



Large-scale EXecution for Industry & Society

Deliverable D5.5

Avio Aero use cases: review of Aeronautics use cases' KPIs and expected impact on Aeronautical market



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GLOSSARY

ACRONYM	DESCRIPTION
ANN	Artificial Neural Network
BD	Big data
CAE	Computer-aided Engineering
CAGR	Compounded Average Growth Rate
CFD	Computational fluid dynamics
CPU	Central processing unit
DOE	Design of experiments
FV	Finite Volume
GPU	Graphics processing unit
HPC	High performance computing
HW	Hardware
KPI	Key Performance Indicator
LP	Low pressure
MPI	Message Passing Interface

OPENMP	Open Multiprocessing
RANS	Reynolds Averaged Navier Stokes
SFC	Specific Fuel Consumption
SME	Small and medium-sized enterprise
SPH	Smoothed-particle hydrodynamics
SW	Software
URANS	Unsteady Reynolds Averaged Navier Stokes
USD	U.S. dollar
WP	Work Package

TABLE OF PARTNERS

ACRONYM	PARTNER
Avio Aero	GE AVIO SRL
Atos	BULL SAS
AWI	ALFRED WEGENER INSTITUT HELMHOLTZ ZENTRUM FUR POLAR UND MEERESFORSCHUNG
BLABS	BAYNCORE LABS LIMITED
CEA	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES
CIMA	CENTRO INTERNAZIONALE IN MONITORAGGIO AMBIENTALE - FONDAZIONE CIMA
CYC	CYCLOPS LABS GMBH
ECMWF	EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS
EURAXENT	MARC DERQUENNES
GFZ	HELMHOLTZ ZENTRUM POTSDAM DEUTSCHESGEOFORSCHUNGSZENTRUM GFZ
ICHEC	NATIONAL UNIVERSITY OF IRELAND GALWAY / Irish Centre for High-End Computing
IT4I	VYSOKA SKOLA BANSKA - TECHNICKA UNIVERZITA OSTRAVA / IT4Innovations National Supercomputing Centre
ITHACA	ASSOCIAZIONE ITHACA
LINKS	FONDAZIONE LINKS / ISTITUTO SUPERIORE MARIO BOELLA ISMB
LRZ	BAYERISCHE AKADEMIE DER WISSENSCHAFTEN / Leibniz Rechenzentrum der BAdW
NUM	NUMTECH
O24	OUTPOST 24 FRANCE
TESEO	TESEO SPA TECNOLOGIE E SISTEMI ELETTRONICI ED OTTICI

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EXECUTIVE SUMMARY

The LEXIS project relies on three large-scale pilot use cases to validate and deploy its technology and infrastructure improvements, assigning to each pilot its own work package. The Work Package 5 (WP5) that this deliverable refers to is dedicated to the Aeronautics Large-scale Pilot and relies on the advanced HPC/Cloud/Big Data (BD) platforms and techniques designed in WP2 (LEXIS Requirements Definition and Architecture Design) along with WP3 (Data system and data management) and WP4 (Orchestration and cloud services), besides having some relationships and interactions also with WP8 (LEXIS Portal for Third Party Companies and SMEs) and with WP9 (Impacts on Targeted Sectors).

Focusing here on the industrial use cases implemented in the WP5, the aim of the Aeronautics Large-scale Pilot led by Avio Aero in LEXIS is to significantly improve the feasibility and exploitation of advanced Computer-Aided Engineering (CAE) numerical modelling capabilities able to predict the fluid-dynamic behaviour of aircraft engine critical components. From both a digital technology and business perspective, a significant change is thus envisaged: faster and more accurate CAE analyses that exploit newly deployed HW/SW resources in an innovative cross-converged HPC/Cloud/BD environment enabling the implementation of greatly improved or newly designed CFD (Computational fluid dynamics)-based engineering methodologies. To meet this ambitious objective in WP5, the industrial applicability of the LEXIS advanced engineering platform is under investigation through two aeronautical engineering case studies, one regarding turbomachinery - the "Turbomachinery Use Case"- and the other one referring to rotating parts representing gearboxes - the "Rotating Parts Use Case", both designed to examine complex fluid dynamic behaviour in aeronautical engine critical components. With a specific look at their differences, Turbomachinery Use Case, that is based on CPU-demanding, data-intensive and time-consuming unsteady CFD simulations of a LP (low pressure) turbine, mainly aims to reduce as much as possible the running time of the adopted CFD application solver to calculate faster all the engineering variables of interest, such as pressure, density, momentum or stagnation energy of the turbomachinery flow field. Instead, Rotating Parts Use Case, which is built on sophisticated CFD simulations aimed at studying complex flow fields in mechanical parts rotating at high speed in a multi-phase mixture (air/oil), is focused on supporting the execution of the used CFD application solver and optimizing its set-up with the final target of predicting key phenomena involved in the rolling gears, like windage effects and resistant torques both impacting on mechanical efficiency and power transmission levels of gearboxes. Looking to the wider scenario of Aeronautics in Europe, the methods developed within WP5 in LEXIS can be transferable to other companies in the aeronautical domain, like European jet engine manufacturers and their OEMs.

In this context, the present Deliverable D5.5, that is the fifth technical deliverable of the whole WP5, is intended to illustrate the measured KPIs (Key Performance Indicators) and the expected impacts on the aeronautical market resulting from the implementation in LEXIS of the two above-mentioned aeronautical engineering case studies included in WP5. More specifically, the targeted KPIs of Turbomachinery Use Case - the improvement of the time needed to execute LP (low pressure) turbine CFD simulations and the advancement in the quality of the design process that is supported by such simulations - will be reviewed and the resulting impacts on the aeronautical market will be presented. On the other side, with regard to Rotating Parts Use Case, the associated KPIs - the speedup of the analysis process for the gearbox simulations and the widening of design process quality - will be assessed and the supposed impacts on the aeronautical market will be illustrated.

