the ACARE goals. In addition, significant percentage area reduction is present in the very high level acoustic bands (> 85 dB(A)) due to the fact that is easier to reduce concentrated areas which exhibit high noise levels as SEL levels are directly tackled by speed. The TE's future assessment of Twin Engine Medium and Tilt-Rotor, coupled with the GRC7 continual improvement of the PhoeniX platform (for example inclusion of various power system modules to simulate the effects on fuel burn, CO_2 and NO_x of actuation, electrical, fuel, environmental control and ice protection systems – provided by Cranfield University), TURBOMECA engine models and increased Technology Readiness Levels, will contribute to the most accurate and complete view of the Clean Sky technology benefits being developed within the GRC ITD.

7 ACKNOWLEDGMENTS

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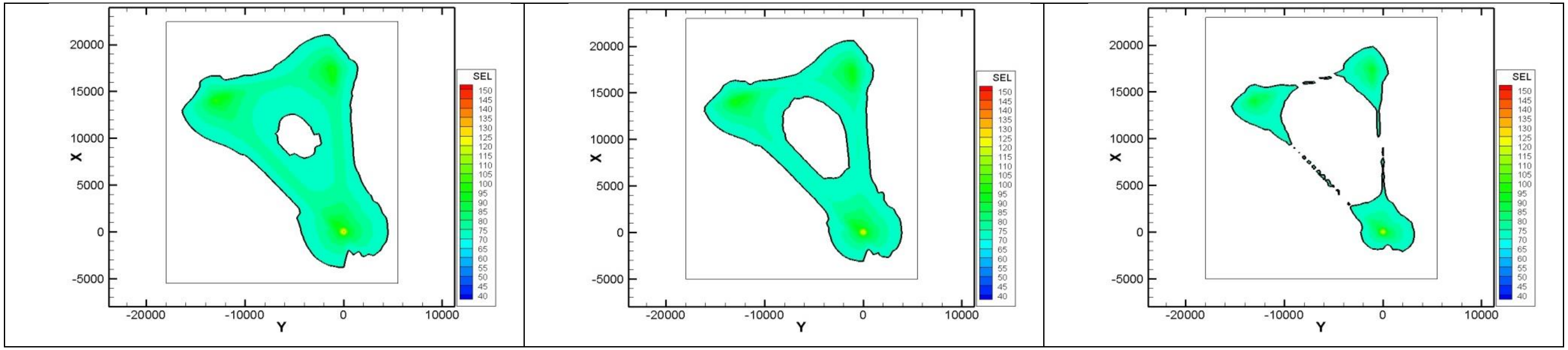
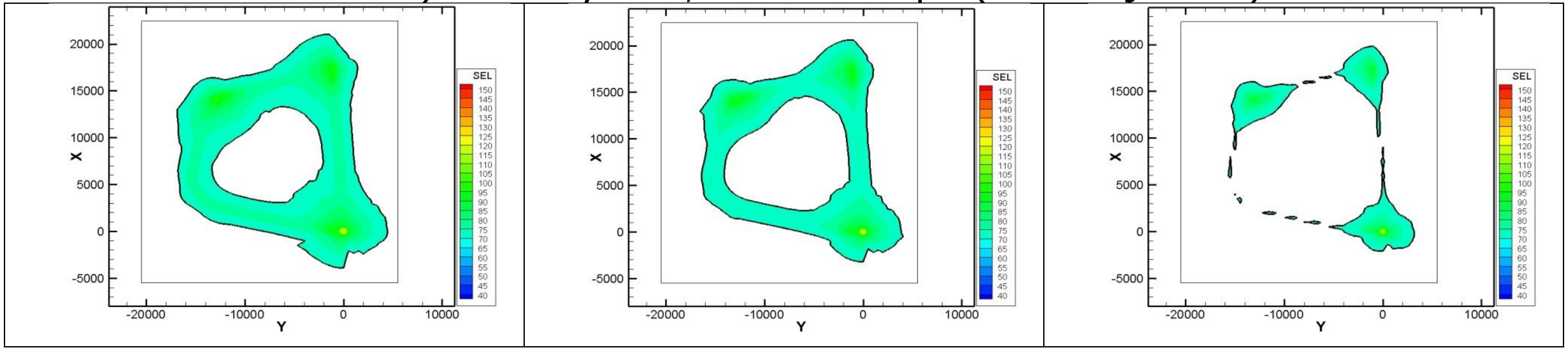
ANNEX A1

NOISE CONTOURS



a) Fuel Economy Baseline, Reference and Conceptual (from left to right columns)



b) Population Avoidance Baseline, Reference and Conceptual (from left to right columns)

Figure A1 Variation of Sound Exposure Level noise contour [km^2] (EMS Mission > 70 dB(A))

By inspecting Figure A1 from Baseline to Conceptual it can be stated that the noise carpet reduces at the middle of the figures. This area corresponds to the densely populated area (see Figure 4). The great white area (noise < 70 dB(A) corresponds to reduced noise. Noise reduction has been obtained thanks to helicopter mass reduction, tip speed reduction, and increased flight speed compared to Baseline. In the conceptual rotorcraft the effect of DSR technology is clearly seen in the flyover segments and the Active Twist effect on approach segments.

R/C	Mission	Mission Type	GRC CleanSky Benefits Applied to Y2020 Reference = Y2020 Conceptual	EUROPA Δ	HELENA Δ	ENGINE Δ
TEL	EMS & Law	Noise reduction requirement < 2000ft altitude, densely populated area	GRC1- Active Twist & Passive Optimized Blades	√	√	
			GRC2- Active devices/vortex on blunt fuse, improved skids & hub cap	√		
			GRC3- Brushless starter generator, power convertor, energy storage, distribution & recovery, electromechanical actuators, piezo actuators	√		
			SAGE ITD- CO_2 and NO_x reduction applied to GSP engine model			√ (GSP)
R/C	Mission	Mission Type	GRC CleanSky Benefits Applied to Y2020 Reference = Y2020 Conceptual	EUROPA Δ	HELENA Δ	ENGINE Δ
SEL	Passenger / Taxi	Noise reduction requirement < 2000ft altitude, densely populated area	GRC1- Active Twist & Passive Optimized Blades	√	√	
			GRC2- Active devices/vortex on blunt fuse, improved skids & hub cap	√		
			GRC3- Brushless starter generator, power convertor, energy storage, distribution & recovery, electromechanical actuators, piezo actuators	√		
			SAGE ITD- CO_2 and NO_x reduction applied to GSP engine model			√ (GSP)
R/C	Mission	Mission Type	GRC CleanSky Benefits Applied to Y2020 Reference = Y2020 Conceptual	EUROPA Δ	HELENA Δ	ENGINE Δ
TEH	Oil & Gas	Performance requirement >2000ft, no noise requirement	GRC1- AGF & Passive Optimized Blades	√		
			GRC2- Passive shape optimization/vortex on blunt aft & improved hub cap	√		
			GRC3- Brushless starter generator, power convertor, energy storage, distribution & recovery, electromechanical actuators, piezo actuators	√		
			GRC6- Thermoplastic tail, transmission shaft, door & floor demonstrators	√		
			SAGE ITD-Engine model representing the (Turbomeca) low NO_x combustion technology			√ (Turbomeca)

Table A1 GRC technologies as implemented in the current version of PhoeniX