Position of the deliverable in the whole project context

This deliverable is a product of WP5 activities carried out so far in *Task 5.1 - HW/SW Integration Requirements*, *Task 5.2 - Turbomachinery Use Case Set-up and Run* and *Task 5.3 – Rotating Parts Use Case Set-up and Run* and is framed in the context of the WP5 project tasks specifically aimed to assess both the KPIs associated to the use cases included in the LEXIS Aeronautics Large-scale Pilot and the impacts on the aeronautical market that may be derived from their implementation.

This Aeronautics Large-scale Pilot relies on CPU-intensive and time-consuming CAE simulations aimed to examine the complex fluid dynamic behaviour of low-pressure turbines and gearboxes respectively through Turbomachinery Use Case and Rotating Parts Use Case, that are the two aeronautical engineering case studies included in LEXIS WP5. The complexity and difficulty in the development of such large-scale test beds arise out of obligation to combine the specification of the used SW application with the proper HW technologies and configurations aiming at the optimal mapping on the HW/SW infrastructure of the computing system used to execute it. Once fully implemented the most suitable HW/SW infrastructural layer, the deployment of the two above-mentioned aeronautical engineering case studies can be assessed through some quantifiable measure of performance over time for the specific objectives included in the considered use cases.

In this context, the present document will review the KPIs related to the two use cases included in the LEXIS Aeronautics pilot and will describe the impacts that may be foreseen in the aeronautical market thanks to the outcomes from the two discussed use cases.

Focusing on the presentation of the KPIs achieved and measured within the two Aeronautics use cases and on the description of the expected impacts on the Aeronautical market, Avio Aero will be singly responsible for writing this deliverable including some contributions from the University of Florence.

From a contractual standpoint, this report document has to be delivered at the end of M36.

Description of the deliverable

The main purpose of this document is to illustrate the KPIs associated with and the possible impacts expected from the deployment in LEXIS of the Aeronautics Large-scale pilot after summarizing the engineering foundation of Turbomachinery Use Case and Rotating Parts Use Case that this pilot is built on.

The description of the KPIs and expected impacts starts from Turbomachinery Use Case in Section 2 and then continues by discussing Rotating Parts Use Case in Section 3.

Finally, in Section 4 we summarize the main outcomes from the assessment of the above-mentioned KPIs and expected impacts analysed in both the considered Aeronautics use cases.

1 INTRODUCTION

Reducing the fuel consumption of aircraft engines is a key requirement for players in the aeronautic industry. Significant efforts are underway to produce reliable turbo-engine performance predictions, using physics-based multi-physics simulations to help anticipate problems typically encountered in the detailed design phases. This demands the adoption of CPU-intensive and time-consuming CAE simulations based on sophisticated numerical solvers.

From a digital technology and business perspective, Avio Aero intends to achieve a marked step change: less time-consuming computational analyses that exploit newly designed, improved and/or tightly coupled HW/SW components able to open the doors to the “real-time” design approach for the engineering of turbines. Furthermore, the big data produced as a result will require proper solutions for quick data access, management, and post-processing.

Framed in this context, the exploitation in LEXIS of both next-generation HPC/Cloud/BD technologies and advanced CFD software solutions is enabling in the Aeronautics Large-scale pilot innovative and faster investigation strategies for the design and optimization of critical aircraft engine’s components. Specific KPIs have been defined for the Aeronautics Large-scale pilot to demonstrate success against the declared objectives within this industrial test bed. This test bed relies on long-running HW-intensive CAE simulations aimed to examine the complex fluid dynamic behaviour of low-pressure turbines and gearboxes through the two aeronautical engineering case studies included in LEXIS WP5, Turbomachinery Use Case and Rotating Parts Use Case, respectively. The achievement of the target values for the KPIs identified for the two above-mentioned case studies is supposed to have some positive impacts in the considered aeronautical industrial sector.

In this deliverable the description of the assessed KPIs and the expected impacts on the aeronautical market that are linked and consequent to the implementation of the WP5 - Aeronautics Large-scale Pilot in LEXIS is provided. In detail, after the introductory part, this deliverable includes 3 main sections:

- 2 - Avio Aero Turbomachinery Use Case: review of KPIs and market impacts,
- 3 - Avio Aero Rotating Parts Use Case: review of KPIs and market impacts
- 4 - Summary.

Section 2 summarizes the measured KPIs and the expected impacts on the aeronautical market resulting from the implementation of Turbomachinery Use Case after introducing it from an engineering standpoint.

Section 3 resumes the obtained KPIs and the impacts foreseen on the aeronautical market deriving from the implementation of Rotating Parts Use Case after briefly describe it from an engineering perspective.

Finally, Section 4 resumes the KPIs and the impacts discussed in this deliverable.

2 AVIO AERO TURBOMACHINERY USE CASE: REVIEW OF KPIS AND MARKET IMPACTS

After providing a description of the underlying engineering foundation, this chapter will review the KPIs related to the Aeronautics Turbomachinery Use Case developed in LEXIS and will illustrate the impacts that may be foreseen in the aeronautical market thanks to the outcomes from the implementation of the discussed use case.

2.1 ENGINEERING FOUNDATION

Playing in the aeronautical market, the demand for reduced fuel consumption is a leading parameter especially for the turbomachinery modules. Nowadays, there are significant efforts to get increasingly reliable performance prediction, using more and more physics-based solutions and multi-physics simulation approaches able to

anticipate problems, typically encountered in the detailed design phases. This implies the adoption of CPU-intensive and time-consuming CAE simulations based on sophisticated numerical solvers.

In this context, Avio Aero intends to obtain a significant change from both a digital technology and business perspective: faster CFD analyses on turbomachinery that can leverage newly designed, enhanced and/or more strictly joined HW/SW components and be so capable to open the doors to the “real-time” design approach applied to the engineering of turbines. Furthermore, the big data produced as result from such CFD simulations will demand proper solutions for accessing, managing and post-processing data in a quick and effective way.

Inside this thread, the improvement of a CFD solver, that is named TRAF [1] and is developed by the University of Florence (UNIFI), is envisaged. Specifically designed to assist turbomachinery designers, this code solves steady/unsteady 3D, Reynolds-averaged Navier-Stokes equations in the finite volume formulation on multi-block structured grids. Extensively validated against several turbomachinery configurations, a basic level of parallelization has been already achieved by means of a hybrid OpenMP/MPI code architecture running on solely CPU-based platforms.

Starting from the production version of the code, that is suitable to run on pure CPU-based HPC infrastructures, LEXIS project has allowed Avio Aero to face and carry out some research and development activities for porting the solver to GPU-accelerated computing platforms in order to drastically reduce the execution time: the 5x speedup was put as real challenging target and represents the value we are comparing the outcomes from the made research with.

A strongly reduced computational time for the TRAF-based CFD investigations included in the implemented Turbomachinery Use Case is not only a great achievement from a digital technology standpoint. From a wider business perspective as well, that means faster availability of engineering information that the designers use to optimize any turbomachinery design they are committed to do. This way of working will become the basis to pursue and hit the challenging targets, enforced from the post COVID-19 market, as described in the next paragraphs.

2.2 REVIEW OF THE TARGETED KPIS

This section will review the two KPIs associated to Turbomachinery Use Case implemented in LEXIS, starting from the improvement in the run-time requested from LP turbine CFD simulations and then moving to highlight benefits in the design process quality made possible by such an improvement.

2.2.1 Improvement of the running time for LP turbine’s simulations

The originally decided objective of reducing the running time of LP turbine unsteady CFD simulations by a factor of at least 5 has been pursued by accelerating the TRAF solver on GPU-equipped HPC architectures. This objective was set with the aim of increasing the number of turbine design iterations per unit time, thus allowing to shorten the time to market and/or lower costs in the context of aircraft engine development. Another aim is to allow more sophisticated and accurate simulations to be affordable in industrial design practice, thus enabling better engine behaviour prediction to guide the design process.

The primary KPI used to measure the achievement of the above stated goal is the so-called “speedup”, defined as the ratio

$$S = \frac{\Delta t_{CPU}}{\Delta t_{GPU}}$$

where the numerator represents the computational (wall clock) time of a given simulation running on a CPU-based architecture, while the denominator is the computational time of the same simulation running on a GPU-equipped platform. It is clear that this ratio is also dependant on the choice of the two simulation setups being compared: in order for the resulting value to be meaningful, the two setups have to be realistic. As far as the baseline CPU-

running setup is concerned, the number of MPI processes should be chosen in such a way that each of them deals with a number of cells comparable to the size of the biggest mesh block, in order to have a balanced workload. Moreover, each MPI process should run on a dedicated CPU core. For the GPU-accelerated setup, the overall number of employed GPUs should be chosen so that the simulation can fit in their on-board memories.

Therefore, the originally set goal translates into achieving a speedup equal to or greater than 5. In order to reach this target, UNIFI has ported the TRAF solver to GPU-equipped HPC architectures and has extensively optimized the code to maximize performance through GPU acceleration: this challenging activity consisted in an initial porting and in multiple optimization campaigns, at the end of which a final optimized version of TRAF was completed.

The latest optimized version of the TRAF code was tested on the Barbora HPC cluster [2] at IT4I with an industrial test case based on a reduced (quarter annulus) version of the turbomachinery pilot case study. In this industrial test case, the baseline calculation was performed by 108 MPI processes on 108 CPU cores (on 3 Barbora nodes), with no GPU acceleration. The GPU-accelerated calculation, instead, employed 16 Barbora GPUs on 4 nodes, by running 16 MPI processes (one MPI process on each GPU). It should be noted that the reduced version of the turbomachinery pilot case was precisely created in order to fit in the on-board memories of Barbora GPUs: the full case would have required to use 16 GPU-accelerated nodes, more than those available on Barbora. In a simulation, each step takes approximately the same time. The average net computational time per step was measured during the tests. The results are displayed in Table 1.

NUMBER OF NODES	MPI PROCESSES × OpenMP THREADS	HARDWARE RESOURCES	NET TIME PER STEP [s]	SPEEDUP
3	108 × 1	108 CPU cores	689.4	(baseline)
4	16 × 1	16 GPUs	97.98	7.04

Table 1 “Reduced” (quarter annulus) industrial test case on Barbora: performance figures of the CPU-based computation setup (baseline) and the GPU-accelerated one

As can be seen, the target speedup of at least 5x is clearly achieved.

The industrial test case was also performed on the more powerful Karolina HPC cluster [3] available at IT4I, in order to assess how the latest GPU-accelerated version of TRAF could perform on state-of-the-art GPUs. Several different setups were tested on different numbers of nodes, and, hence, on different numbers of GPUs. Since each Karolina GPU has more than twice the on-board memory of a GPU on Barbora, it was even possible to run the reduced industrial test on just 1 Karolina node (equipped with 8 GPUs). Table 2 shows the performance figures obtained respectively on 1, 2, 3, 4 nodes and, specifically for the last three setups, reports the parameter “m” in the second column, that represents a variable number of OpenMP threads (equal to the number of mesh blocks each MPI process has to deal with).

NUMBER OF NODES	MPI PROCESSES × OpenMP THREADS	HARDWARE RESOURCES	NET TIME PER STEP [s]	SPEEDUP
1	8 × 8	8 GPUs	110.6	6.23
2	16 × m	16 GPUs	56.66	12.2
3	24 × m	24 GPUs	44.14	15.6
4	32 × m	32 GPUs	32.22	21.4

Table 2 “Reduced” (quarter annulus) industrial test case on Karolina: performance figures of the best performing GPU-accelerated setups with 1, 2, 3, and 4 nodes

As can be observed, it was possible to obtain a speedup above 5 even on just one Karolina node: the achieved value was 6.23. By exploiting 32 GPUs, the maximum speedup of 21.4 was achieved, with respect to the baseline setup (which was run on Barбора CPUs).

2.2.2 Improving design process quality

Leveraging the very remarkable speedup improvements obtained by porting the TRAF code on GPU-accelerated HPC environments, Avio Aero research future activity will then move to revamp the turbine design system methodology through:

- *The review of optimization processes* based henceforth on the URANS (Unsteady Reynolds Averaged Navier Stokes equations) solvers instead of the currently used RANS (Reynolds Averaged Navier Stokes equations) ones. In this way, unsteady effects will be taken into account to get more accurate and physics-based results. The relevance of optimization tasks was a little lost in the recent past since design outcomes from RANS tools struggled to convert predicted numerical benefits into the reality of every-day engine's operational life. This penalty is linked to the fact that interaction effects between turbomachinery rows were completely neglected. Current target, in line with market trends as reported in Section 2.3, will be the achievement of concrete improvements in the thermodynamic Low Pressure Turbine module efficiency, just minimizing blades' interaction and flow unsteadiness loss contribution.
- *The adoption of GPU-accelerated computing platform*, as the technical outcomes highlighted in the previous paragraph strongly suggest. By drastically cutting back on execution time, the GPUs will enable to explore faster the space of solutions in LP turbine unsteady CFD simulations. Thus, the collection of a larger amount of simulation results allows to markedly boost next and extensive ANN (Artificial Neural Network) investigations, operating on a wide variety of design space parameters, aimed at defining the so-called Optimum candidate in terms of constraints and performance.

The newly revised engineering procedure should include three main steps. Firstly, a set of turbine blading geometries are selected and the related CFD simulations aim to predict the turbomachinery flow field making use of the URANS CFD solver "TRAF". Once population of results has been created, also working in different operating conditions, a meta-model has to be built. This will finally allow designers to select the optimum candidate fully fitting the design requirements.

Figure 1 shows these three important steps in the turbine optimization process leading to increase design quality: expected benefits should be around -0.30% in terms of engine Specific Fuel Consumption (SFC).

In this respect, it should be noted that the discussion of the KPI presented here in terms of improvement of the design process quality is only qualitative and not measurable at this stage because the quantitative evaluation for this KPI was not included in the scope of WP5 and a dedicated project to quantitatively assess that improvement is instead required.

The -0.3 % benefit is indeed a projection coming from some preliminary Avio Aero analyses carried out on legacy engines already operating on the market by comparing numerical solutions with/without the application of the novel internal procedure.

WORKFLOW WITH THREE STEPS

INITIAL POPULATION, META-MODEL BUILD, OPTIMUM CANDIDATE SELECTION

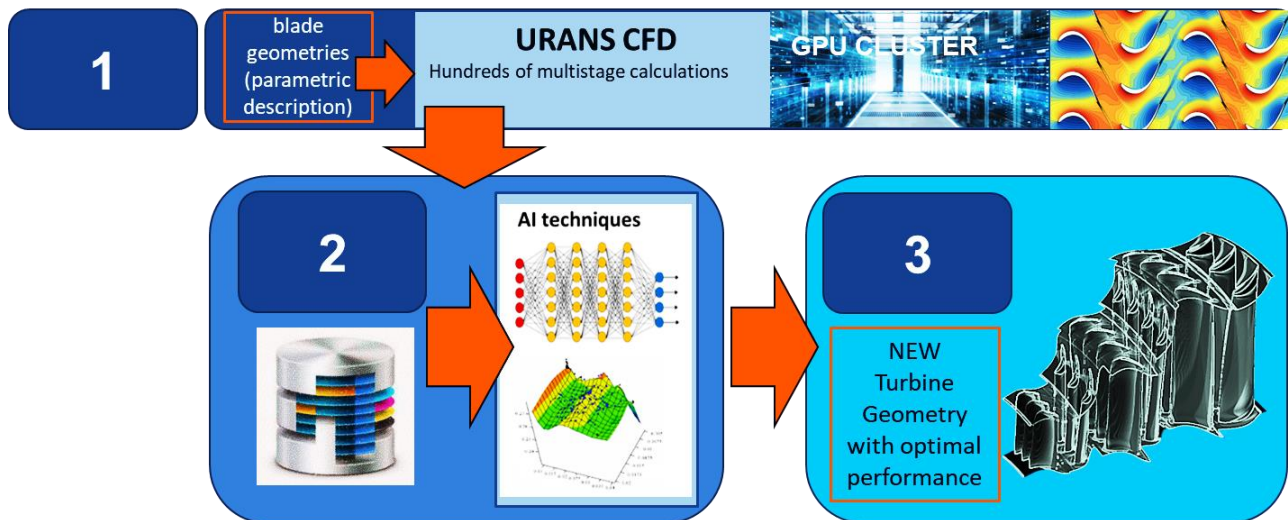


Figure 1 Optimization process using URANS SW based on GPU-equipped computing platform

2.3 EXPECTED IMPACTS ON THE AERONAUTICAL MARKET

The COVID-19 pandemic has impacted the industrial verticals adversely, resulting in a sudden dip in 2020 aircraft engines orders and deliveries. Major players like General Electric Company (US), Safran SA (France), Honeywell International Inc (US), MTU Aero Engine (Germany), and Rolls Royce PLC (UK), whose businesses are spread across various countries (North America, Europe, Asia Pacific, Middle East, Africa, and Latin America), have recorded important losses both in production and services globally.

Now that the general situation is starting to improve and the world is returning to its so-called normalcy, the aircraft engine market size is projected to grow [4] from USD 60.8 billion in 2021 to USD 92.9 billion by 2026, at a CAGR (Compounded Average Growth Rate) of 8.9% from 2021 to 2026, as shown in Figure 2.

The market is strongly characterized by the rising request for highly fuel-efficient aircraft engines driven by the worldwide more and more pressing demand of limiting as much as possible pollution effects negatively acting on our atmosphere: a greener world is a priority and must become reality.

That said, it is easy to understand that, nowadays, aero engine designers will be committed to a really difficult job and will be required to use a new generation of HW/SW platforms for engineering in order to obtain the best possible engine configuration and performance. In this view, LEXIS project has demonstrated itself to provide a really impactful and advanced engineering platform, where sophisticated engineering tools and state-of-the-art hardware technologies have been stressed for being improved and finally validated.

Some market forecasts in Aeronautics report that aero-engine SFC reduction is predictable in the order of -0.30%, corresponding for a long-range flight to eliminate tons and tons of pollutants.

According to this trend, the great results previously illustrated in the Section 2.2 qualify the adopted engineering approach as a fundamental decision-making tool without which next-generation aeronautical turbomachinery products would be out of the market.

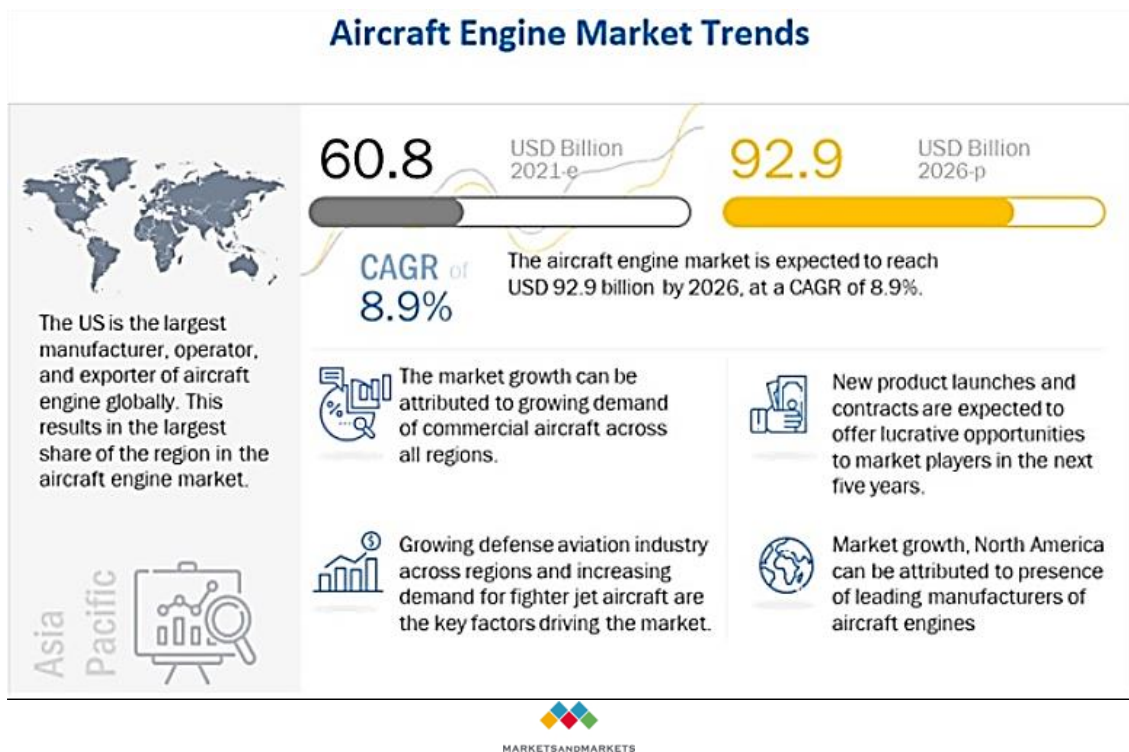


Figure 2 Aircraft Engine Market trends in 2021-2026 [4]

3 AVIO AERO ROTATING PARTS USE CASE: REVIEW OF KPIS AND MARKET IMPACTS

This chapter, after providing a description of the engineering foundation underlying the Aeronautics Rotating Parts Use Case, will focus on the assessment of the associated KPIs and will describe the impacts on the aeronautical market resulting from the implementation of the discussed use case.

3.1 ENGINEERING FOUNDATION

In the context of CFD engineering analyses, today challenges are arising when studying complex flow fields in mechanical parts that rotate at high speed in the presence of air and lubricating oil.

Nowadays this kind of engineering investigations is at the leading edge of numerical technology and perfectly fits to the need of designing gearboxes capable to withstand with the highest transmission efficiency. The challenge here is to predict and simulate, with increasing accuracy, the flow field operating inside aeronautic gearboxes where the combination of jet lubrication and high tangential speeds precludes the possibility of neglecting the interactions between liquid and gaseous phase.

The simulation of these phenomena typically requires a large amount of compute resources and takes considerable running time. In this context, the commercial solver Altair nanoFluidX™ [5] will be used and widely tested in different conditions so as both to provide a high quality of analysis and to minimize the computational time as much as possible.

These two latter drivers mixed together represent a key factor to improve business productivity and pave the way for assuring performance and reliability to the next-generation aeronautical engines.

3.2 REVIEW OF THE TARGETED KPIS

This section will review the two KPIS related to Rotating Parts Use Case, starting to examine the speedup obtained in the CFD investigations on gearboxes then moving on to the widening of the quality in the design process that is assisted by the discussed CFD simulations.

3.2.1 Speedup of the analysis process for the gearbox simulations

The process applied to improve the running time of the CFD investigations on gearboxes is described in Table 3. The reported data refers to the run-time needed to perform an air-oil mixture simulation for an industrial gearbox, representative of next generation engines' products. This is the most complex simulation required to assess a fluid-dynamic behaviour.

In Table 3, firstly, experimental data related to the preparation and test execution are highlighted. Goal is to put in evidence that experimental activity covers at least 2 months. This work is highly labour-intensive and results in a highly cost solution if compared to the numerical approach one.

As far as the numerical approaches are concerned, traditional FV (Finite Volume) CFD computational times are also reported just to reaffirm the non-applicability of this type of modelling to products such as gearboxes in favour of Smoothed-Particle Hydrodynamics (SPH) methods, like the one developed in LEXIS, that are less time consuming. The remaining part of Table 3 describes the deployment path carried out for nanoFluidX® over the three-years LEXIS project, summarized in main points hereafter:

- The preliminary phase was firstly dedicated to training in order to understand how the nanoFluidX software is working and only later aimed at increasing, thanks to a comparison with basic experimental data collected at UNIFI, the results' accuracy. This goal has implied a consistent increase of the particles' amount used in every SPH simulation to correctly reproduce air and oil motions.
- After having set-up best practices for correct air/oil simulation, basic version of air-oil mixture was executed using 16 GPUs of the Barбора cluster along 2020. Computational time has increased due to a bigger number of particles involved in the simulation, equal to about 200 million after lowering the diameter. The running time is very high and requires 1 week and half.
- The ultimate version of nanoFluidX methodology (2021) incorporates, first, some improvements introduced while deploying the pre-processing and post-processing phases. The former one has been simplified by Altair team, while the latter takes benefits from excel macros and scripts generated along the long development phase. Secondly, the execution of nanoFluidX on the final version of LEXIS platform (taking advantage from the new advanced GPUs NVIDIA A100 available at Karolina HPC cluster) allows to cut of about 30%-40% the simulation running time, despite the extremely large amounts of small diameter-particles involved in the computation.

Comprehensive benefits, including pre/post-processing phases, lead to save almost 40% of overall simulation time.

CFD VALIDATION IN LEXIS PROJECT	EXPERIMENTS	FV CFD	nanoFluidX VERSION 2019 START VERSION	nanoFluidX VERSION 2020 TARGETING ACCURACY	nanoFluidX V2021 HW/SW OPTIMIZATION
Machining	> 3 weeks				
Assembly	> 2 weeks				
Testing	> weeks				
Pre-processing	32 × m	> 2 weeks	2 days	2 days	1 day
Simulation runtime		8-12 weeks	6 days (oil & air separately) Particles # range 60-80 Million	10 days (mixture oil+air frozen field) Particles # range 120-200 Million	6 days (mixture oil+air frozen field) Particles # range 120-400 Million
Hardware		Hundreds of CPUs	Max 16 GPU V100 Barbora cluster	Max 16 GPU V100 Barbora cluster	Max 32 GPU A100 Karolina cluster
Post-processing		2 days	2 days	2 days	1 days

Table 3 Summary of nanoFluidX evolution and computing time

3.2.2 Widening of design process quality

Through Rotating Parts Use Case in LEXIS project, Avio Aero aims to develop enablers supporting the digital (r)evolution being applied to the design and development of gearboxes, that are a key product within the Avio Aero business.

The main goal is replacing, or at least supporting, the traditional gearbox design approach based on correlations, expertise and legacy data with a completely new CFD numerical method capable of quickly and reliably validating the industrial solutions that Avio Aero is going to insert in the next-generation gearboxes. Checking the general behaviour of the air-oil mixture, its distribution, the scavenging capabilities as well as keeping the resistant torque levels under control are the most important issues to be addressed during the design and analysis phases. For this reason, securing the accuracy and reliability of the numerical solver underlying the above-mentioned CFD investigations is the top priority.

The preliminary step in the validation process of the newly designed CFD methodology has been focused to make sensitivity studies aimed to investigate the size of the flow particles and to set up the numerical model to effectively reproduce the physical phenomena. The key results finally obtained are resumed in Table 4 showing firstly the physical media considered, secondly the engineering parameters of interest, then the green check mark indicating the good accuracy level achieved and, finally, the nanoFluidX practice summarized in terms of particle diameter to be selected for the right balancing of simulation fidelity and running time.

PHYSICS	VALIDATION	ACCURACY LEVEL	PRACTICE
OIL flow SIMULATION	RES. TORQUE	✓	Optimum particle 1/20 oil-jet diameter
AIR flow SIMULATION	LIQUID FILM FORMATION	✓	
AIR flow SIMULATION	WINDAGE TORQUE	✓	1 particle per oil-jet diameter
OIL flow SIMULATION	MATING PROCESS TORQUE	✓	Particle 1/5 oil-jet diameter = minimum to get liquid behaviour

Table 4 Fidelity practices for oil and air simulation with nanoFluidX

After validating the newly introduced CFD-based engineering approach, the next step will be dedicated to defining a new design process as follow-up of LEXIS project. This should be done in the short-term period in order just to improve current products' design on the way. Basic scheme is shown hereafter in Figure 3.

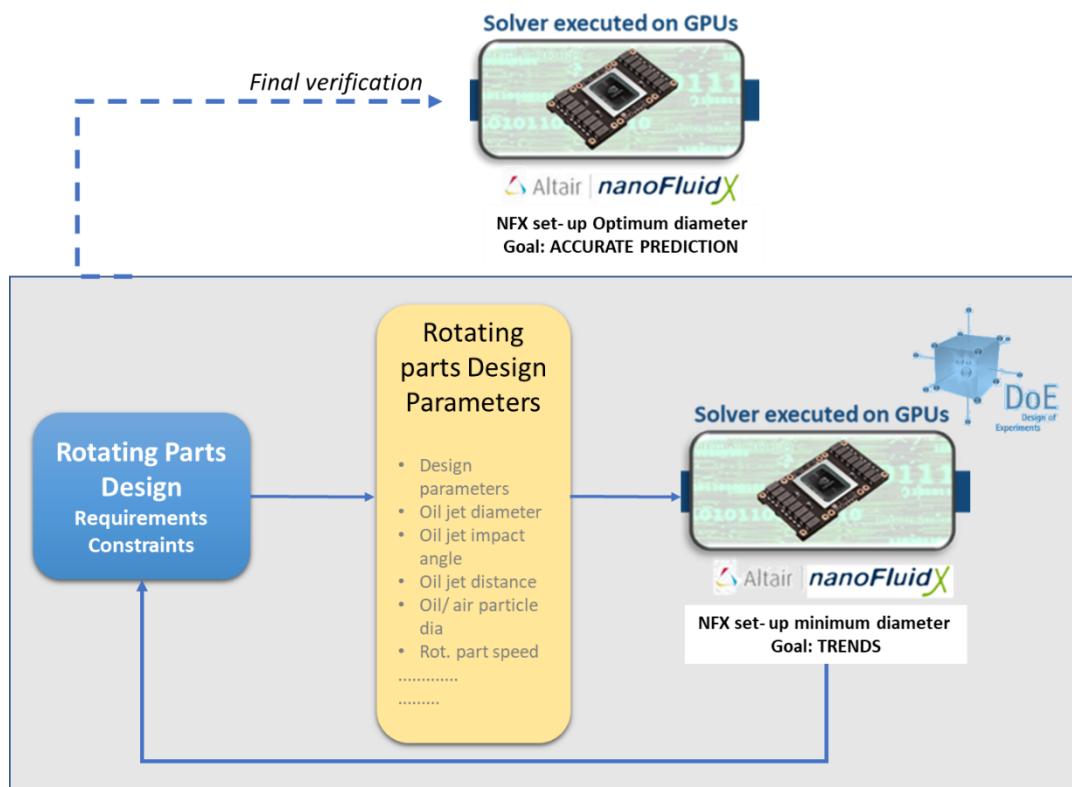


Figure 3 Design of Experiments for gearbox design

Firstly, traditional set-up of requirements for a new gearbox and its related constraints covering safety, performance and durability aspects must be defined. Afterwards, nanoFluidX simulations will be launched to investigate effects of selected parameters (like oil jet diameter, oil jet impact angle, oil jet distance from the rotating wheel, different wheel speed). Particles' granularity will be fixed at the minimum value assessed in the LEXIS validation phase to get quick, but low, accurate answers for improving design issues. Target here is to get trends and derivatives of parameters versus performance.

Final validation of gearbox design will be carried out by selecting particles' diameters sufficiently small, in line with the previously defined best practices. Goal here is to get accurate and reliable performance data.

This new procedure is expected to provide, besides assuring standard safety aspects, important gains in mechanical efficiency and gearbox sizing optimization. Consequent weight savings are expected to range among 1,00–3,00 [kg] acting to reduce aero-engine specific fuel consumption from -0.3% to -0.1 %. The former value refers to a short-range aircraft while the latter one is for a long-range aircraft mission.

Design of experiments technique applied to gearboxes design is the first step preparing rotating parts to be assessed by a more complex optimization procedure, similarly to the approach that has been reported in the Section 2.2.2 for the Turbomachinery Use Case. The unique difference between these two fundamental aeronautical products (turbine and gearbox) is the maturity level of CFD application software, that is much more consolidated in turbomachinery products after some decades of usage and evolution.

3.3 EXPECTED IMPACTS ON THE AERONAUTICAL MARKET

Gearboxes are key aeronautical engine components not only for the airplanes' market but also play an important role in helicopters. As for the aircrafts' market described above at paragraph 2.3, in 2020 the COVID-19 pandemic has led to a significant drop in demand for helicopters globally, with a corresponding reduction in revenues for various suppliers, service providers across all markets owing to late delivery, manufacturing shutdown, limited staff at manufacturing facilities, and limited availability of equipment.

Actual forecasts see a recovery of the global aeronautical demand by 2022 fully. Manufacturers will have to undertake important efforts to design new products, at the state-of-the-art, and regain pre-COVID market and sales shares. In this revamping frame, while assuring standard levels of safety imposed by international regulations, gearboxes will be required to:

- Minimize as much as possible overall weight and size, in order to reduce fuel consumption and to enhance cost-effectiveness,
- Optimize power transmission performance.

From that perspective, it can be said that:

- Simulating the lubrication of a gearbox remains a complex computing task, almost out of reach to many traditional CFD software. The Smoothed-Particle Hydrodynamics method, that the solver nanoFluidX is based on, has demonstrated to offer, during the LEXIS project roll-out, remarkable advantages in the CFD investigations included in Rotating Parts Use Case, because of its particle-based and Lagrangian nature: particles naturally follow the fluid flow induced by mechanical movements.
- Adopting these innovative CFD approaches, like the nanoFluidX-based one, will provide a break-through lever to help and enrich company expertise to make the right choices in terms of gearbox design parameters and/or simulate in a virtual environment some conditions to be reproduced experimentally on the field. Engineers can test and compare several design choices, optimize oil flow quantity to improve design efficiency and quality while reducing manufacturing cost (less oil means less carter volume/space, so less material and weight).

Against this background, the results from the research and development tasks in LEXIS must be considered as a fundamental step of engineering progress in Aeronautics without which future aeronautical rotating parts products will not be able to correctly respond to the market needs and to successfully sustain post-COVID growth in a robust way. To this aim, as a complement to the aircraft engines growth already presented in the section 2.3, Figure 4 illustrates the expected trends in the short period global helicopter market [6].

Global Helicopter Market Trends

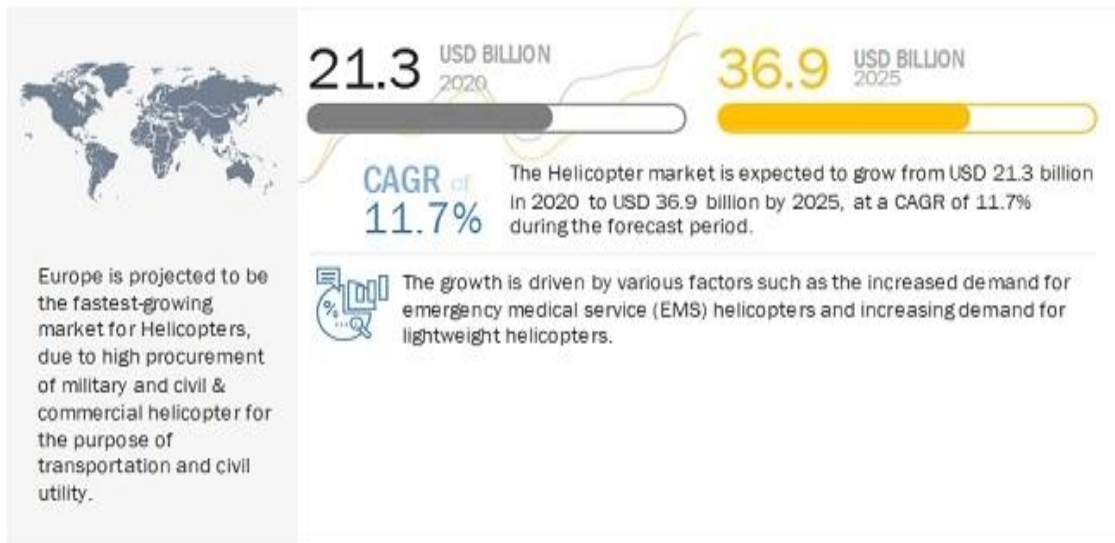


Figure 4 Global market helicopter trends in the short period [6]

4 SUMMARY

In this deliverable the measured KPIs and the expected impacts on the aeronautical market resulting from the implementation in LEXIS of the two aeronautical engineering case studies included in WP5, the Turbomachinery Use Case and the Rotating Parts Use Case, have been presented.

For Turbomachinery Use Case, the review of the two targeted KPIs - the improvement of the time needed to execute LP turbine CFD simulations and the advancement in the quality of the design process that is supported by such simulations - has been carried out here. Such analysis has revealed that the successfully achieved target in terms of computing speedup through the GPU-based acceleration of the TRAF solver allows turbomachinery designers not only to explore faster the space of fluid dynamics solutions, but also to pave the way for a more effective optimization process fully fitting the design constraints and technical requirements of low pressure turbines. Moreover, the impacts that may be foreseen in the aeronautical market thanks to the outcomes from the implementation of Turbomachinery Use Case have been also illustrated, showing that the engineering approach adopted in the discussed use case may represent a fundamental decision-making tool without which next-generation aeronautical products may be out of the market.

On the other hand, with regard to Rotating Parts Use Case, the details about the assessment of the associated KPIs -the speedup of the analysis process for the gearbox simulations and the widening of design process quality- have been provided here. The reported discussion has shown that remarkable benefits in terms of running time reduction resulting from the adoption of SPH methods allow gearbox designers to investigate the multiphase fluid-dynamic behaviour of high-speed gearboxes faster than using traditional FV CFD approaches. Moreover, it has been argued that the newly developed CFD methodology is supposed to provide important gains in mechanical efficiency and gearbox sizing optimization, so leading to increase the design quality. Finally, the impacts on the aeronautical market that result from the implementation of Rotating Parts Use Case have been also highlighted, indicating that the newly introduced CFD -based engineering approach, which has been validated in this use case, may be considered as a key step of engineering progress in the context of next-generation aeronautical rotating parts products.

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